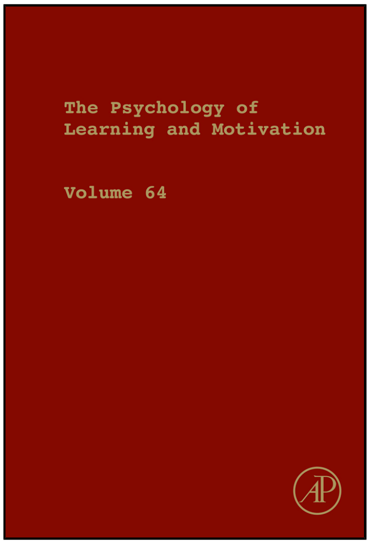

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CHAPTER ONE

Beyond Born versus Made: A New Look at Expertise

David Z. Hambrick[*,1], **Brooke N. Macnamara**[§], **Guillermo Campitelli**[¶], **Fredrik Ullén**[||] **and Miriam A. Mosing**[||]
[*]Department of Psychology, Michigan State University, East Lansing, MI, USA
[§]Department of Psychological Sciences, Case Western Reserve University, Cleveland, OH, USA
[¶]School of Psychology and Social Science, Edith Cowan University, Perth, Australia
[||]Department of Neuroscience, Karolinska Institutet, Stockholm, Sweden
[1]Corresponding author: E-mail: hambric3@msu.edu

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Abstract

Why are some people so much more successful than other people in music, sports, games, business, and other complex domains? This question is the subject of one of psychology's oldest debates. Over 20 years ago, Ericsson, Krampe, and Tesch-Römer (1993) proposed that individual differences in performance in domains such as these largely reflect accumulated amount of "deliberate practice." More controversially, making exceptions only for height and body size, Ericsson et al. explicitly rejected any direct

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role for innate factors ("talent") in the attainment of expert performance. This view has since become the dominant theoretical account of expertise and has filtered into the popular imagination through books such as Malcolm Gladwell's (2008) *Outliers*. Nevertheless, as we discuss in this chapter, evidence from recent research converges on the conclusion that this view is not defensible. Recent meta-analyses have demonstrated that although deliberate practice accounts for a sizeable proportion of the variance in performance in complex domains, it consistently leaves an even larger proportion of the variance unexplained and potentially explainable by other factors. In light of this evidence, we offer a "new look" at expertise that takes into account a wide range of factors.

1. INTRODUCTION

No one can deny that some people are vastly more skilled than other people in certain domains. Consider that the winning time for the New York City Marathon in 2014—just under 2 h and 11 min—was more than *2 h* better than the average finishing time (http://www.tcsnycmarathon.org/results). Or consider that Jonas von Essen, en route to winning the 2014 World Memory Championships, memorized 26 decks of cards *in an hour* (http://www.world-memory-statistics.com).

What are the origins of this striking variability in human expertise?[1] Why are some people so much better at certain tasks than other people? One particularly influential theoretical account attempts to explain individual differences in expertise in terms of *deliberate practice* (e.g., Boot & Ericsson, 2013; Ericsson, 2007; Ericsson, Krampe, & Tesch-Römer, 1993; Ericsson, Nandagopal, & Roring, 2005; Keith & Ericsson, 2007). Here, we describe the mounting evidence that challenges this view. This evidence converges on the conclusion that deliberate practice is an important piece of the expertise puzzle, but not the only piece, or even necessarily the largest piece. In light of this evidence, we offer a "new look" at expertise that takes into account a wide range of factors, including those known to be substantially heritable.

The rest of the chapter is organized into the following sections. We describe the deliberate practice view (Section 2) and then review evidence that challenges it (Section 3). Then, we review evidence for factors other than deliberate practice that may also account for individual differences in

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[1] Throughout this chapter, we use the term *expertise* to refer to performance within a particular domain (i.e., domain-specific performance).

expertise (Section 4). We then describe an integrative approach to research on expertise (Section 5). Finally, we summarize our major findings and comment on directions for future research (Section 6).

2. THE DELIBERATE PRACTICE VIEW

The question of what explains individual differences in expertise is the topic of one of psychology's oldest debates. One view is that experts are "born." This view holds that although training is necessary to become an expert, innate ability—*talent*—limits the ultimate level of performance that a person can achieve in a domain. Nearly 150 years ago, in his book *Hereditary Genius,* Francis Galton (1869) argued for this view based on his finding that eminence in domains such as music, science, literature, and art tends to run in families, going so far as to conclude that "social hindrances cannot impede men of high ability, from becoming eminent [and] social advantages are incompetent to give that status, to a man of moderate ability" (p. 41). The opposing view is that experts are "made." This view argues that if talent exists at all, its effects are overshadowed by training. John Watson (1930), the founder of behaviorism, championed this view when he guaranteed that he could take any infant at random and train him to become "any type of specialist [he] might select...regardless of his talents" (p. 104).

The modern era of scientific research on expertise traces back to the 1940s and the research of the Dutch psychologist Adriaan de Groot (1946/1978). Himself an internationally competitive chess player, de Groot investigated the thought processes underlying chess expertise using a "choice-of-move" paradigm in which he gave chess players chess positions and instructed them to verbalize their thoughts as they considered what move to make. From analyses of their verbal reports, de Groot discovered that there was no association between skill level and the number of moves ahead a player thought in advance of the current move. Instead, he found evidence for a perceptual basis of chess expertise. As de Groot put it, the grandmaster "immediately 'sees' the core of the problem in the position" whereas the weaker player "finds it with difficulty—or misses it completely" (p. 320). de Groot attributed this ability to a "connoisseurship" (p. 321) that develops through years of experience playing the game.

Nearly 30 years later, de Groot's (1946/1978) work was the inspiration for Chase and Simon's (1973a) classic study of chess expertise, which marks the beginning of cognitive psychologists' interest in expertise. Testing three chess players—a master, an intermediate-level player, and a beginner—Chase and Simon found that there was a positive relationship between chess skill and memory for chess positions, but only when they were plausible game positions. When the positions were random arrangements of pieces, there was almost no effect of chess skill on memory. Based on these findings, Chase and Simon (1973b) concluded that although "there clearly must be a set of specific aptitudes...that together comprise a talent for chess, individual differences in such aptitudes are largely overshadowed by immense individual differences in chess experience. Hence, the overriding factor in chess skill is practice" (p. 279).

The experts-are-made view has held sway in the scientific literature ever since. Over 20 years ago, in a pivotal article, Ericsson et al. (1993) proposed that individual differences in performance in complex domains (music, chess, sports, etc.) largely reflect differences in the amount of time people have spent engaging in *deliberate practice,* which "includes activities that have been specially designed to improve the current level of performance" (p. 368). In the first of two studies, Ericsson et al. recruited violinists from a Berlin music academy and asked them to estimate the amount of hours per week they had devoted to deliberate practice since taking up the violin. The "best" violinists had accumulated an average of over 10,000 h of deliberate practice by age 20, which was about 2500 h more than the average for the "good" violinists and about 5000 h more than the average for the least accomplished "teacher" group. In a second study, Ericsson et al. found that "expert" pianists, who were selected to be similar in skill level to the good violinists in the first study, had accumulated an average of over 10,000 h of deliberate practice by age 20, compared to only about 2000 h for "amateur" pianists (see Ericsson, 2006; for further discussion of these results).

Ericsson et al. (1993) concluded that "high levels of deliberate practice are necessary to attain expert level performance" (p. 392). More controversially, they added:

> *Our theoretical framework can also provide a* sufficient account *of the major facts about the nature and scarcity of exceptional performance. Our account does not depend on scarcity of innate ability (talent) and hence agrees better with the earlier reviewed findings of poor predictability of final performance by ability tests. We attribute the dramatic differences in performance between experts and amateurs-novices to similarly large differences in the recorded amounts of deliberate practice.*
>
> ***Ericsson et al., (1993, p. 392), emphasis added***

Ericsson et al. further claimed that "individual differences in ultimate performance can largely be accounted for by differential amounts of past and current levels of practice" (p. 392), and stated:

> *We agree that expert performance is qualitatively different from normal performance and even that expert performers have characteristics and abilities that are qualitatively different from or at least outside the range of those of normal adults. However, we deny that these differences are immutable, that is, due to innate talent. Only a few exceptions, most notably height, are genetically prescribed. Instead, we argue that the differences between expert performers and normal adults reflect a life-long period of deliberate effort to improve performance in a specific domain.*
> *(p. 400)*

Ericsson and colleagues have maintained their view over the past two decades. Ericsson et al. (2005) explained:

> *the individual differences in genetically determined capacities and fixed structures required for the development of elite performance appear to be quite limited, perhaps even restricted, to a small number of physical characteristics, such as height and body size. The expert performance framework attempts to explain the large individual differences in performance in terms of individual differences in sustained deliberate practice.*
> *(p. 305)*

Similarly, Keith and Ericsson (2007) argued that "an individual's level of performance in a particular domain is the result of effortful practice activities in which he or she has engaged in over the course of several years with the explicit goal of performance improvement" (p. 135), and clarified that deliberate practice "activities can be designed by external agents, such as teachers or trainers, or by the performers themselves" (p. 136; see also Ericsson, 1998, for this point). Ericsson (2007) claimed that "it is possible to account for the development of elite performance among healthy children without recourse to unique talent (genetic endowment)—excepting the innate determinants of body size" (p. 4), and reflected: "My own thoughts on exceptional ability were influenced by my family and education in Sweden, where views that genetic endowment limited the acquisition of superior performance among otherwise healthy individuals were discouraged." (p. 5).

3. CHALLENGES TO THE DELIBERATE PRACTICE VIEW

It is difficult to overstate the impact of the deliberate practice view. At the time of this writing, the Ericsson et al. (1993) article has been cited over 5400 times (Source: Google Scholar), making it one of the most cited articles in the psychological literature, and nearly a hundred theses and dissertations have been conducted on deliberate practice over the past two decades (Source: ProQuest Dissertations & Theses Global). Citing Ericsson and colleagues' research, one of us noted in a *New York Times* op-ed that there is no denying the "power of practice" (Hambrick & Meinz, 2011a).

Ericsson and colleagues' findings have also filtered into popular culture. Most notably, Ericsson et al.′s (1993) findings were the inspiration for what the writer Malcolm Gladwell termed the "10,000 hour rule" in his bestselling book *Outliers* (2008)—the idea that it takes 10,000 h to become an expert. The 10,000 h rule has since inspired thousands of internet articles and blog posts, and even a rap song that was the theme music for a *Dr Pepper* commercial.[2] No psychologist has had a greater impact on the public's view of expertise than Ericsson.

Nonetheless, it seems fair to say that Ericsson and colleagues' view has been met with considerable skepticism in the scientific literature. Gardner (1995) commented that Ericsson and colleagues' view "requires a blindness to ordinary experience—as well as to decades of psychological theorizing" (p. 802; for a reply, see Ericsson & Charness, 1995), and Schneider (1998) noted that he was "very sympathetic to the model of skill acquisition initially developed by Ericsson and colleagues" but questioned the "basic assumption that progress in a given domain is solely a function of deliberate practice" (p. 424). Winner (2000) observed that "Ericsson's research demonstrated the importance of hard work but did not rule out the role of innate ability" (p. 160), and Anderson (2000) stated that "Ericsson and Krampe's research does not really establish the case that a great deal of practice is sufficient for great talent" (p. 324). Detterman, Gabriel, and Ruthsatz (1998) described the position advocated by Ericsson and colleagues as "absurd environmentalism" (p. 411).

More recently, Gagné (2007, 2013) criticized Ericsson for misrepresenting evidence contrary to his (Ericsson's) view and for caricaturing opposing positions so as to create "straw men" (for a reply, see Ericsson, 2013a), and Tucker and Collins (2012) noted that Ericsson "overlooks a body of

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[2] Ericsson has discussed the 10-year rule extensively (e.g., Ericsson et al., 1993; Boot & Ericsson, 2013), but has emphasized that the 10,000-*hour* rule was invented by Malcolm Gladwell, and that the findings from his (Ericsson's) research were only the "stimulus" for the 10,000-hour rule (see Ericsson, 2012). We do not attribute the 10,000-hour rule to Ericsson. For comment by Ericsson on the 10,000-hour rule, see: https://web.archive.org/web/20150614160055/http://www.abc.net.au/radionational/programs/allinthemind/practice-makes-perfect/3611212#.

scientific literature which strongly disproves his model" (p. 555; for a reply, see Ericsson, 2013b). Marcus (2012) wrote:

> *The psychologist Anders Ericsson went so far as to write, 'New research shows that outstanding performance is the product of years of deliberate practice and coaching, not of any innate talent or skill.' How I wish it were true…. Practice does indeed matter—a lot—and in surprising ways. But it would be a logical error to infer from the importance of practice that talent is somehow irrelevant, as if the two were in mutual opposition.*
> *(p. 97)*

Ackerman (2014) added that "until Ericsson shows cognitive expertise development in a randomly selected group of subjects, including those with moderate mental retardation, there is no reason to believe that such development can be accomplished" (p. 105).

