It Takes More Than Practice and Experience to Become a Chess Master: Evidence from a Child Prodigy and Adult Chess Players

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Abstract

Ericsson’s theory of deliberate practice and Chase and Simon’s recognition-action theory both hold that the key to reaching master level performances in chess is to engage in at least 10 years or 10,000 hours of deliberate practice. Moreover, Ericsson claims that the primary source of individual differences in chess skill is deliberate practice time. Two studies were conducted to investigate whether deliberate practice or other chess-related experience is sufficient to explain individual differences in chess expertise and to investigate other factors that may contribute to chess expertise. Study 1 investigated the amount of time a young and exceptional chess player, CS, had studied alone and engaged in other chess-related experiences. CS spent little time studying alone and little time engaging in other chess-related experiences. Nonetheless, she achieved an exceptional chess level. CS’s achievement is difficult to reconcile with the 10 years or 10,000 hours rule. Finally, CS performed exceptionally well on a test of visual short-term memory. Study 2 investigated factors contributing to the chess ratings of 77 adult chess players. Time spent studying alone and time spent engaging in other chess-related activities were strongly related to chess skill. However, contrary to the theory of deliberate practice, other factors including domain-general fluid intelligence, domain-specific fluid intelligence, and domain-specific crystallized intelligence all contributed substantially to the prediction of chess ratings even after controlling for practice and other chess-related activities. These findings support the view that spending time studying alone and playing chess is necessary but not sufficient for achieving a very high level of chess performance.

Keywords

child prodigy, chess players, individual differences, expertise, deliberate practice

Introduction

Psychologists have long been interested in how people become experts. Although it is evident that there are substantial individual differences in performance across a wide variety of tasks (see Howard, 2009), there is disagreement about the relative importance of various sources of individual differences. Some researchers argue that the primary source of individual difference is natural ability, whereas others argue that the primary source is practice, with natural ability making little to no difference.

Much of the research on expertise has involved the study of chess. In this domain, Chase and Simon (1973) argued for the primacy of practice in the acquisition of skill. According to their recognition-action theory “each familiar pattern serves as the condition part of a production. When this condition is satisfied by recognition of the pattern, the resulting action is to evoke a move associated with this pattern and to bring the move into short-term memory for consideration” (Chase & Simon, 1973, p. 269). Thus, they argued that chess expertise is due primarily to the ability to recognize familiar patterns of pieces, and *experience* allows players to learn more patterns. Further, Simon and Chase (1973) argued that after from 10,000 to 50,000 hours of practice, chess players store a sufficient number of patterns in their long-term memory to play at master strength. It is worth noting that Simon and Chase (1973) did not deny the role of talent in chess expertise and acknowledged the practice interacts with talent. However, they argued that the acquisition of chess skill depends, in large part, on building up familiar chess patterns, which are acquired via practice or domain-specific experience. They summarized their view of the role of practice in skill acquisition as follows: “The overriding factor in chess skill is practice. The organization of the Master’s elaborate repertoire of information takes thousands of hours to build up, and the same is true of any skilled task (e.g., football, music). That is why *practice* is the major independent variable in the acquisition of skill” (Chase & Simon, 1973, p. 279).

Evidence for recognition-action theory includes Kasparov’s high-quality play in a simultaneous exhibition (Gobet & Simon, 1996) and the high correlation between players’ results in speed chess and standard chess (Burns, 2004). The argument that these findings support recognition-action theory is based on the assumption that simultaneous exhibitions and speed chess do not provide sufficient time for calculation, and therefore move choice in these situations is based predominantly on fast automatic processes. However, Chang and Lane (2016) found that players take considerable time on key moves in speed chess and play other moves very quickly. This is also likely true in simultaneous exhibitions. This implies that calculation and other slow processes are involved in speed chess. Chang and Lane (2016) also found that stronger players calculated more and better than did weaker players, again undermining the evidence for recognition-action theory.