Other scientists have criticized Ericsson and colleagues' methodological approach—the *expert performance approach* (see Boot & Ericsson, 2013; Ericsson & Smith, 1991). Noting that reputation, credentials, and years of experience may correlate weakly with actual performance in a domain, Ericsson and colleagues have emphasized the importance of measuring expertise under controlled conditions using laboratory tasks representative of a domain. The paradigmatic example is the choice-of-move task from de Groot's (1946/1978) chess research. However, Hoffman et al. (2014) have argued that restriction of expertise research to laboratory tasks removes many important professions from consideration, including those in which it is not possible or practical to devise laboratory tasks to capture the essence of expertise in the domain (e.g., astronaut; see also Weiss & Shanteau, 2014). More generally, Wai (2014) noted that "Ericsson appears unable to go beyond his own framework and definitions to incorporate the approaches of others as well as the full network of evidence surrounding the development of expertise" (p. 122).

Thus, although Ericsson and colleagues' view has had enormous impact on both scientific and popular views of expertise, it has been sharply criticized on both conceptual and methodological grounds in the scientific literature.

3.1 Empirically Evaluating the Deliberate Practice View

We have challenged the deliberate practice view on empirical grounds. The major question we have tried to address in our research is simply how important deliberate practice is as a predictor of individual differences in expertise. That is, can individual differences in domain-specific performance largely be accounted for by accumulated amount of deliberate practice, as Ericsson and colleagues have argued?

To answer this question, Hambrick, Oswald, et al. (2014) performed a reanalysis of studies of music and chess, two of the most popular domains for research on expertise. There were two criteria for including a study in the reanalysis: (1) continuous measures of some activity interpretable as deliberate practice and of domain-specific performance were collected, and (2) a correlation between the measures was reported. Hambrick et al. identified six studies of chess and eight studies of music that met these criteria. Ericsson (2013b) noted that correlations between deliberate practice and performance underestimate the true relationship between the two variables, because neither variable can be assumed to be perfectly reliable:

> *The collected reliability of cumulated life-time practice at different test occasions in large samples has typically been found to range between 0.7 and 0.8 implying that estimates of training history could never account for more than 49–64% of variance in measures of performance—even less for measures of performance that are not perfectly reliable.*
> *(p. 534)*[3]

Therefore, using the standard psychometric approach (Hunter & Schmidt, 1990), Hambrick et al. corrected each correlation for the unreliability of both deliberate practice and performance, and asked specifically how much of the *reliable* variance in performance does deliberate practice explain.

Not surprisingly, deliberate practice and performance correlated positively in all of the studies included in the reanalysis. However, even after correcting for unreliability, the correlations indicated that deliberate practice left more of the variance in performance unexplained than it explained. To be exact, as shown in Figure 1, the average proportion of reliable variance in performance explained was 34% for chess and 29.9% for music. Thus, deliberate practice did not largely account for individual differences in expertise in either domain. In a subsequent meta-analysis of a larger number of music

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[3] Ericsson's (2013b) point that less-than-perfect reliability attenuates correlations is correct. However, per the standard formula for a correlation in classical measurement theory ($r_{xy} = r_{x_t y_t}(r_{xx} r_{yy})^{1/2}$, where r_{xy} is the observed correlation, $r_{x_t y_t}$ is the correlation between the "true" scores, and r_{xx} and r_{yy} are the reliabilities of x and y, respectively; see Schmidt & Hunter, 1999), if the reliability of one variable (e.g., deliberate practice) ranges from 0.70 to 0.80, then it could never be expected to account for more than 70–80% of the variance in the other variable (e.g., performance), not 49–64%, and even less if the other variable is not perfectly reliable.

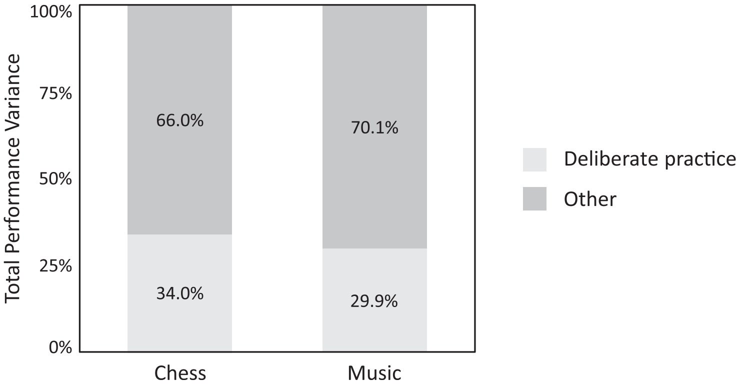

Figure 1 Average percentage of variance in chess performance (left) and music performance (right) accounted for by deliberate practice, correcting for measurement error. The light gray region represents reliable variance explained by deliberate practice; the dark gray region represents reliable variance not explained by deliberate practice. *Adapted with permission of Elsevier from Hambrick, Oswald, et al. (2014), Figures 1 and 3.*

studies, Platz, Kopiez, Lehmann, and Wolf (2014) found that deliberate practice explained 36% of the reliable variance in music performance (avg. corrected $r = 0.61$).

In a commentary, Ericsson (2014a) claimed that Hambrick, Oswald, et al. (2014) rejected his view based on a "common sense basis" (p. 98). In a published reply, Hambrick, Altmann, et al. (2014) explained that they rejected the deliberate practice view on an *empirical* basis—the finding that deliberate practice does not largely account for individual differences in expertise in two of the most widely studied domains in research on expertise. Ericsson also criticized Hambrick, Oswald et al.'s (2014) analysis for ignoring "the effects of forgetting, injuries, and accidents, along with the differential effects of different types of practice at different ages and levels of expert performance" (p. 84). Hambrick, Altmann, et al. (2014) pointed out that Ericsson has never considered all of these factors in his own studies and that their reanalysis included studies that Ericsson has explicitly praised and used to argue for the importance of deliberate practice (e.g., Charness, Tuffiash, Krampe, Reingold, & Vasyukova, 2005).

Macnamara, Hambrick, and Oswald (2014) have since performed a meta-analysis that covers all of the major domains in which the relationship between deliberate practice and expertise has been studied: games, music, sports, education, and professions. To be included in the meta-analysis, a study had to collect measures of one or more activities interpretable as reflecting deliberate practice (i.e., an activity specifically created to improve performance in a domain) and refer to at least one publication on deliberate practice by Ericsson and colleagues to place the study in the deliberate practice literature. A study also had to collect a measure of performance reflecting skill in a particular domain and report an effect size reflecting the relationship between that measure and deliberate practice (or provide information necessary to compute an effect size).[4] Macnamara et al. allowed that deliberate practice could be either self-directed or teacher-directed, consistent with Keith and Ericsson's (2007) aforementioned point that deliberate practice activities can be designed by external agents or by performers themselves, and with how Ericsson and colleagues have operationally defined deliberate practice in their own research (as discussed in more detail below).

Through a search of over 9300 documents, Macnamara et al. (2014) identified 88 studies that met these criteria, with a total of 157 effect sizes, and a total sample size of over 11,000. Nearly all of these effect sizes were positive, indicating that high levels of deliberate practice are associated with high levels of performance. But, again, the results indicated that deliberate practice left more of the variance in performance unexplained than it explained. To be exact, on average, deliberate practice explained 12% of the variance, leaving 88% unexplained. Macnamara et al. did not correct individual effect sizes for unreliability, because very few studies in the meta-analysis reported a reliability estimate for both deliberate practice and performance. However, they did correct average effect sizes from the meta-analysis, and across a wide range of reliability assumptions, deliberate practice still explained well less than half of the variance in performance.

Moderator analyses revealed that the effect of deliberate practice was strongest for games (26%), music (21%), and sports (18%), and much weaker for education (4%) and professions (<1%, and not statistically significant). The effect sizes for education and professions may be smaller because deliberate practice is less well defined in these domains and/or because the participants in these studies differed in the amount of prestudy expertise, and thus in the amount of deliberate practice necessary to reach a given level of skill. The relationship between deliberate practice and performance also

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[4] The data file for Macnamara et al. (2014) is openly available at https://osf.io/rhfsk.

tended to be larger for activities in which the task environment is highly predictable (e.g., running) than for activities in which the task environment is less predictable (e.g., handling an aviation emergency). This finding is consistent with laboratory research showing that training has a greater impact on performance in predictable tasks than less predictable tasks (e.g., consistently- vs variably-mapped tasks; see Ackerman, 1987).

Moderator analyses further revealed that studies that relied on retrospective estimates of deliberate practice reported higher effect sizes than studies that used a log method in which activity was recorded on an ongoing basis. Indeed, deliberate practice explained 20% of the variance in performance for studies that used a retrospective interview, compared to 12% for studies that used a retrospective questionnaire and only 5% for those that used a log method. This finding suggests that the relationship between deliberate practice and performance may be weaker than what our meta-analysis indicates. That is, the log method presumably yields more valid estimates of deliberate practice than retrospective methods, given that people do not have perfect memory for the past. Ericsson alluded to this point about validity as follows:

> *With better research using daily practice diaries during the entire development of music and chess performance, we might find that individual differences in the amount and timing of deliberate practice [do] not account for all observed variance, but current data cannot claim to show that.*
>
> ***(as quoted in Szalavitz, 2013[5])***

Finally, considering the type of performance measure, the relationship between deliberate practice and performance was considerably weaker for studies that used an objective measure of performance—either a standardized measure (e.g., chess rating; avg. $r = 0.28$) or a laboratory task (avg. $r = 0.37$)—than for studies that used group membership (avg. $r = 0.51$). If using an objective measure of performance is ideal for expertise research, this finding further suggests that the true relationship between deliberate practice and performance is weaker than has often been claimed.

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[5] This quotation is from a popular article (see http://web.archive.org/web/20150731145946/http://healthland.time.com/2013/05/20/10000-hours-may-not-make-a-master-after-all/). Because quotations in popular articles are sometimes not verbatim and may misrepresent the views of the person quoted, we e-mailed the journalist who wrote the article (Maia Szalavitz) to verify the accuracy of this quotation. She confirmed that the quotation is verbatim from an e-mail she received from K. Anders Ericsson, except the word in brackets (Maia Szalavitz, personal communication, June 4, 2013).

In an even more recent meta-analysis, Macnamara, Moreau, and Hambrick (2015) found that the relationship between deliberate practice and sports performance varied by skill level. Specifically, deliberate practice explained only 1% of the variance in performance for studies that used elite-level athletes (e.g., Olympians vs national-level performers), compared to 19% for studies that used sub-elite athletes, and 29% for studies that used mixed samples with both elite and sub-elite athletes. This finding is inconsistent with the claim that "[i]ndividual differences, even among elite performers, are closely related to assessed amounts of deliberate practice" (Ericsson et al., 1993, p. 363), and instead suggests that deliberate practice may lose its predictive power at elite levels of performance.

Ericsson (2014b) has dismissed the results of Macnamara et al.'s (2014) meta-analysis, arguing that only *one* of the 88 studies (or 1 out of 157 effect sizes) that was included meets his criteria for accurately estimating the relationship between accumulated deliberate practice and performance (see also Ericsson, 2014c; for the supplemental material for this commentary). The one study he accepts is Ericsson et al.'s (1993) second study (the study of pianists). However, Ericsson again rejects studies that he has explicitly cited as support for the importance of deliberate practice in the past, including some of his own studies. For example, he rejects his study of darts (Duffy, Baluch, & Ericsson, 2004) because there was no record of a teacher or coach supervising and guiding all or most of the practice. Yet, he and his colleagues explicitly and repeatedly referred to measures that they collected in this study as measures of "deliberate practice" (see, e.g., Duffy et al.'s (2004) Table 3, p. 240) and concluded that the finding of large differences between expert and novice dart players in these measures "supports one of the main tenets of Ericsson et al.'s (1993) theory whereby expertise is acquired through a vast number of hours spent engaging in activities purely designed to improve performance, i.e., deliberate practice" (p. 243).[6]

Ericsson (2014b) rejects studies by other researchers that he has used to support the deliberate practice view in the past, as well. For example, he rejects Charness et al.'s (2005) study of chess, again because there was no record of a teacher. Yet, he once stated that this study "reports the most

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[6] Not even in the report of Ericsson et al.'s (1993) study of pianists, or in the biographical interview that was used in this study (see Krampe, 1994; Appendix A, "Retrospective Estimates for Past Amounts of Practice Alone"), can we find any record that the participants were asked to restrict their practice estimates to *only* activities that were supervised and guided by a teacher.

compelling and detailed evidence for how designed training (deliberate practice) is the crucial factor in developing expert chess performance" (Ericsson, 2005, p. 237). For the same reason, he rejects Sonnentag and Kleine's (2000) study of insurance agents, even though he once explained that "[i]n a study of insurance agents Sonnentag and Kleinc [sic] (2000) found that engagement in deliberate practice predicted higher performance ratings" (Ericsson, 2006, p. 695). We credit Ericsson for his vigorous defense of his view, but we do not believe it is acceptable to use studies to argue for the importance of deliberate practice, and then later reject those studies on the grounds that they did not actually measure deliberate practice.

Ericsson (2014b) makes two more general points in his commentary that bear on the deliberate practice view. First, he states:

> *I have never claimed that deliberate practice can explain all reliable variance in attained performance….On the contrary I have acknowledged for decades that height and body size…cannot be changed by training, yet influence the attainment of elite performance in some domains of expertise.*
>
> ***(Ericsson, 2014b, pp. 5–6)***

However, even in domains in which it is not reasonable to argue that height and body size are factors in performance, the available evidence indicates that deliberate practice leaves a large amount of the variance in expertise unexplained. The most obvious example of such a domain is chess. In Charness et al.'s (2005) aforementioned studies of chess, the higher of the two correlations between deliberate practice and performance in these studies was 0.54 before correction for unreliability and 0.63 after correction (see Hambrick, Oswald, et al.'s, 2014, Table 1). Thus, deliberate practice explained about 40% of the reliable variance in chess rating in that study (i.e., $0.63^2 \times 100 = 39.7\%$), leaving 60% unexplained.

Second, Ericsson (2014b) argues that the correlation between estimated amount and *actual* amount of deliberate practice may range from 0 to nearly 1.0—in other words, that estimates of deliberate practice are "contaminated" to some unknown degree by activities not meeting the criteria for deliberate practice. He explains:

> *The duration of deliberate practice may be correlated with the total duration of practice alone with a correlation ranging from 0.0 to almost 1.0 depending on age and skill level of performer and the particular domain of expertise. However, until studies have successfully measured these correlations it is not possible to estimate the proportion of deliberate practice from estimates of practice alone.*
>
> ***(Ericsson, 2014b, p. 5)***

However, the measure of deliberate practice in the one study that Ericsson argues can be used to accurately estimate the relationship between deliberate practice and performance—Ericsson et al.'s (1993) study of pianists—was total duration of practice alone. If it is not yet known what proportion of this measure is *actual* deliberate practice, as opposed to other activities, then all that can be concluded based on the results of that study (or any other study to date) is that deliberate practice accounts for somewhere between 0% and 100% of the variance in performance—and thus that there is no scientific evidence at all that deliberate practice accounts for individual differences in expertise. Even if the measure of deliberate practice in Ericsson et al.'s study of pianists was in some non-obvious way "purer" than measures of deliberate practice in all of the other studies that have been conducted since, this would mean that the case for the importance of deliberate practice rests largely, or entirely, on the results of a single study with a total sample size of only 24.

Our take is that deliberate practice–as it has been operationally defined and measured in research over the past two decades by Ericsson and colleagues and by others who have used their research as a model—explains a sizeable amount of the variance in expertise, but leaves an even larger amount unexplained. Thus, while the deliberate practice view offers a parsimonious account of expertise, it is not supported by the available empirical evidence. To be sure, crucial questions about the relationship between deliberate practice and performance remain, such as why the relationship appears to be stronger for studies that use a retrospective method to measure deliberate practice than for those that use a log method. One possible explanation for this finding is that when asked to retrospectively estimate deliberate practice, people rely on current level of skill rather than on accurate recollections of past engagement in practice. This could lead to inflated estimates of the relationship between deliberate practice and expertise. Nevertheless, we think it is unlikely that the true relationship between deliberate practice and performance will ultimately be found to be zero or trivially small.

3.2 Findings from Individual Studies

The results of individual studies are consistent with this conclusion. In their exemplary studies, Charness et al. (2005) had chess players provide estimates of serious chess activity and calculated measures of both the accumulated amount of these activities as well as amount in the most recent year. In addition, participants reported the number of years of private chess instruction and number of years of group lessons. For each study, and for a combined data set ($N = 375$), Charness et al. regressed chess rating onto these variables. Variance in chess rating accounted for was 41% for the first study, 31% for the second study, and 34% in the combined data set. In a study of 90 chess players, Gobet and Campitelli (2007) found a weaker, but still significant and sizeable, positive relationship between individual deliberate practice and chess rating ($r = 0.42$, or 17.6% of the variance). Moreover, there was a large amount of variability in deliberate practice, even among the most highly skilled players in the sample. Indeed, one player became a chess master after just over 728 h of individual deliberate practice, while it took another player over 16,000 h (see Campitelli & Gobet, 2011, for further discussion). For total deliberate practice, which included individual and group practice, the range was from 3016 to 23,608 h ($r = 0.57$ with chess rating).

In another impressive study, Howard (2012) collected estimates of engagement in chess-related activities from 533 chess players, ranging in skill from intermediate to grandmaster. Howard found that, along with starting age, a set of practice and other experiential variables accounted for 49% of the variance in chess rating. Total number of tournament games (log) was the strongest single predictor of chess rating ($r = 0.62$; $r = 0.33$ for log total study hours). One potential problem with Howard's study is that he used an internet survey instead of in-person experience interviews (see Ericsson & Moxley, 2012). However, averages for the experience variables were very similar to those obtained through in-person interviews in Charness et al.'s (2005) studies. It could also be argued that in-person interviews introduce experimenter bias that internet surveys do not, and thus that the latter approach is superior for collecting at least certain types of information.

The preceding studies used a cross-sectional design in which participants differing in expertise were tested within a narrow band of time. The obvious advantage of this design over a longitudinal design is that it allows researchers to investigate individual differences in expertise without having to wait months, years, or even decades for the participants to reach their final level of skill. Nevertheless, as Sternberg (1996) reminded, correlation does not imply causation: "deliberate practice may be correlated with success because it is a proxy for ability: We stop doing what we do not do well and feel unrewarded for" (p. 350). Similarly, commenting on Ericsson and colleagues' finding of a correlation between deliberate practice and skill level in music, Winner (2000) observed, "Hard work and innate ability have not been unconfounded" (p. 160).

de Bruin, Smits, Rikers, and Schmidt (2008) investigated this issue by performing a longitudinal analysis comparing Dutch chess players who were enrolled in a national chess training program, but dropped out ("drop-outs"), to players who had remained in the program ("persisters"). There was no difference in the effect of deliberate practice on chess rating in the two groups, leading de Bruin et al. to conclude that "those who ultimately arrive at expert level in chess do so not because of a predisposition to perform deliberate practice more efficiently, but because they put in more hours of deliberate practice" (p. 494). Based on this evidence, Ericsson and Towne (2010) argued against the hypothesis that the correlation between deliberate practice and chess expertise is an artifact of drop-outs. However, it is critical to note that the "drop-outs" in this study had only dropped out of a training program for elite chess players. de Bruin et al.'s analysis does not speak to the critical question of whether people quit chess much earlier (e.g., after 50—100 h of training) because of lack of ability. Thus, Sternberg's (1996) and Winner's (2000) point that correlations between deliberate practice and expertise may be inflated due to selective drop-out remains an important caveat to conclusions about the importance of deliberate practice based on cross-sectional findings.

Two recent case studies of chess further challenge the primacy of deliberate practice. Howard (2011) used biographical and autobiographical sources, along with publicly available chess ratings, to investigate the link between practice and chess skill in the Polgár sisters. Starting at a young age, under the supervision of their father, Susan, Sofia, and Judit Polgár received intensive chess instruction on a near-daily basis. Howard found that the sisters differed both in the highest rating they achieved and in the amount of practice they accumulated to reach that rating. For example, one of the sisters reached a rating of 2735 in an estimated 59,904 h of practice, whereas another peaked at 2577—more than a standard deviation lower—in an estimated 79,248 h of practice. Howard also found that the two sisters who became grandmasters had accumulated a great deal more practice by the time they reached their peak rating than had the eight grandmasters in his sample who reached top-ten in the world ($M = 14{,}021$ h, $SD = 7374$ h). In the other case study, Gobet and Ereku (2014) examined the success of Magnus Carlsen—the highest rated chess player in the world by a wide margin—and found that he had significantly *fewer,* not more, years of deliberate practice than the next 10 best players in the world, even using a starting age that is conservative by three years (age 5, when Carlsen learned the moves, instead of age 8, when he has noted he started playing the game seriously).

SCRABBLE has also been used in a few studies of expertise. Using official SCRABBLE ratings as an index of skill, Tuffiash, Roring, and Ericsson (2007) recruited samples of "elite" and "average" SCRABBLE players and had them provide estimates of engagement in various SCRABBLE-related activities, including an activity that would seem to meet the theoretical description of deliberate practice—serious study. (The elite players were representative of players in the top division of the National SCRABBLE Championship, whereas the average players were representative of the average player in the National SCRABBLE Association.) Although the elite group had accumulated more serious study than the average group, for both groups, the standard deviations for serious study were very similar to the means: average group ($M = 1318$, $SD = 1465$) and elite group ($M = 5084$, $SD = 4818$). This indicates that there was a large amount of variability in the data. As for chess, it appears that people differ greatly in the amount of deliberate practice they require to reach a given level of skill in SCRABBLE.

Research on music further challenges the deliberate practice view. In a study by Sloboda and colleagues (see Sloboda, 1996; Sloboda, Davidson, Howe, & Moore, 1996) that Ericsson has cited to support the importance of deliberate practice, students at a selective music school ("high achievers") were found to have accumulated more "formal practice" than students who were learning an instrument at a nonmusic school ("players for pleasure"). However, Sloboda et al. (1996) noted that there were some students at each skill level who did "less than 20% of the mean amount of practice" and others who did "over four times as much practice than average" (p. 301), and added "it appears that there are a few individuals in all groups who manage to attain grade examination passes on very little practice" (p. 301).

Moreover, in Ericsson et al.'s (1993) study of pianists, accumulated deliberate practice ranged from about 10,000 to over 30,000 h among the expert group (see Figure 2). The expert pianists ranged in age from 20 to 31, and thus some of this variability in deliberate practice was presumably due to age (i.e., more deliberate practice for the older pianists). However, the most practiced expert could have been no more than 11 years older than the least practiced expert, and yet the difference in deliberate practice between these subjects was about 20,000 h. At 4 h a day, a person would have to practice nearly 14 years without missing a single day to accumulate this amount of deliberate practice. Thus, it seems likely that some of the pianists in Ericsson et al.'s sample required much less deliberate practice than others to become experts. Ericsson et al. did report extremely high correlations between

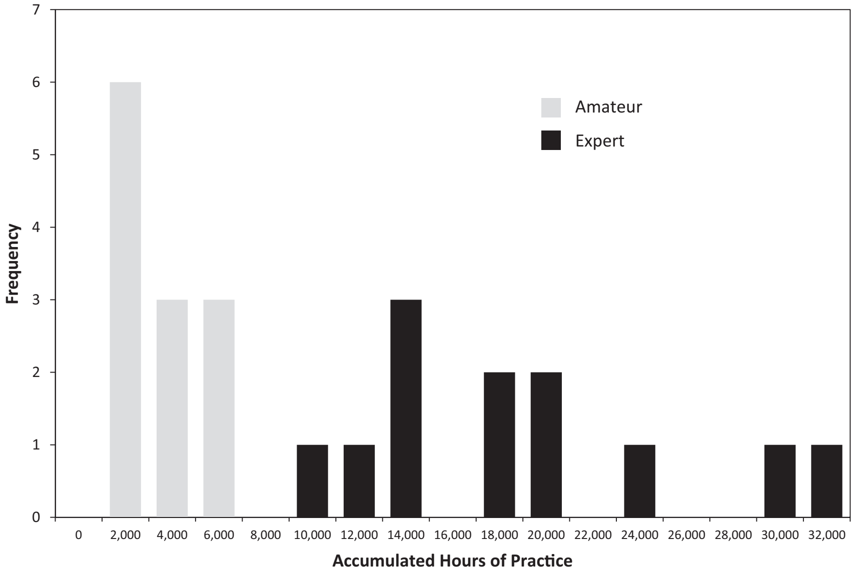

Figure 2 Histogram showing range of deliberate practice for amateur pianists (light gray bars) and expert pianists (dark gray bars) in Ericsson et al. (1993, Study 2). The values used to generate this histogram come from a scatterplot in Ericsson et al.'s Figure 15 (right panel). The first author of this chapter (Hambrick) requested data from the authors of the study, but they were unable to provide it because it is stored on magnetic tape for mainframe computers (Ralf Krampe, personal communication, December 5, 2011). Thus, we extracted the log values from Ericsson et al.'s Figure 15 using Dagra's graphical extraction software (Version 2.0), and then reversed the values to hours (i.e., hours of deliberate practice $= 10^{\text{Log hours}}$). The correlation between the extracted log values and the performance values matches the correlation in Ericsson et al.'s Figure 15 (right panel) exactly ($r = -0.857$). Means are not reported for this variable in Ericsson et al., but the means for the extracted values are very similar to those found in other reports of this study (Krampe, 1994; Krampe & Ericsson, 1996). Thus, we assume that the extracted values accurately capture the variability in the data. In Ericsson et al.'s Figure 15, the variable is labeled "Log-accumulated practice (hours)". We assume that this variable can be interpreted as *deliberate* practice, because elsewhere Ericsson and colleagues describe it as such (see Law, Côté, & Ericsson, 2007).

deliberate practice and performance in a piano-related task ($rs > |0.85|$). However, it must be assumed that these correlations are highly inflated, because an extreme-groups design was used in this study (see Preacher, Rucker, MacCallum, & Nicewander, 2005; for a discussion of issues with extreme-groups designs).