Ericsson, Krampe, and Tesch-Romer (1993) also emphasized the importance of practice but focused on the importance of coaches and tutors in acquiring skills rather than on Chase and Simon’s (1973) automatic learning of familiar chess patterns. Specifically, they stated that “expert performance is acquired slowly over a very long time as a result of practice and that the highest levels of performance and achievement appear to require at least around 10 years of intense prior preparation” (p. 366). Subsequently, Ericsson and Lehmann (1996) concluded that “in chess, sports, and many other domains with thousands of active participants, individuals attain internationally recognized levels of exceptional performance only after spending about 10 years in intense preparation” (p. 296). Furthermore, Ericsson, Prietula, and Cokely (2007) argued that that “… our research shows that even the most gifted performers need a minimum of *ten years (or 10,000 hours)* of intense training before they win international competitions” (p. 119, emphasis added).

Ericsson et al.’s (1993) study of violinists and pianists is a widely cited and influential source of evidence for the overriding importance of practice. These authors estimated the deliberate practice times of violinists at different levels of expertise by asking participants to report the number of hours per week they had practiced alone. They found that the mean reported time practiced alone was approximately 10,000 hours for the best students, 8,000 hours for the good students, and 5,000 hours for future teachers. Similar results were found for the pianists for whom the mean times for experts and amateurs were approximately 10,000 hours and 2,000 hours, respectively. Emphasizing their belief in the primacy of deliberate practice, Ericsson et al. (1993) 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, in the following statement, denied a role for natural abilities:

> 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 (p. 400).

Elaborating on this view, Ericsson (2007) argued that nearly anyone can become an expert with enough deliberate practice and discounted the importance of natural ability by stating "… in well-established domains of expertise even the most 'talented' cannot reach an international level in less than around a *decade of experience and intense preparation*" (p. 14, emphasis added). Similarly, Ericsson, Roring, and Nandagopal (2007) stated that "there is compelling evidence for the requirement of engagement in domain-related activities prior to attaining high levels of performance and that even the most 'talented' need *10 years or more* of intense involvement before they reach a level where they can consistently demonstrate superior performance in international adult competitions in sports, sciences and the arts" (p. 16, emphasis added).

It is worth noting that Ericsson's view is that expertise always develops gradually with practice rather than developing gradually in some people and developing rapidly in others. As stated clearly by Ericsson (1998), "The evidence suggests that expert performance can be attained without unique and innate capacities (talent) as individuals gradually increase their mastery in a single domain over years and decades" (p. 96). Although Ericsson never claimed that deliberate practice can explain all reliable variance in attained performance (Ericsson, 2014a, 2014b), he has hypothesized that the only other factors that *might* have an effect on skill acquisition are the small number of physical characteristics relevant to some domains. These factors do not appear to be present in many domains including the domain of chess. This view that expertise is due primarily to practice was popularized by Gladwell's (2008) *Outliers* and cited in other popular books including *Talent is Overrated* (Colvin, 2010) and *The Genius in All of Us* (Shenk, 2010).

Two sources of evidence have the potential to contradict the view that natural ability does not play an important role in the acquisition of expertise. First, the existence of prodigies would demonstrate the importance of natural ability unless it can be argued convincingly that these prodigies acquired their expertise through thousands of hours of practice. Ericsson et al. (1993) made this argument in the case of Bobby Fischer. The second potential source of evidence is based on the idea that if expertise is solely a function of practice, then practice should account for essentially all variance in skill and other variables such as IQ should not contribute independently to expertise. Evidence to the contrary would leave open the possibility that natural ability is an important factor in skill acquisition.

Natural ability has been defined in terms of the ability to profit from domain-specific experience (Chassy & Gobet, 2010; Ullén, Hambrick & Mosing, 2015). As Chassy and Gobet (2010) stated, "Within one domain of expertise, allelic variability accounts for the differences in speed with which expertise is acquired" (p. 22). In other words, some individuals profit from an hour training more than others, and this ability to profit from training may be mediated by genetic factors. In this paper, we adopt the definition of natural ability as the ability to profit from domain-specific experience. Natural ability may be the result of genes and/or early experience. According to this view of natural ability, people have different cognitive and physical abilities, and, regardless of whether these abilities are environmentally or genetically determined, these abilities contribute to individual differences in the speed and level of acquisition of expertise. It is important to note that this view of natural ability does not discount the importance of practice and training but posits the importance of individual differences in the ability to profit from training, practice, and experience.