There has also been an extensive amount of research on expertise in sports. Johnson, Tenenbaum, and Edmonds (2006) compared the training histories of elite and sub-elite swimmers. Five of the elite swimmers had won at least one Olympic gold medal, and the other three had been ranked in the top five in the world. The sub-elite swimmers did not meet these lofty criteria, but were still highly accomplished, having participated in national events such as the NCAA championship. Not surprisingly, all of the swimmers had accumulated a large amount of deliberate practice. The overall average was about 7500 h. However, the difference between the groups was not significantly different. In fact, if anything, the mean was higher for the sub-elites (7819 h) than for the elites (7129 h). Furthermore, there was a large amount of variability in amount of deliberate practice. One of the elites—winner of Olympic gold in 1996 and 2000—had started competitive swimming at age five and had accumulated over 7000 h of deliberate practice. However, another elite swimmer did not begin competitive swimming until he was a senior in high school, and had accumulated only about 3000 h of deliberate practice. This late bloomer won Olympic gold after less than *2 years* of serious swimming. Thus, as Macnamara et al. (2015) concluded in their meta-analysis of sports studies, deliberate practice may lose its predictive power at elite skill levels.

In one of the few longitudinal studies of expertise to date, Schneider and colleagues (Schneider, Bös, & Rieder, 1993; Schneider, 1997) tested for effects of a wide range of factors on the development of expertise in elite youth tennis players. (About 10% of the players were ultimately ranked in the top 100 in the world, and a few were rated in the top 10.) The participants completed tests of psychological and physical characteristics, motivation, basic motor abilities, and tennis-specific skills. In addition, biographical interviews were conducted with the players, and their parents and coaches. Measures of competitive tennis success (i.e., ranking) were then obtained for multiple time points. Given the importance and rarity of this type of study, and the high quality of this particular study, we reproduce the structural equation model from the most recent report of the results in Figure 3. As shown, the player's preference for tennis and the coach's rating of future success were strongly predictive of tennis-specific skills, which were strongly predictive of tennis ranking. However, basic motor abilities had an indirect impact on ranking through tennis-specific skills. Schneider thus concluded that "[a]lthough individual differences in basic motor abilities were not large in this highly selected sample, they made a difference when it came to predicting individual tennis performance" (p. 14). Reviewing these and other findings, Schneider (2015) concluded that "whereas Ericsson and colleagues believe that the amount of deliberate practice is a sufficient predictor of

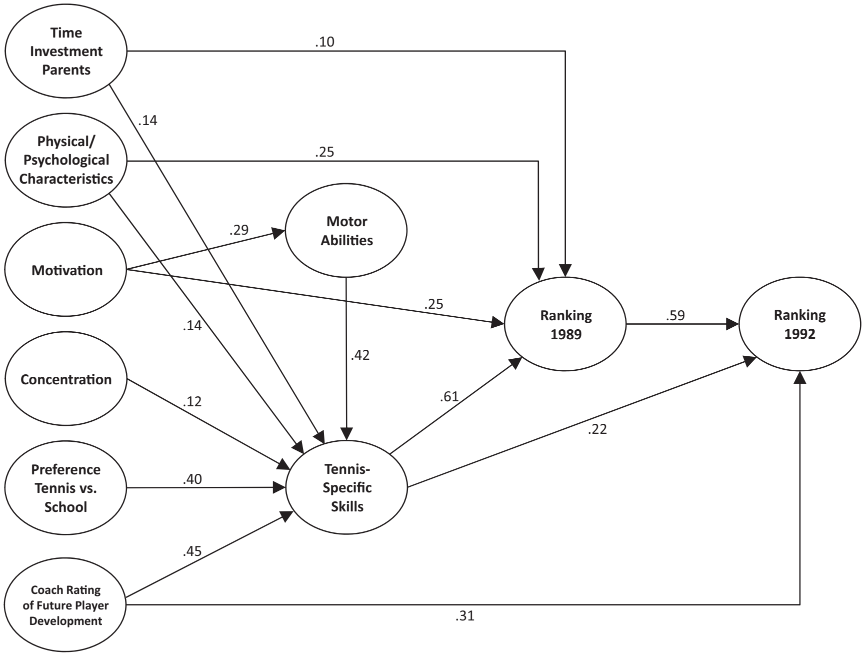

Figure 3 Structural equation model from Schneider (1997) predicting tennis-specific skills and tennis ranking. *Reproduced with permission of Taylor and Francis from Schneider (1997), Figure 5.*

subsequent expert performance, the developmental findings suggest that individual differences cannot be completely ignored when it comes to predicting the development of expertise" (p. 251).

Using a biographical research approach, Lombardo and Deaner (2014) investigated the role of training in athletic success through analyses of biographies and autobiographies of elite sprinters. In one study, Lombardo and Deaner examined the biographies of 15 Olympic gold medalists in the 100-m and 200-m sprints—from Jesse Owens in 1936 to Usain Bolt in 2008 and 2012—and recorded any mention of exceptional (or unexceptional) speed relative to peers. All 15 of the sprinters were recognized as having exceptional speed prior to or from the outset of training. Moreover, the sprinters were found to require between 1 and 7 years to reach world class status, with a mean of 4.6 years ($SD = 2.0$) for the men and 3.1 years ($SD = 2.4$) for the women. In a second study, Lombardo and Deaner used archival records to document the 20 fastest American male sprinters in history. Eight of the 12 sprinters for whom data were available were found to reach world class status in fewer than 10 years ($M = 8.7$, $SD = 3.8$).

These findings are inconsistent with the claim that "winning performances at international competitions within competitive domains of expertise requires more than a decade of preparation" (Boot & Ericsson, 2013, p. 147). At least in sprinting, the 10-year rule does not hold true.

An intriguing case study of deliberate practice and sports expertise is in progress. In April, 2010, having read about Ericsson and colleagues' research, 30-year old Dan McLaughlin quit his job as a commercial photographer, and with virtually no prior experience playing golf, set out to reach the Professional Golfer's Association (PGA) Tour—the highest level of competitive golf in the world—through 10,000 h of deliberate practice. With input from Ericsson and colleagues, McLaughlin worked with golf teaching professionals to design a training regimen based on the concept of deliberate practice (McLaughlin, 2014). McLaughlin regularly records his progress in an online log—the "10,000 hour countdown" (see http://web.archive.org/web/20150803113448/http://thedanplan.com/countdown/), including the number of hours of deliberate practice remaining, the score he shot if he played a round of golf, and qualitative information about his performance. At the 5-year mark, McLaughlin's lowest score for 18 holes was 70, and his lowest handicap (a standardized index of skill level) was 2.6, putting him above the 95th percentile for amateur golfers in the United States (see http://thedanplan.com/).[7]

While McLaughlin's progress is impressive, there are notable examples of people taking up golf relatively late in life (even as adults) and acquiring a much higher level of skill over a 5-year period. In her autobiography, Babe Didrikson Zaharias recalls that she played her first round of golf at age 21 (Zaharias, 1955). Three years later, Zaharias won the Texas Women's Amateur and went on to become one of the greatest golfers in history (Van Natta, 2011). Greg Norman, who was the top-ranked golfer in the world for 331 weeks (see http://www.owgr.com/ranking), recalls in his autobiography that he received his first set of golf clubs at age 15, and soon thereafter recorded his first official score—a 108 (Norman & Phillips, 2006). Just over 3 years later, Norman competed in the Australian Open, and finished with the second lowest score for an amateur and 35th overall. Three years after that, he won his first professional tournament, beating two of the best players in the world at the time. As another example, Larry Nelson took up golf at

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[7] For interviews with Dan McLaughlin, K. Anders Ericsson, and others involved in The Dan Plan, see a segment of Golf Channel's *Golf in America* at https://www.youtube.com/watch?v=v4GT0vGS-lA.

age 21. Three-and-a-half years later, he qualified for the PGA Tour, and he has since won 41 professional tournaments, including three major championships (Riach, 2003; Yocom, 2008). Deliberate practice does not appear to be the only factor involved in reaching an elite level of performance in golf, and it may not be the most important factor.

There have also been a few studies of the relationship between deliberate practice and professional expertise. In one of the best to date, Chow and colleagues (Chow, Miller, Seidel, Kane, Andrews, & Thornton, 2015) investigated the impact of deliberate practice on expertise in psychotherapy. The participants were professional psychotherapists, who over a 4-year period asked their more than 1600 clients to complete a questionnaire to assess the effectiveness of their treatment in terms of symptoms, functioning, and risk. The psychotherapists themselves completed a questionnaire in which they estimated the amount of time they spent engaging in activities outside of work to improve therapeutic skills (i.e., deliberate practice). Consistent with previous work (Ericsson et al., 1993), Chow et al. found a statistically significant relationship between average number of hours per week spent alone in deliberate practice and client outcomes. High levels of deliberate practice were associated with lower levels of client distress at the end of therapy. However, even among the therapists with the best client outcomes (the top quartile), there was a large amount of variability in deliberate practice (see Chow et al., Figure 1). Some of the top therapists reported engaging in much more deliberate practice than others.

To sum up, there is now a sizeable body of evidence to indicate that a large amount of variance in expertise is explained by factors other than deliberate practice. To put it another way, in terms of its contribution to individual differences, deliberate practice appears to be an important piece of the expertise puzzle, but only one piece, and not even necessarily the largest piece. What, then, are the other pieces of the puzzle?

4. WHAT ELSE MATTERS?

4.1 Opportunity Factors

Obviously, people are not born with the specialized skills and knowledge that are necessary for success in complex domains such as music and chess. Thus, it stands to reason that people who have a greater opportunity to train in these domains will have an advantage over those who have less of an opportunity to train. As a stark illustration, there are currently over 300 players in Major

League Baseball (MLB) from the Dominican Republic (http://mlb.mlb.com/dr/active_players.jsp?pagina=5)—more than any other country in the world except the United States—and none from Haiti, which borders the Dominican Republic on the island of Hispaniola. The major reason for this difference is almost certainly opportunity: baseball is a national priority in the Dominican Republic (Klein, 1993), but not in much poorer Haiti.

Nationality is an example of an "opportunity" factor that would be expected to impact expertise indirectly, through deliberate practice and other forms of training. Parental influence is another example. Bloom and colleagues interviewed highly accomplished musicians, artists, athletes, and academics to better understand the origins of their success (Bloom, 1985). The overall conclusion of the study was that "no matter what the initial characteristics (or gifts) of the individuals, unless there is a long and intensive process of encouragement, nurturance, education, and training, the individuals will not attain extreme levels of capability in these particular fields" (Bloom, 1985, p. 3).

Birth date is another example of an opportunity factor. For some sports, such as hockey, there is some evidence that individuals born early in the year have a greater chance of reaching the professional ranks than individuals born later in the year (Barnsley, Thompson, & Barnsley, 1985). One proposed explanation of these *relative age effects* is that players born near the eligibility cutoff for participation at a given age level (e.g., in a league) will be older and physically more mature and capable than players with a later birth date, and thus will be singled out as "talented" and given more opportunities to train and acquire expertise.

4.2 Basic Ability Factors

Some people acquire complex skills much more rapidly than other people. Consider that Magnus Carlsen achieved grandmaster status—the highest possible rating in tournament chess—at age 13, less than 5 years after competing in his first chess tournament (Agdestein, 2013). Or consider that Donald Thomas won his first collegiate high jump competition with almost no training in the event (Epstein, 2014), and within two years competed in the Olympics. Cases such as these raise the question of whether people differ in the basic abilities—*talents*—that they can bring to bear on acquiring expertise.

We have focused on the role of *working memory capacity* (WMC) as a form of intellectual talent. WMC is the ability to maintain information in an active and accessible state over a short period of time (Engle, 2002) and is measured with tasks such as *operation span*, in which the participant attempts to solve arithmetic equations while simultaneously remembering words. WMC correlates moderately with performance in a wide range of complex cognitive tasks, including text comprehension, decision making, and reasoning (Hambrick & Engle, 2003). Heritability estimates for WMC are usually around 50% (e.g., Ando, Ono, & Wright, 2001; Kremen et al., 2007; Polderman et al., 2006).

Consistent with classical models of skill acquisition (e.g., Anderson, 1982; Fitts & Posner, 1967), Ericsson and colleagues have argued that WMC and other basic abilities impact performance only initially during training, after which their influence is circumvented through specialized knowledge and skills that develop through deliberate practice. As Ericsson and Charness (1994) stated, "[t]he effects of extended deliberate practice are more far-reaching than is commonly believed. Performers can acquire skills that circumvent basic limits on working memory capacity and sequential processing" (p. 725). And as Ericsson (2014a) reiterated, "[t]he acquisition of expert performance, where acquired mechanisms gradually circumvent the role of any basic general cognitive capacities and thus reduce and even eliminate significant relations between general cognitive ability and domain-specific performance at the expert level of performance" (p. 83).

Though they did not explicitly frame it as such, Robbins et al. (1996) tested this *circumvention-of-limits hypothesis* using an experimental approach. Chess players, ranging in skill from "weak club player" to master, performed a move-choice task while performing secondary tasks designed to suppress various components of the working memory system, or with no secondary task (the control condition). Robbins et al. found that a secondary task designed to tap the *central executive* component of working memory—the domain-general system responsible for higher-level cognitive processes (Baddeley & Hitch, 1974)—was severely disruptive to participants' performance in the move-selection task, regardless of skill level. A secondary task designed to tap the *visuospatial sketchpad* was similarly disruptive. These results suggest that working memory directly influences performance in chess. More recently, Foroughi, Werner, Barragán, and Boehm-Davis (2015) found that interruptions designed to clear the transient working memory were disruptive to reading comprehension in skilled readers.

We have used an individual differences approach to evaluate the circumvention-of-limits hypothesis. As illustrated in the left panel of Figure 4 the prediction that follows from this hypothesis is an interaction between a domain-general factor (e.g., WMC) and a domain-specific factor (e.g., deliberate practice) on domain-specific performance. That is, at high levels

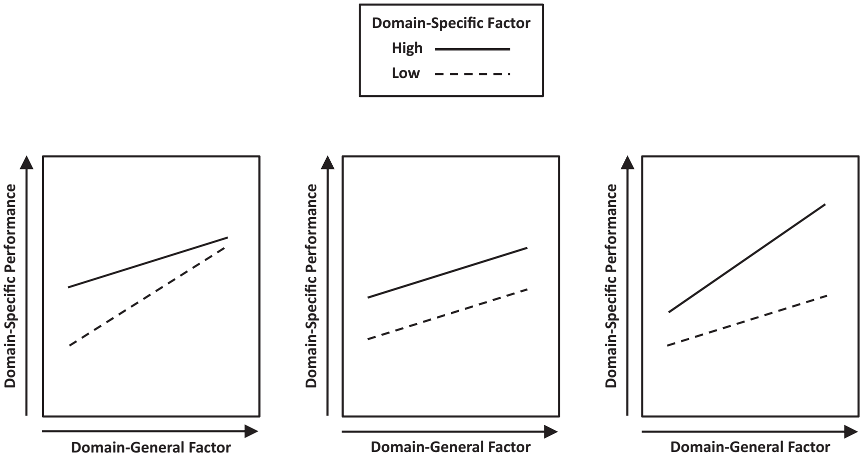

Figure 4 Three hypotheses concerning effects of domain-general and domain-specific factors on domain-specific performance (expertise): *circumvention-of-limits hypothesis* (left panel), *building blocks hypothesis* (middle panel), and *rich-get-richer hypothesis* (right panel).

of the domain-specific factor (e.g., deliberate practice), the domain-general factor (e.g., WMC) is less predictive of performance than at lower levels of the domain-specific factor. There are two alternative hypotheses (see also Hambrick & Engle, 2002). The *building blocks hypothesis* (middle panel) predicts additive effects of the domain-general and domain-specific factors on performance; that is, the effects of domain-general factors on performance are statistically equivalent across levels of the domain-specific factors. The *rich-get-richer hypothesis* (right panel) predicts a domain-general × domain-specific interaction, but in the opposite direction to that predicted by the circumvention-of-limits hypothesis: a stronger effect of the domain-general factor at high levels of the domain-specific factor.

To test these possibilities, Meinz and Hambrick (2010) had 57 pianists, ranging in skill from beginner to professional, complete a questionnaire to assess deliberate practice, along with tasks to measure both WMC and sight-reading ability. (Sight-reading involves playing music with little or no preparation.) Deliberate practice accounted for nearly half (45%) of the variance in sight-reading performance, but WMC accounted for an additional 7% of the variance. More important, there was no deliberate practice × WMC interaction. Instead, consistent with the building-blocks hypothesis, the effect of WMC on performance was as large at low levels of deliberate practice as at higher levels of deliberate practice. For all but the most difficult piece of music they used in their study, Kopiez and Lee (2006) also reported significant positive correlations between a measure of working memory and sight-reading performance (see Hambrick & Meinz, 2012; for a review of music studies). Furthermore, in a study of Texas Hold'Em poker, Meinz et al. (2012) found that WMC positively predicted performance in poker skill tasks (e.g., hand evaluation), even at high levels of poker knowledge. Similarly, Toma et al. (2014) found that both SCRABBLE and crossword experts outperformed control subjects on two tests of WMC.

Research on prodigies lends further support to the conclusion that WMC plays an important role in acquiring expertise. Ruthsatz and Detterman (2003) documented the case of a 6-year old piano prodigy ("Derek") who had played in numerous concerts, appeared on national television, and released two CDs of his music. Derek scored at or above the 95th percentile on tests of musical aptitude. He also scored well above the average on the verbal reasoning (130), abstract reasoning (114), and quantitative reasoning (120) subsets of the Stanford-Binet Intelligence Scale, and above the 99th percentile on the short term memory subtest (158). More recently, Ruthsatz and Urbach (2012) administered a standardized IQ test (the Stanford-Binet) to eight child prodigies, six of whom were musical prodigies. Despite full-scale IQs that ranged from 108 to 147—just above average to exceptional—all of the prodigies were at or above the 99th percentile for working memory (indeed, six scored at the 99.9th percentile). Adding nine prodigies to the sample (for a total *N* of 17), Ruthsatz and colleagues found an average score of 140 ($SD = 11.8$) for working memory—2.5 standard deviations above the mean (Ruthsatz, Ruthsatz-Stephens, & Ruthsatz, 2014).

Taken together, this evidence suggests that there are conditions under which WMC limits the ultimate level of performance a person can achieve in a domain. This is not to say that there are *no* conditions under which WMC and other basic abilities can be circumvented. Hambrick et al. (2012) found that visuospatial ability predicted success in a geological bedrock mapping task in which the goal was to infer the geological structure of an area based on observable features (rock outcrops, topography, etc.), but only in participants with low levels of geological knowledge. Similarly, in a study of pilots, Sohn and Doane (2004) found that WMC predicted success in an aviation situational awareness task, but only in pilots who scored low on an aviation-specific test measuring skilled access to long-term memory (i.e., long-term working memory; Ericsson & Kintsch, 1995). For pilots who scored high on this test, there was no relationship between WMC and performance in the situation-awareness task.

As we have noted elsewhere (Hambrick & Meinz, 2011b), this mixed evidence for the circumvention-of-limits hypothesis suggests that there may be task and situational factors that moderate the interplay between domain-general and domain-specific factors. For example, in contrast to domains in which the stimulus input is static (e.g., geological bedrock mapping), tasks in which the input changes continuously and rapidly and is unpredictable (e.g., sight-reading) may make it more difficult to rely on long-term memory knowledge structures to circumvent WMC and other basic abilities. Admittedly, this is a posthoc speculation, and as we discuss later, a goal for future research is to develop a framework for making testable predictions about how task/situational factors impact expertise.

Numerous other studies have investigated the relationship between expertise and traditional measures of IQ and specific cognitive abilities (verbal ability, visuospatial ability, etc.). This research has tended to suffer from serious methodological limitations (see Ackerman, 2014), including use of (1) extremely small sample sizes, leading to low statistical power and precision; (2) samples with restricted ranges of cognitive ability and/or expertise, limiting the degree to which the variables can correlate; (3) single tests of cognitive ability, leaving open the question of whether results are test-specific; (4) tests with unknown reliability and validity; and (5) research designs that confound skill level (e.g., novice vs expert) with other factors that may account for group differences in cognitive ability (e.g., educational status). Further complicating matters, participants are sometimes children, and other times adults.

Not surprisingly, then, the results of these studies concerning ability–expertise relations are inconsistent (see Ericsson, 2014a; for a review). Whether in terms of correlations or differences in group means, relationships between cognitive ability and expertise are sometimes found to be statistically significant and sizeable, and other times not. A comprehensive review of this literature is beyond the scope of this chapter. A few examples will suffice to illustrate the inconsistency. Using small samples of tournament chess players as participants, Unterrainer et al. (Unterrainer, Kaller, Halsband, & Rahm, 2006; Unterrainer, Kaller, Leonhart, Rahm, 2011) reported nonsignificant correlations between IQ and chess rating: $r\text{s} = -0.08$ ($N = 25$) and -0.07 ($N = 30$), respectively. However, using a considerably larger sample ($N = 90$), Grabner, Stern, and Neubauer (2007) found a correlation of 0.35 ($p < 0.001$) between IQ and chess rating.

One study on the relationship between cognitive ability and expertise stands out as methodologically superior: Masunaga and Horn's (2001) study of GO expertise. What do the results of this study suggest? In this study, participants ($N = 263$) representing wide ranges of age, cognitive ability, and expertise in the board game GO completed tests of both domain-general and domain-specific cognitive abilities. The domain-general battery included standard tests of fluid reasoning (Gf), short-term memory (Gsm), and perceptual speed (Gs), whereas the domain-specific battery included "GO-embedded" tests. The GO-embedded tests were designed to measure Gf, Gsm, and Gs, but with GO-specific content. Particularly relevant to the present discussion, the GO reasoning test was explicitly modeled after tasks used to objectively measure skill in chess (e.g., de Groot, 1946/1978). The participants were given GO game positions and asked to choose the next best move. The best answers in this task were determined by GO professionals (see Masunaga's, neé Takagi, 1997, dissertation for additional information on the development of the task).