One of the most important sources of evidence supporting the importance of natural ability is the study of precocious children. The very existence of prodigies would seem to contradict the argument for the universal primacy of deliberate practice and support the view that natural ability plays a critical role.

Child prodigies have been defined as children under 10 years old whose performance is at a level that is rare even in highly-skilled adults (Feldman, 1993; Ruthsatz & Detterman, 2003). As Winner (2000) stated, “Gifted children, those with unusually high ability in one or more domain, not only develop more rapidly than typical children, but also appear to be qualitatively different” (p. 153). Generally, their extraordinary talents are specific to domains such as music, chess, math, sports and arts. Recent studies have suggested that across domains, a child prodigy must possess at least a moderate level of general intelligence (Feldman & Morelock, 2011).

Bobby Fischer was one of the greatest chess players of all time and has often been cited as a prime example of a prodigy because he learned how to play chess at the age of six and became a grandmaster at the age of 15 (Brady, 2011). However, Ericsson et al. (1993) based on Brady’s (1973) book, *Bobby Fischer: Profiler of a Prodigy*, suggested that Fischer was only a year shy of the bounds of the 10-year practice when he became a grandmaster and dedicated sufficient time to practice so that his performance could be explained in terms of deliberate practice (e.g., Ericsson & Charness, 1994; Ericsson et al., 1993; Ericsson, Roring, et al., 2007). Therefore, according to Ericsson, Fischer’s early accomplishments could be explained by practice and without appealing to natural ability. Although the explanation of Fischer’s chess expertise in term of deliberate practice appears dubious because his performance was far better than that of many other chess players who studied extensively and played far more than nine years, it cannot be decisively refuted. However, there are other chess prodigies whose achievements are extraordinarily difficult to explain by deliberate practice. These include Ruslan Ponomariov (born in 1983), Peter Leko (born in 1979) and Magnus Carlsen (born in 1990). Based on these contemporary prodigies’ ages when they started playing chess and ages they obtained the grandmaster title, Gobet and Campitelli (2007) concluded that “although there is substantial evidence suggesting that domain-specific practice is essential for the acquisition of high-level expert performance, it may be the case that inter-individual variability has been underestimated in previous research” (p. 162). This conclusion is consistent with the findings from other studies reexamining the cases of Magnus Carlsen (Gobet & Ereku, 2014) and the Polgar sisters (Howard, 2011). Hence, these prodigies’ exceptional achievements are difficult to account solely in terms of deliberate practice. These findings led Campitelli and Gobet (2011) to conclude that extensive practice is necessary but not sufficient to achieve expertise.

Since there is only anecdotal evidence concerning the number of hours exceptional young chess players practiced, there is no definitive answer as to whether they practiced 10,000 hours before being able to play at a world-class level. However, there is indisputable evidence that some achieved that level in less than 10 years of chess playing and/or studying. Perhaps the most convincing example is Karjakin who learned to play chess when he was 5 and obtained a grand master title when he was only 12 years and 7 months old.