Figure 5 presents a reanalysis of Masunaga and Horn's (2001) published results using structural equation modeling (SEM; from Hambrick & Macnamara, 2016). (All that is required for SEM is a correlation matrix

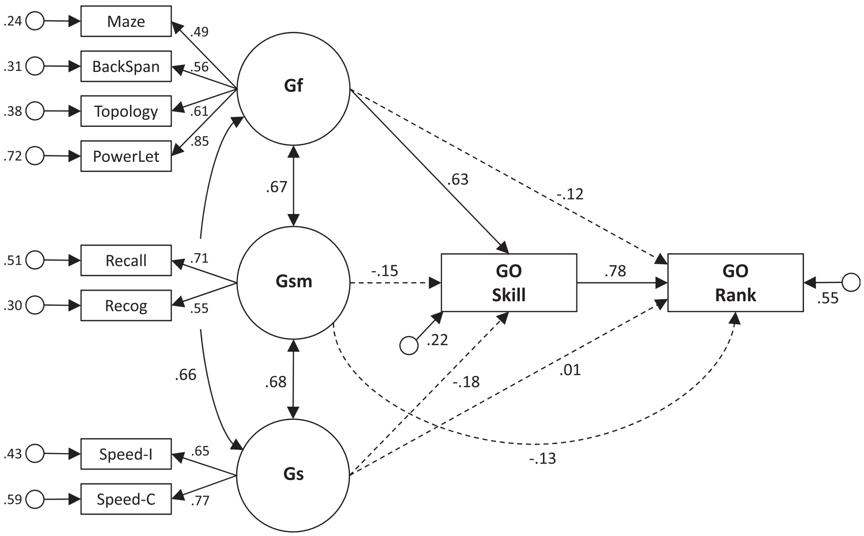

Figure 5 Reanalysis of published results of Masunaga and Horn (2001), with domain-general cognitive abilities (Gf, Gsm, and Gs) predicting GO skill and GO rank. Values adjacent to single-headed arrows are standardized path coefficients; values adjacent to double-headed arrows are correlations. Solid paths are statistically significant ($p < 0.01$). Correlations for reanalysis obtained from Masunaga and Horn's Tables 6, 9, and 10. Model fit is excellent: $\chi^2(27) = 28.45$, $p = 0.39$, CFI = 1.0, NFI = 0.96, RMSEA = 0.01. $R^2 = 0.22$ for GO skill and 0.55 for GO rank.

among the variables of interest, which Masunaga and Horn provided.) One of the major advantages of SEM over other statistical approaches is that it permits analysis of data at the level of *latent variables* (see Kline, 2011; for an excellent introduction to SEM). A latent variable captures variance common to multiple observed variables, and thus statistically cancels out task-specific factors and random measurement error. The purpose of the SEM reanalysis shown in Figure 5 was to test for effects of latent variables representing the domain-general abilities on GO skill, as measured by the GO reasoning task, and on GO ranking. As shown, domain-general Gf was positively predictive of GO skill (0.63, $p < 0.001$): high levels of Gf were associated with high levels of GO skill. In turn, GO skill was positively predictive of GO rank (0.78, $p < 0.001$). (These relationships were very similar after statistically controlling for age in the model: 0.54 and 0.76, respectively, ps < 0.001.) This evidence suggests that domain-general Gf contributes to individual differences in the type of task that the expert performance approach requires for use in expertise research (Ericsson & Smith, 1991; Boot & Ericsson, 2013).

Grabner, Stern, and Neubauer's (2007) study of chess expertise is also worthy of further discussion, given that the study used a relatively large sample with wide ranges of both expertise and cognitive ability, and multiple tests of cognitive ability with established reliability and validity. The participants (chess rating = approximately 1300 to 2400, or novice to master) completed a standardized test of intelligence, with numerical, verbal, and figural subscales. The sample was approximately one standard deviation above the mean for the general population in general intelligence (i.e., $M = 114$, $SD = 14$). Moreover, chess rating correlated moderately and positively with general intelligence ($r = 0.35$), and both numerical intelligence ($r = 0.46$) and verbal intelligence ($r = 0.38$). (The correlation with figural intelligence was near zero.) From their data, Grabner et al. estimated the minimum verbal and numerical IQ necessary to achieve an "expert" or "advanced" status (Elo rating > 2200) to be between 110 and 115 (or 0.67 and 1 *SDs* above the mean of the general population). For full-scale IQ, the lowest IQ for a player with an Elo rating above 2200 was about 103.[8]

The results of the landmark Study of Mathematically Precocious Youth are also relevant (see Robertson, Smeets, Lubinski, & Benbow, 2010).

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[8] We thank Roland Grabner for e-mailing us a scatterplot from this study showing the correlation between full-scale IQ and chess rating (personal communication, May 6, 2015).

As part of a youth talent search, a large sample of children took the SAT by age 13, and those scoring in the top 1% ($N > 2000$) were identified and tracked over the next two decades. Even within this group, SAT score predicted individual differences in objective measures of educational and professional accomplishment. For example, compared to participants in the 99.1 percentile for overall SAT score, participants who had scored in the 99.9 percentile were 3.6 times more likely to have earned a doctorate, 5 times more likely to have published an article in an STEM journal, and 3 times more likely to have registered a patent (Lubinski, 2009). More recently, Lubinski, Benbow, and Kell (2014) found that accomplishments of intellectually talented individuals (top 1% for mathematical reasoning) far exceeded base-rate expectations. For example, 2.3% of the sample were CEOs at major companies, and 4.1% had earned tenure at a major research university.

Cognitive ability does not *always* predict individual differences in expertise. With a sample size of over 700, Lyons, Hoffman, and Michel (2009) analyzed data from the National Football League's (NFL) Combine, a weeklong event in which players who aspire to play in the NFL demonstrate their skills and perform various tests of physical and mental ability. Lyons et al. found that scores on a standardized test of cognitive ability (the Wonderlic Personnel Test) generally correlated near zero with success in the NFL across all positions considered. Berri and Simmons (2011) performed a more detailed analysis of the performance of quarterbacks, and once again found no evidence that Wonderlic scores predicted future NFL performance. Football may thus be a domain in which cognitive ability does not play any appreciable role in success. Alternatively, it could be that cognitive abilities not captured by the Wonderlic, such as WMC, perceptual speed, and psychomotor speed predict performance in football, or that team-level factors override the impact of individual-level factors.

To summarize, there is consistent and compelling empirical evidence that cognitive ability predicts individual differences in expertise in some, if not all, domains. Ericsson has reached a different conclusion in his own reviews. Ericsson, Prietula, and Cokely (2007) concluded that "there is no correlation between IQ and expert performance in fields such as chess, music, sports, and medicine" (p. 116) and that the "only innate differences that turn out to be significant—and they matter primarily in sports—are height and body size" (p. 116). And in a more recent review, Ericsson (2014a) concluded:

> *Let it be clear that I am not claiming that correlation between domain-specific performance and general cognitive ability is exactly zero!! My current conclusion is that*

> *these studies have* not yet *established the fact that the attainable level of domain-specific performance is predictable from scores from tests of general cognitive ability.* *(p. 87)*

However, as we and others have noted (Ackerman, 2014; Hambrick, Altmann, et al., 2014), Ericsson appears to overlook evidence that contradicts this conclusion. For example, in his most recent review, Ericsson (2014a) mentioned Meinz and Hambrick's (2010) study of piano sight-reading, but he did not mention the central result of this study—that there was no interaction between WMC and deliberate practice, indicating that WMC was as predictive of sight-reading performance at low levels of deliberate practice as at high levels. As another example, although Ericsson correctly noted that the domain-general cognitive ability measures correlated near zero with GO rating in the Masunaga and Horn (2001) study, he does not mention the fact that nearly all of the other correlations between these cognitive ability measures and the GO-embedded measures were statistically significant (i.e., $p < 0.01$ for 50 out of 56 of the *r*s).

Moreover, Ericsson (2014a) makes material errors in his review (see Hambrick, Altmann, et al., 2014). This is understandable, particularly given the scope of his review. All the same, these errors are serious enough that they could lead to significant confusion if the scientific record is not corrected. One material error directly relevant to this discussion is Ericsson's claim that Grabner et al. (2007) "report that one chess master with a rating close to 2400 had an IQ of around 80" (Ericsson, 2014a, p. 87). If true, this would be somewhat surprising. A person with an IQ of around 80 (the 9th percentile for the general population) falls in the range for what is sometimes referred to as *borderline intellectual functioning* (see Peltopuro, Ahonen, Kaartinen, Seppälä, & Närhi, 2014). However, Grabner et al. reported no such result. There was one player with a rating close to 2400 and a *figural* IQ of 70, indicating that this individual had low scores on the figural reasoning subtests. However, this same player had a numerical IQ of 117 (the 87th percentile), a verbal IQ of 113 (the 81st percentile), and a full-scale IQ of 103 (the 58th percentile; Roland Grabner, personal communication, May 6, 2015). There is no report in Grabner et al.'s article of a chess master with a rating close to 2400 and an IQ of around 80.

Ericsson (2014a) also makes points concerning the relationship between cognitive ability and expertise that do not stand to reason. For example, he notes that Garry Kasparov's IQ was estimated at 120 based on Raven's Progressive Matrices (Der Spiegel, 1987), "which is very close to the average of all chess players…thus not very predictive of world-class chess performance"

(Ericsson, 2014a, p. 87). However, one case does not a correlation make: if Kasparov was an outlier, and other world champion chess players (Boris Spassky, Bobby Fischer, Magnus Carlsen, etc.) had extremely high IQs, then IQ could still be *highly* predictive of world-class chess performance.

Thus, although we credit Ericsson (2014a) for his review—it will be essential reading for anyone interested in expertise for years to come—we disagree with his claim that there is currently no evidence to suggest that cognitive ability significantly predicts expertise. To be sure, correlations between cognitive ability and expertise are often not as large as those between deliberate practice and expertise, but neither are they trivially small, from either a statistical or a practical perspective. This conclusion is broadly consistent with evidence that cognitive ability is the single best predictor of job performance and maintains its predictive validity even in highly experienced employees (see Schmidt & Hunter, 2004). It also falls in line with Ackerman's (2014) observation that "there is ample evidence from over 100 years of research supporting the conclusion that abilities are significantly related to individual differences in the attainment of expert performance" (p. 104).

4.3 Personality Factors

A central theme of the biographies of many elite performers is intense commitment to their domains—a singular devotion seeming to border on the pathological. As a student, Marie Curie frequently forgot to eat, and even after winning her first Nobel Prize, she would work in her lab past midnight (Goldsmith, 2005). The golfer Ben Hogan is said to have hit practice balls until his hands bled and then soaked his blistered hands in pickle brine to toughen them so he could practice more (Dodson, 2005). Winner (2000) described such focus as a "rage to master," and noted that children who possess this quality "have a powerful interest in the domain in which they have high ability, and they can focus so intently on work in this domain that they lose sense of the outside world" (p. 162; see also Winner, 1996a, 1996b).

Ericsson et al. (1993) hypothesized that a number of personality factors predispose people to intense commitment to their domain:

> *within our framework we would expect that several 'personality' factors, such as individual differences in activity levels and emotionality may differentially predispose individuals toward deliberate practice as well as allow these individuals to sustain very high levels of it for extended periods.*
> *(p. 393)*

This view leads to the prediction that deliberate practice should mediate the effect of personality factors on domain-specific performance. There is support for this prediction. In a study of Spelling Bee contestants, Duckworth, Kirby, Tsukayama, Berstein, and Ericsson (2012) found that "grit"—a personality factor reflecting persistence in accomplishing long-term goals (Duckworth & Gross, 2014)—positively predicted deliberate practice, which in turn positively predicted spelling performance. Along the same lines, in a study of classical musicians, Bonneville-Roussy, Lavigne, and Vallerand (2011) found that "passion" positively predicted "mastery goals," which positively predicted deliberate practice, which positively predicted music performance (see Vallerand, 2015; see also Hallam, 1998). Similarly, in a study of chess players, de Bruin, Rikers, and Schmidt (2007) found that a measure of motivation to engage in deliberate practice positively predicted accumulated amount of deliberate practice, which in turn positively predicted chess rating.

This evidence supports the idea that people differ in their propensity to engage in deliberate practice, which translates into individual differences in expertise. However, personality factors may also impact performance directly. For example, Grabner et al. (2007) found that chess rating correlated positively with a measure of the ability to regulate the expression of emotions, even after controlling for a number of other factors (intelligence, number of tournament games, motivation, etc.). High levels of emotional control were associated with superior chess skill. Susceptibility to performance anxiety and to "choking" under pressure are other personality-type factors that could impact performance directly, independent of deliberate practice.

4.4 Other Domain-Relevant Experience Factors

Experts spend a considerable amount of time training, but obviously they engage in other forms of domain-relevant experience as well. Ericsson et al. (1993) distinguished deliberate practice from two other types of domain-relevant activities, which they termed *work* and *play*, as follows:

> *Work includes public performance, competitions, services rendered for pay, and other activities directly motivated by external rewards. Play includes activities that have no explicit goal and that are inherently enjoyable. Deliberate practice includes activities that have been specially designed to improve the current level of performance.*
> *(p. 368)*

The deliberate practice view claims that these other forms of domain-relevant experience are weaker predictors of domain-specific performance than deliberate practice. As Boot and Ericsson (2013) explained, "Ericsson and colleagues...make a critical distinction between domain-related activities of work, play, and deliberate practice, and claim that the amount of accumulated time engaged in deliberate practice activities is the primary predictor of exceptional performance" (p. 146).

This claim leads to the prediction that measures of deliberate practice should correlate more strongly with expertise than measures of engagement in either work or play. There is some evidence to support this prediction. For example, in their two studies, Charness et al. (2005) found that log hours of tournament play (work) did not significantly predict chess rating after controlling for log hours of serious study (deliberate practice). However, this prediction is not always supported. Howard (2012) found total number of games correlated almost twice as strongly with chess rating as total study hours did, and in a study of insurance salespeople, Sonnentag and Kleine (2000) found that the number of cases handled—a measure that fits the description of work—correlated more strongly with a measure of sales performance ($r = 0.37$) than measures of both current and accumulated deliberate practice did ($rs = 0.21$ and 0.13). As another example, Moxley, Ericsson, Scheiner, and Tuffiash (2015) found that log number of years of participating in crossword puzzle tournaments correlated significantly with performance in the American Crossword Puzzle Tournament ($r = 0.32$). *A priori,* participating in a tournament would seem to be a clear instance of what Ericsson et al. (1993) described as work.

Other studies have found that play positively predicts performance. For example, Ford and Williams (2012) found that youth soccer players who had received professional scholarships at age 16 had engaged in significantly more soccer play-like activities per year than the soccer players at the same clubs who had been asked to leave at age 16 for not making significant progress. Haugaasen, Toering, and Jordet (2014) found similar results with youth soccer players: those who had received professional contracts had engaged in more play activities during early development (ages 6—8) than their soccer club counterparts who had not received professional contracts. On a related note, Côté and colleagues have found that *deliberate play,* which they define as activities that are "intrinsically motivating, provide immediate gratification, and are specifically designed to maximize enjoyment" (Côté, Baker, & Abernethy, 2007, pp. 185—186), can be as predictive of expertise as deliberate practice (see, e.g., a study of ice hockey by Soberlak & Côté, 2003).

To sum up, there is evidence that forms of domain-relevant experience other than deliberate practice, including what Ericsson et al. (1993) termed work and play, significantly predict expertise, and are perhaps even more predictive than deliberate practice in some domains.

4.5 Developmental Factors

For the obvious reason that expertise in virtually all domains is acquired gradually, a complete account of the origins of expertise must take into account developmental factors. One developmental factor is *starting age*. Reviewing evidence from a small number of studies, Ericsson et al. (1993) concluded that "we find that the higher the level of attained elite performance, the earlier the age of first exposure as well as the age of starting deliberate practice" (p. 389) and "[a]cross many domains of expertise, a remarkably consistent pattern emerges: The best individuals start practice at earlier ages and maintain a higher level of daily practice" (p.392). Ericsson et al. further argued that the benefit of starting early (vs later) is a longer period of time to accumulate deliberate practice: "[t]he individuals who start early and practice at the higher levels will have a higher level of performance throughout development…than those who practice equally hard but start later" (p. 392).

This argument leads to the prediction that the effect of starting age on performance should be mediated through deliberate practice. Consistent with this hypothesis, in an initial report of data from their study of chess players (reported in Charness, Krampe, & Mayr, 1996), Charness and colleagues found that the relationship between starting age and chess rating was nonsignificant after statistically controlling for accumulated amount of deliberate practice. However, both Gobet and Campitelli (2007) and Howard (2012) found that the correlation between starting age and chess rating was statistically significant even after statistically controlling for accumulated amount of deliberate practice. This evidence is consistent with the possibility that there is a critical period for acquiring some complex skills, just as there may be for language.

A complete account of expertise must also take into account effects of aging. Though it is clear that various aspects of physical, sensory, perceptual, motor, and cognitive functioning decline in adulthood (Santrock, 2012), findings from cross-sectional research on aging and expertise are inconsistent. For example, although Masunaga and Horn (2001) found a near zero correlation between age and GO ranking among amateur players ($r = 0.04$), Moxley and Charness (2013) found an average correlation of -0.28 between age and performance in best move tasks in chess. One possible explanation for this inconsistency is selective attrition; that is, weak performers may quit. A more consistent pattern of results emerges from longitudinal studies: performance increases up to a peak age, after which it decreases. In intellectual domains, the peak age tends to be in the mid-30s to mid-40s. For example, in a longitudinal analysis of over 5000 chess players, Roring and Charness (2007) found a peak age of 43.8 years for chess rating, and Simonton (1991) documented peak ages (i.e., age of best contribution) in the mid-30s to early-40s for academic domains. In physical domains, the peak age is much earlier. For example, Schulz and Curnow (1988) found that the average age of Olympic gold medal winners is in the early 20s for short-distance running events (e.g., 22.9 years for the 100 m) and the late 20s for long-distance events (e.g., 27.9 for the marathon). It has been suggested that age-related decline in skill is not inevitable and instead reflects reduction in deliberate practice (Krampe & Ericsson, 1996), but at present, there is very little evidence to support this hypothesis (see Hambrick & Macnamara, 2016).

4.6 Genetic Factors

The finding that (1) deliberate practice leaves a large amount of individual differences in expertise unexplained and (2) basic abilities known to be influenced by genetic factors correlate with expertise in these same domains, suggests that individual differences in genetic factors also contribute to individual differences in expertise. However, this evidence is merely suggestive of a genetic contribution, for the obvious reason that these same basic abilities are also known to be influenced by *environmental* factors. More direct evidence for an impact of genetic factors on expertise comes from behavioral genetics research.

Although it is difficult to quantify the degree to which two people's environments are similar, it is relatively easy to quantify the degree to which they share genetic factors. This is because inheritance of most genetic material follows very simple rules, which were first postulated by Gregor Mendel in the mid-1800s based on his experiments with pea plants (Mendel, 1866). Biometrical theory can be used to calculate the average amount of genetic sharing between two relatives at the genome-wide level. Like siblings, a child shares 50% of their autosomal (i.e., non-sex chromosome) DNA with each of their parents. By contrast, grandparents share on average 25% of their genetic material with their grandchildren (like half-siblings and members of avuncular relationships). Making use of this information about differences in average genetic sharing between relatives, analysis of data from related individuals (the family design) enables statistical estimation of the relative magnitude of genetic and environmental influences on trait variation (Blokland, Mosing, Verweij, & Medland, 2013).

The twin study is the most commonly used family design, and compares within-pair similarity of identical (monozygotic; MZ) and non-identical (dizygotic; DZ) twins. MZ twins are genetically identical, whereas DZ twins share on average only 50% of their genetic loci. However, both types of pairs have shared prenatal environments (as they were conceived at the same time and shared the womb) and also share much of their rearing environment, as they are born at approximately the same time and grow up together in the same family environment. Such environmental influences common to the two members of a twin pair are generally referred to as shared environmental influences and are assumed to make the twins more similar to each other. Finally, there are also environmental influences that are unique to each one of the twins and will make the members of a twin pair more different from each other (e.g. a trauma, different friends or teachers). Such influences are referred to as non-shared environmental influences. In twin modeling, the non-shared environmental estimates will also include measurement error. Via SEM, genetic versus environmental influences on the variance in a trait can be disentangled and quantified. Heritability refers to the proportion of the phenotypic variance in a trait that is attributable to the effects of genetic variation (Neale & Cardon, 1992).

Twin research has now convincingly established that observed (or *phenotypic*) differences in complex human traits are influenced by both genetic and environmental factors, including their interaction and correlation (Polderman et al., 2015). For example, heritability estimates typically range from 50% to 70% for general intelligence, and from 30% to 50% for specific cognitive abilities and personality traits (Plomin, DeFries, McClearn, & McGuffin, 2008). Given that these same factors appear to play an important role in expertise, it is reasonable to also expect genetic influence on variation in expertise (Bouchard & McGue, 2003; Harris, Vernon, Johnson, & Jang, 2006; Plomin & Spinath, 2004), and there is evidence that this is the case. Coon and Carey (1989) used a sample of over 800 same-sex twin pairs to investigate the heritability of music accomplishment. The twins in this sample were identified through a survey given to roughly 600,000 high school juniors who took the National Merit Scholarship test in 1962 (see Loehlin & Nichols, 1976). The twins completed a survey to determine whether they were identical or fraternal, and then completed a 1082-item psychosocial survey that included several questions about both music accomplishment and music practice. For a measure of musical achievement, the heritability estimate was 38% for males and 20% for females. Vinkhuyzen, van der Sluis, Posthuma, and Boomsma (2009) analyzed data from a study in which 1685 twin pairs rated their competence in chess, music, and several other domains and found even stronger evidence for a role for genetic factors. For endorsement of "exceptional talent," heritability ranged from 50% to 92%.

More recently, in a large sample of adolescent twins, Plomin and colleagues found that genetic factors accounted for over half of the variation between expert and less skilled readers, where experts were defined as individuals who scored above the 95th percentile on a standardized test of reading ability (Plomin, Shakeshaft, McMillan, & Trzaskowski, 2014). Similarly, moderate heritability estimates for objective measures of music ability have been reported in a number of studies. Drayna, Manichaikul, de Lange, Snieder, and Spector (2001) reported heritability estimates of 80% for performance on the Distorted Tunes Test, which requires the participant to identify incorrect pitches from familiar melodic stimuli. Ullén, Mosing, Holm, Eriksson, and Madison (2014) had a sample of over 10,000 twins complete a test of musical aptitude (the Swedish Musical Discrimination Test) and found heritability estimates of 50% for rhythm discrimination, 59% for melody discrimination, and between 12% and 30% for pitch discrimination. Evidence further suggests that the predisposition to practice seems to be partly heritable: in two studies, heritability estimates were between 38% and 70% for music practice (Hambrick & Tucker-Drob, 2014; Mosing, Madison, Pedersen, Kuja-Halkola, & Ullén, 2014).

Behavior genetic studies have also shed light on the nature of phenotypic associations between practice and performance. Mosing et al. (2014) found that both music practice and music aptitude were substantially heritable and that *genetic pleiotropy*—which occurs when one gene or set of genes influences multiple traits—explained much of the association between these two factors. Furthermore, the results of monozygotic intrapair difference modeling, using a co-twin control design, did not support a causal effect of music practice, for either music discrimination (Mosing et al., 2014) or for accuracy of motor timing (Ullén, Mosing, & Madison, 2015). That is, identical twins differing massively in accumulated amount of practice (as much as 20,000 h) performed similarly on tests of these abilities. Similarly, using the National Merit Twin Sample, Hambrick and Tucker-Drob (2014) reported common genetic effects on music practice and music accomplishment. However, the genetic effect on music practice explained only about a quarter of the genetic effect on music accomplishment. This finding is inconsistent with the idea that genetic effects on expertise are entirely mediated through factors that predispose people to engaging in practice. Hambrick and Tucker-Drob also found that the importance of genetic factors for musical accomplishment *increased,* rather than decreased, with practice. This evidence runs counter to Ericsson's (2007) claim that training activities "selectively activate dormant genes that all healthy children's DNA contain" (p. 4), and instead suggests that training may activate dormant genes, variants of which *differ* across individuals. This evidence is in line with an earlier twin study on training of the rotary pursuit task, which found that genetic influences on performance as well as learning rate increased after 3 days of training (Fox, Hershberger, & Bouchard, 1996).

Taken together, findings of these twin studies indicate that there are both direct and indirect effects of genetic factors on expertise. More specific information about the role of genetic factors in expertise comes from molecular genetics research, which seeks to identify associations between specific genes and performance. In a series of studies, North and colleagues documented correlations between genotype for the ACTN3 gene, which codes the alpha-actinin-3 protein in fast-twitch muscles, and performance in various sprint events. For example, in one study (Yang et al., 2003), compared to 18% of control subjects, only 6% of 107 elite athletes from various short-distance events had a variant of ACTN3 that made them alpha-actinin-3 deficient. Even more striking, *none* of the most elite athletes in the sample—the 32 Olympians—were alpha-actinin-3 deficient.

There is also an emerging molecular genetic literature on music (see Tan, McPherson, Peretz, Berkovic, & Wilson, 2014; for a review). In a very recent study, Di Rosa and colleagues (Di Rosa, Cieri, Antonucci, Stuppia, & Gatta, 2015) used Ingenuity Pathway Analysis (IPA) to identify possible interactions between genes potentially related to musical ability and those deleted in individuals with Williams Syndrome—a genetic disorder that is associated with serious deficits in some cognitive domains but surprisingly good musical skills. Di Rosa et al. reported a potential interaction between a gene related to Williams Syndrome (STX1A) and one related to music skills (SLC6A4). Both of these genes are involved in serotonin transporter expression, suggesting that serotonin may be involved in the development of musical abilities.

5. TOWARD A COMPREHENSIVE MODEL OF EXPERTISE

Nearly 20 years ago, Simonton (1999) urged psychologists to think broadly about the potential causes of expertise:

> *it is extremely likely that environmental factors, including deliberate practice, account for far more variance in performance than does innate capacity in every salient talent domain. Even so, psychology must endeavor to identify all of the significant causal factors behind exceptional performance rather than merely rest content with whatever factor happens to account for the most variance.*
> *(p. 454)*

More recently, Kaufman (2014) noted, "Other traits beyond deliberate practice are critical for the development of expert performance." Here, we have discussed a wide range of factors that may contribute to individual differences in expertise. How can all these factors be investigated in an integrative fashion?