As noted previously, another approach relevant to the role of natural ability is to examine how much variance in chess players’ ratings can be explained by practice and whether other factors explain additional variance. A good example is the study by Charness, Krampe, and Mayr (1996) who assessed the relationship between eight variables and chess rating and found that time studying alone and number of books owned were the only two significant predictors, with the “time studying alone” accounting for 36% of the variance. Using Spearman’s (1904) equation to correct for unreliability of measures with reliability estimates of .8 for deliberate practice and .91 for chess rating, as used by Hambrick, Oswald et al. (2014), the variance explained by time studying alone is corrected to 50%. Subsequently, Charness and his colleagues (2005) used six variables focusing on the relationship between deliberate practice (studying alone) and chess skill. They measured the total number of hours that players had seriously studied chess, played in tournaments, the number of years of private instruction and group instruction, and the current hours/week spent seriously studying chess and playing in tournaments. They found that these variables explained 34% of the variance in chess ratings. The correlations between chess rating and the amount of time spent studying alone were .54 and .48 in two subsamples. After correcting for unreliability, the correlations between current skill rating and studying alone were .63 and .56 in samples 1 and 2, respectively. The variance in chess skill explained by deliberate practice (studying alone) were therefore 40% and 32%. Gobet and Campitelli (2007) used Charness et al.'s (1996) method to study 90 chess players and found that the correlation between cumulative hours of studying alone and skill level was .42 (explaining 18% of variance). After correcting for unreliability, the variance explained by individual practice (studying alone) was 24%. In addition, Howard (2012) used seven variables to predict chess rating, and found the number of games, number of study hours, and age beginning serious practice were the only three significant predictors. Number of games played was the strongest predictors in the model and correlated .33 with chess rating. After correcting for unreliability, this correlation is .39. Importantly, both Gobet and Campitelli (2007) and Campitelli and Gobet (2011) found that there was great variability in the amount of practice players who eventually became masters had engaged in before becoming masters. For example, one player required 16,000 hours of individual practice (or studying alone), whereas another player required only 728 hours. Similarly, one player required 14,200 hours of group practice, whereas another player required only 1,600 hours. Moreover, Gobet and Campitelli (2007) found that one player was able to become a master with a total of only 3,000 hours of practice which included both individual and group practice. It took another chess player 23,600 hours of practice to reach the same chess level. This variability among chess players strongly supports the proposition that "domain-specific practice is necessary but not sufficient to acquire master level" (Gobet & Campitelli, 2007, p. 168).

Meta-analyses had been conducted to estimate the proportion of variance in chess players' ratings and expertise in music that can be explained solely by practice. In one such meta-analysis, Hambrick, Oswald, et al. (2014) found that the mean proportions of reliable variance explained by deliberate practice in chess and music were 34% and 30%, respectively, leaving about 66% of the variance unexplained and presumably due to other factors. Platz, Kopiez, Lehmann, and Wolf (2014) did a meta-analysis of 13 studies and found that the correlation between deliberate practice time and music was .61, indicating that deliberate practice explains 36% of the variance. Platz et al. (2014) argued that results should be interpreted in terms of r rather than r^2 in line with Hunter and Schmidt's (2004) suggestion. However, the main point of Hunter and Schmidt's (2004) paper was that the report of r^2 is not statistically incorrect, but it makes the important relationship seems small. Thus, their correlation of .61 still shows that the variance that can be explained by deliberate practice is 36% (see reply by Hambrick, Altmann, Oswald, Meinz, & Gobet, 2014a).

Ericsson (2014c) criticized Hambrick, Oswald, et al.'s (2014) study on several grounds. One of Ericsson's key criticisms is that the studies in Hambrick, Oswald, et al.'s analysis "ignores 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). However, Hambrick, Altmann, et al. (2014b) noted that the factors they considered were the same as those in the original study conducted by Ericsson et al. (1993) in which skill level in music was predicted by self-reports of the time spent practicing alone. Moreover, they pointed out that their re-analyses included the study conducted by Charness et al. (2005) that Ericsson cited frequently and without criticism as evidence to support his viewpoint. In addition, Macnamara, Hambrick, and Oswald (2014) conducted a more comprehensive meta-analysis and found that the variance explained by deliberate practice was 20% for the studies using retrospective interview, 12% for studies using a retrospective questionnaire, and only 5% for studies using logs. This suggests that the variance explained by deliberate practice may be less than the variance presented by Hambrick, Oswald, et al. (2014). Since the log method explained the lowest percentage of variance and if this method is the most accurate, it follows that variance explained by deliberate practice is lower than previously estimated.

The second key criticism by Ericsson is that most studies included in Macnamara et al.'s (2014) meta-analysis study did not either meet his criteria for accurately estimating deliberate practice time or the studies they included did not cover the entire range of performance (i.e., including novice) to represent the domain of chess. Thus, Ericsson (2014a, 2014b) argued that among all the 88 studies (or 157 effect sizes) in Macnamara et al.'s paper only one met his criteria of deliberate practice, which was Ericsson et al.'s (1993) study of pianists. In spite of Ericsson's (2014b) arguments that these studies did not meet his criteria for deliberate practice, Ericsson previously credited their methods and used their findings as evidence to support his viewpoint of deliberate practice. For example, among these studies, one study in particular was conducted in the domain of chess by Charness et al. (2005). According to Ericsson's (2014b) criteria, Charness et al.'s (2005) study would not meet the criterion of deliberate practice because it measured the amount of time that chess players had studied alone and these activities were not designed by teachers or coaches, and they did not include novice in their sample. However, Ericsson described Charness et al.'s (2005) study by stating that it "reports the most compelling and detailed evidence for how designed training (deliberate practice) is the crucial factor in developing expert chess performance" (Ericsson, 2005, p. 237). Moreover, Ericsson has frequently used Charness et al.'s (2005) results to support the primacy of deliberate practice (e.g., Ericsson, Nandagopal, & Roring, 2009). In sum, these studies and meta-analyses call into question Ericsson's assertion of the primacy of deliberate practice.

More recently, a number of theoretical models have been proposed emphasizing the interaction between practice/experience and natural ability. For example, Ullén, Hambrick, and Mosing (2015) proposed the Multifactorial Gene-Environment Interaction model for expertise, which considers both genetic and environmental factors in acquiring skills and assumes that expertise is the product of genetic factors, environmental factors, and their interactions. In addition, Campitelli, Gobet and Bilalić (2014) used a simulation to investigate three competing models: Practice-Motivation (PM), Practice-Intelligence (PI), and Practice-Plasticity-Processes (PPP) models. The PM model of individual differences in expertise emphasizes the number of hours and the motivation toward practice whereas PI model emphasizes practice, playing, and intelligence. Finally, the PPP model emphasizes practice, playing, and neural plasticity. These theoretical models and the computational simulation are substantial contributions.

In summary, a number of studies and theoretical approaches support the proposition that some people require much less practice than others to reach an elite level of performance and chess-related experience (studying alone and playing chess) are important but not sufficient to explain the individual difference in skill. This paper investigated the role of practice and natural ability in chess expertise in two studies. In Study 1, we interviewed and tested a gifted young chess player and in Study 2, we explored practice and cognitive factors that could potentially contribute to the individual difference in chess expertise.

Study 1

In Study 1, we conducted an investigation of talented young chess player who we will refer to as CS. One aim of this study was to investigate the development of this young chess player's expertise. We were interested in the developmental trajectory of CS's chess expertise and whether the time she spent studying and playing chess is consistent with the view that chess experience generally and/or deliberate practice in particular is the primary basis of chess expertise.

We also tested CS on a variety of cognitive tasks in search of specific cognitive abilities that could be responsible for her chess expertise. The tasks were selected and investigated based on previous studies (e.g., Bilalić, McLeod, & Gobet, 2007; Frydman & Lynn, 1992; Grabner, Neubauer, & Stern, 2006; Grabner, Stern, & Neubauer, 2007; Halberda, Mazzocco, & Feigenson, 2008; Unterrainer, Kaller, Halsband, & Rahm, 2006).

We are aware of only one contemporaneously conducted study of a talented young player's cognitive abilities: Baumgarten's (1939) study of Sammy Reshevsky which was done when Reshevsky was 9 years old. Although Reshevsky's performance on most tasks was unexceptional or very poor (he was not tested in his native language), he did perform exceptionally well on the following test of visual short-term memory: "He was allowed four minutes to examine 40 figures, each drawn in a special square on a sheet of paper; the paper was then removed. He was able to restate the figures without a single mistake, and in the correct order" (p. 246).

Baumgarten noted that this was a far better result than he had ever seen with adults. Similarly, Ruthsatz and Detterman's (2003) case study of a musical prodigy found that his most striking cognitive ability was his extraordinary short-term memory.

Method

Participants

Young Chess Player. At the time of testing, CS was a 10-year-old female chess player who had obtained a United States Chess Federation (USCF) rating of 2141 (at the 96.6th percentile of the entire USCF population and at the 99th percentile of the entire USCF female population based on the database in USCF in 2015: 64,069 members and 8,982 female members, respectively). In addition, CS was in the top 46 USCF females (regardless of residence or federation), and in the top 30 USCF females in the U.S.

Children. A total of 34 healthy 10-year-old children were recruited from different elementary schools from Houston, Texas, and Taipei City in Taiwan. Sixteen of the children are boys and 18 are girls.