5.1 Existing Theoretical Models to Guide Research on Expertise

There exist a number of theoretical frameworks that can guide integrative research on expertise (see Subotnik, Olszewski-Kubilius, & Worrell, 2011; for a comprehensive review). One of the most prominent is Gagné's *Differentiating Model of Giftedness and Talent* or DMGT (Gagné, 2009, 2013, 2014). The DMGT describes how outstanding levels (top 10%) of genetically influenced abilities ("gifts") are transformed into outstanding levels of knowledge and skill ("talents") in occupational fields. DMGT posits that talent development is moderated by "catalysts"—intrapersonal factors such as physical and mental abilities, and environmental factors such as cultural milieu and availability of resources. A more general model—the *Comprehensive Model of Talent Development* (Gagné, 2015)—describes the progression from biological foundations to gifts and then to talents. Simonton (2014) has proposed a somewhat similar model to direct research on individual differences in creative performance. This model posits that both environmental and genetic factors impact creative performance through cognitive abilities and dispositional traits, which may impact performance directly and through deliberate practice.

Another important theoretical framework is Zielger and colleagues' *Actiotope Model of Giftedness* (AMG). The AMG posits that excellence in a domain reflects not only individual difference characteristics, but also the person's entire *actiotope,* which comprises the "actions and the possibilities for acting possessed by individuals" and "an individual and the material, social and informational environment in which that individual actively interacts" (Ziegler, Vialle, & Wimmer, 2013, p. 3). (The inspiration for the term *actiotope* is *biotope*, which is very similar in meaning to *habitat*.) Zielger and colleagues differentiate between two types of "capital" that impact learning—*learning capital* and *educational capital*. Learning capital includes characteristics of learners themselves—for example, a learner's goals (*telic capital,* from the Greek "telos," for goal or purpose) and their attentional resources (*attentional learning capital*). By contrast, educational capital includes characteristics of learners' environments—for example, investment in schools (*economic educational capital*) and the availability of institutions and individuals to support the learning process (*social educational capital*).

Several other models may be useful for identifying possible determinants of individual differences in expertise. One such model is Ackerman and colleagues' PPIK theory—*Intelligence-as-Process, Personality, Interests, and Intelligence-as-Knowledge* (see Ackerman, 1996; Ackerman & Beier, 2004). Extending Cattell's (1971) *Investment Theory of Intelligence,* PPIK posits that the acquisition of domain knowledge—the core factor of the adult intellect—is influenced by constellations of personality traits, abilities, and interests (or "trait complexes"). In a model of occupational and academic performance, Schmidt (2014) proposed that introversion and fluid intelligence are the primary causes of general interest in learning (intellectual curiosity). Intellectual curiosity is the primary cause of crystallized intelligence (including knowledge), which in turn is the primary cause of occupational and academic performance. Gardner's (1983, 1999) *Theory of Multiple Intelligences* could also be used as a guide for identifying basic abilities that are relevant to acquiring expertise in various domains, as could Sternberg's (1985) *Triarchic Theory of Intelligence,* which posits analytical, practical, and creative intelligences. Côté and colleagues' *Developmental Model of Sport Participation* could be used to identify forms of domain-relevant experience other than deliberate practice that may predict expertise (e.g., deliberate play; see Côté et al., 2007).

Task and situational factors must also be included in a comprehensive account of expertise. Feltovich and colleagues' analysis of situations that create difficulty in developing high levels of proficiency in medical practice is particularly relevant (Feltovich, Coulson, & Spiro, 2001; see also Hoffman et al., 2014). Through cognitive task analysis and interviews with subject matter experts, these researchers identified several "dimensions of difficulty" that make tasks require mental effort, such as *static versus dynamic, discrete versus continuous,* and *sequential versus simultaneous.* A key question for future research is whether these task/situational factors interact with individual-difference factors in predicting expertise. For example, as alluded to earlier, a static task environment may afford greater use of retrieval structures (i.e., Ericsson & Kintsch's, 1995, long-term working memory) to encode and maintain rapid access to domain-relevant information than a dynamic task environment, making circumvention of working memory limitations possible in the former situations but not the latter.

5.2 Multifactorial Gene–Environment Interaction Model

Figure 6 illustrates a model for investigating expertise from an integrative perspective. The model is an instantiation of the *Multifactorial Gene–Environment Interaction Model* (MGIM) of expertise recently proposed by Ullén, Hambrick, and Mosing (2015). The MGIM considers expertise at both the genotypic and phenotypic levels and assumes genetic factors, nongenetic factors, and their interactions to be important influences throughout the model. The MGIM includes both *distal* predictors of expertise—factors that influence performance indirectly through other factors (e.g., opportunity factors, deliberate practice)—and *proximal* predictors of performance—factors that may influence performance directly (e.g., basic ability factors, domain-specific knowledge factors). It also includes factors that are both proximal *and* distal predictors, in that they have both direct and indirect effects on performance (e.g., ability factors, personality factors). Finally, the model captures interactions between factors (e.g., task/situational × ability interactions).

As illustrated in the reanalysis of the results of Masunaga and Horn's (2001) study of GO expertise (see Figure 5), SEM is the optimal approach for testing the MGIM. Along with permitting analysis of data at the latent level, SEM permits analysis of either cross-sectional or longitudinal data. It also allows the researcher to test multiple relationships involving multiple variables in a single analysis and to statistically compare different configurations of variables representing competing models. Finally, SEM can be used to test for nonlinear relationships, such as interactions between individual difference and task/situational variables. In short, SEM can accommodate most any type of quantitative data (behavioral, genetic, or neural) collected in studies of expertise and can be used to test for many different types of relationships.

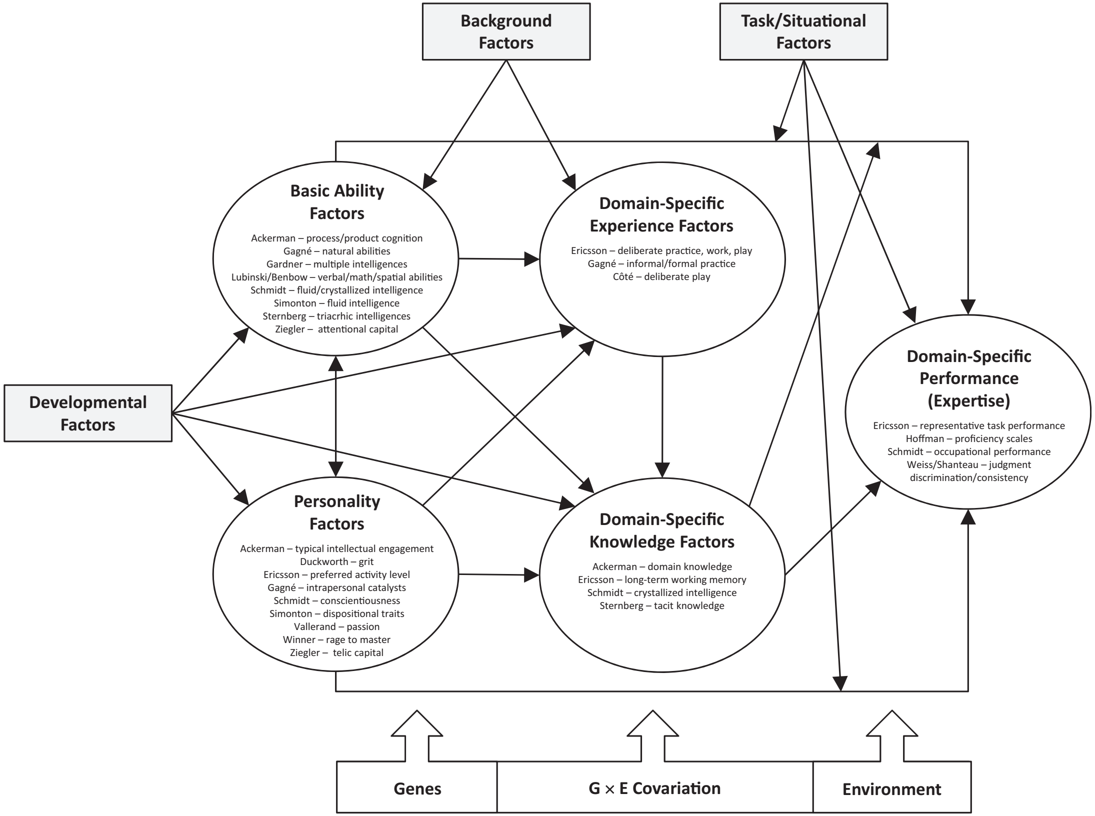

Figure 6 Instantiation of the multifactorial gene—environment interaction model (MGIM; Ullén et al., 2015) illustrating possible influences of different types of factors on expertise (names refer to associated theorists).

5.3 A Mathematical Simulation Approach

Mathematical simulation offers another way to investigate the origins of expertise. One of us (Campitelli, Gobet, & Bilalić, 2014) has used such an approach to investigate how well three models of chess expertise capture five major results found in the chess expertise literature: (1) there are very young chess players with remarkable achievements; (2) there is a moderate correlation between chess rating and both chess playing and chess practice; (3) there is a critical period (i.e., players that start practicing chess at earlier ages are much more likely to achieve higher levels of expertise in chess); (4) the correlation between chess expertise and intelligence is much higher in children than in adults; and (5) there is a decline in chess skill in older adults.

The simulation included three competing models. The *practice-motivation (PM) model* was the implementation of the deliberate practice view. The only differences among individuals in this model are the number of hours of practice and the motivation toward engaging in practice. The *practice-intelligence (PI) model* explains differences in chess skill based on differences in practice, playing, and intelligence. Finally, the *practice-plasticity-processes (PPP) model* indicates that the differences in chess skill are accounted for by differences in practice, playing, and neural plasticity. Differences in neural plasticity lead to differences in the acquisition of domain-specific patterns and heuristics. Note that in this model the correlation between chess skill and intelligence is due to the fact that neural plasticity affects both the acquisition of chess skill and intelligence.

The results of the simulation indicate that PPP was able to capture four of the five criteria (all but the fourth, which none of the models captured). By contrast, PM and PI captured at most three criteria. Obviously, a mathematical simulation is not a behavioral test of the models, but the simulation clearly shows that a model that only explains individual differences in chess skill based on differences in practice would never be able to account for well-established findings in the literature. This approach is interesting in its own right and could also be used to guide specification of factors and models in SEM research.

6. BEYOND EXPERTS ARE BORN VERSUS MADE

Our review of evidence concerning the origins of expertise can be summarized in the following points:

1. Though undeniably important from a statistical and practical perspective, deliberate practice does not account for all, nearly all, or even the majority of the variance in expertise.
2. Basic abilities predict expertise in some domains and sometimes even in highly skilled performers.
3. Personality factors predict expertise indirectly through deliberate practice, but may also predict expertise directly.
4. Forms of domain-relevant experience other than deliberate practice (e.g., work) positively and meaningfully predict expertise.
5. Genetically influenced factors account for individual differences in expertise, both indirectly through training and directly.
6. Models of expertise that only take into account deliberate practice will never adequately account for the major facts of expertise.

Over the past several decades, expertise has emerged as a vital area of psychological research, and all indications are that interest is only increasing, as evidenced by recent special issues of the journals *Intelligence* (Detterman, 2014) and *Frontiers in Psychology* (Campitelli, Connors, Bilalic, & Hambrick, 2014) devoted to the topic (see also Kaufman, 2013, for an edited volume). The intensity of the debate over the origins of expertise may to some degree reflect pre-theoretical biases—beliefs about why some people are more successful in various realms than others. No scientist can claim to be totally immune from such biases, and it is important to remain cognizant of such biases to maintain objectivity in this area of research. The debate may also reflect a clash between the two disciplines of scientific psychology—the *experimental* and the *differential* (Cronbach, 1957). Experimental psychologists seek to identify general trends in data, as reflected in means, whereas differential psychologists seek to explain individual differences, as reflected in measures of variance. Adherents of these approaches may “talk past each other.”

Whatever the case, we believe that the most fruitful approach for future research on the origins of expertise is to embrace the idea that expertise is, at its core, a multiply determined phenomenon whose richness and complexity can never be adequately understood by focusing on one, or one class, of determinant, or by using one methodological approach. The experts are born versus made debate is over, and now the task for scientists is to develop and test theories that take into account the myriad ways that experts are born *and* made, using the most appropriate methodological approaches to test these theories. A respectful and open-minded exchange of ideas among researchers with diverse perspectives on expertise will make this a reality and advance understanding of topic of enduring fascination to scientists and non-scientists alike.

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