Adult Chess Players. A total of 79 chess players were recruited from different chess clubs and chess tournaments from Dallas, Fort Worth, College Station, Beaumont, Galveston, Houston, and surrounding areas in Texas and from Taipei City in Taiwan. Two participants were excluded from the final analysis. The first excluded participant did not perform two cognitive tasks and the chess knowledge task. The second excluded participant did not fill out the survey regarding the estimates for the amount of studying alone and playing chess hours. The final sample of 77 chess players consisted of 67 males and 10 females, with a mean age of 35 years and an age range of 18 years to 77 years. The chess players had a wide range of chess skills (*M* = 1683, *SD* = 574, *Min* = 381, *Max* = 2651), including several players at grandmaster level. These participants were the same sample as the one used in Lane and Chang's (2018) study.

Procedures

Young Chess Player. Data were collected during one day of informal face-to-face interviews with CS and her parents and one day of testing seven cognitive tasks, one chess memory task, and one chess knowledge task. The time for CS to complete these cognitive, chess memory, and chess knowledge tasks was the same with other participants. During the interview, CS and her family were encouraged to talk about her experience playing chess, her friendship with other chess players, her hobbies, her entry into playing chess, and her general beliefs about chess. Information was sought in three important areas. First, we were interested in learning how she had become interested in chess. Second, we wanted to learn more about informal learning experiences that occurred before her first formal engagement with chess activities. Finally, we wanted to learn about her involvement in any formal or informal training and practice experience after she started playing chess seriously, including her coaching experience, how many hours she had seriously studied alone, and how many hours she had seriously played chess with opponents.

Children. To be eligible to participate in this study, the children had to be 10 years old and have had little or no experience playing chess. The children performed seven cognitive ability tasks, and it took about 45 to 60 minutes to complete the tasks.

Adult Chess Players. To be eligible to participate in this study, the chess players had to be at least 18 years old and have a USCF rating. Participants were asked to perform the seven cognitive tasks, one chess memory task, one chess knowledge tasks, and fill out a chess-related survey. The time spent completing the experiment was approximately 120 minutes. Data from all of these tasks were also analyzed in Lane and Chang's (2018) study.

Materials

Detailed descriptions and materials of all the tasks and survey were provided in Chang's (2016) dissertation.

Cognitive Abilities Tasks. A total of seven cognitive tasks were used. All the participants performed the tasks in the same order: forward digit span, backward digit span, approximate number system, visuo-spatial forward span, visuo-spatial backward span, automated symmetry span, and visual short-term memory.

1. Forward and backward digit spans. In a forward digit span, the participants were asked to repeat them back in the correct order immediately after the presentation of the list of pseudo-random numbers. In a backward digit span, the participants were asked to recall the digits in reverse of the presented order. The longest length that the participant recalled correctly one at least one of two lists was the participant's score. Each participant obtained one score for the forward digit span and one score for the backward digit span.
2. Approximate number system (ANS) task. The participants' ANS was assessed by using a 10-minute computerized task. The Weber fraction (w) was calculated to estimate the participant's discrimination sensitivity and internal noise by modeling individual participant's performances in accordance with Weber's law based on the method described in Halberda et al.'s (2008) paper. Each participant obtained one w value. A lower w value means a higher discrimination sensitivity.
3. Forward and backward visuo-spatial memory spans. A computerized version of Corsi's (1972) block-tapping task was used to measure the participants' visuo-spatial short-term memory (forward span) and visuo-spatial working memory (backward span). In the forward visuo-spatial memory span, the participants were asked to recall the sequence of colored block locations in the order in which they had appeared by clicking on the blocks and given unlimited time to do so. In the backward visuo-spatial memory span, the participants were asked to recall the locations in reverse of the presented order. The longest length that the participant recalled correctly at least one of two lists was the participant's score. Each participant has two scores: one score for the forward visuo-spatial span and one score for the backward visuo-spatial span.
4. Automated symmetry span. Unsworth, Heitz, Schrock, and Engle's (2005) automated symmetry span task was applied to measure the participants' dynamic working memory, involving both the storage and processing of information. Each participant obtained one score. A higher value means a higher working memory capacity.
5. Visual short-term memory task. The participants' visual short-term memory was assessed by using a 5-minute computerized task with sequential comparison paradigm. In this task, there were a total of 2 blocks, and each block had 30 trials. For each block, the participants pressed the space bar to initiate the task. Each trial starts with a 1000 ms fixation followed by an array. After 500 ms, the array disappeared, and the screen went blank for 900 ms. The same number of colored squares reappeared in the same

location, but with one of the colors of the squares having either changed to another color or maintained the same (see Figure 1). The number of squares presented on screen, also called set size, in each trial ranged from 2 to 7. Each set size had 10 trials. Half of the trials in each set size were the "same" and half were "different." The participants were instructed to detect whether or not there were any color changes. The participants had an unlimited amount of time to make their responses by pressing either "A" (two arrays are the same) or "L" (two arrays are different) in the keyboard. One single *d'* value for each participant in each set size was calculated, and a mean *d*-prime was calculated across six set sizes. A higher mean *d'* means a higher sensitivity to detect signal change and a higher visual short-term memory capacity.

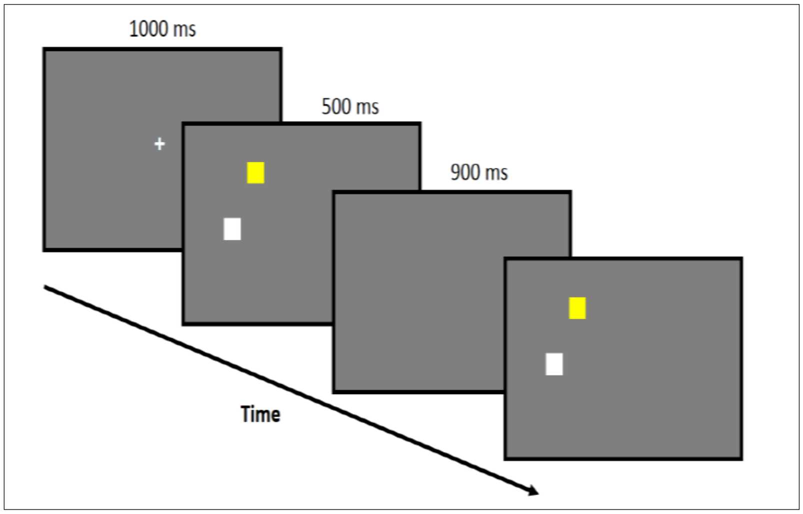

Figure 1. Visual short-term memory task.

Chess Knowledge Task. van der Maas and Wagenmakers' (2005) Verbal Knowledge Test from the Amsterdam Chess Test (ACT), which was adapted in part from Pfau and Murphy (1988), was used to investigate CS's and chess players' chess knowledge. This task consisted of a total of 18 four-alternative multiple-choice questions varying in difficulty. The participants were required to perform this task using pencil and paper without any time limitation.

Chess Memory Task. CS's and chess players' ability to reconstruct positions was accessed by administrating the Memory Test from van der Maas and Wagenmakers' (2005) ACT. Each position was presented for 10 seconds, followed by a blank screen for 2 seconds. Then the participants were asked to reconstruct the briefly shown positions on an actual chess board. The percentage of accuracy of the reconstructed pieces was calculated.

Chess-Related Background Survey. To be consistent with previous research, Charness et al.'s (2005) simplified version of the survey was adopted to obtain CS's and chess players' (1) demographics; (2) chess-related developmental milestones; and (3) cumulative and current chess activities. In order to understand CS's enjoyment of chess-related activities, the assessment of her enjoyment of on each of the various chess activities were asked in the questionnaires. She was asked to respond using a 7-point Likert scale, with a rating of 1 indicating "not at all enjoyable" and 7 indicating "very enjoyable." CS was also asked to estimate her time investment in two categories: (1) serious analysis of chess positions she did alone (e.g., using chess books, magazines, data bases) and (2) the amount of time she spent seriously playing opponents. The survey questions were delivered orally to CS, with the responses written down by the first author on the questionnaire. The adult chess players were asked to fill out the survey.

Number of Games Played in Tournaments. CS's and chess players' number of games played in FIDE and USCF were obtained from each official website: https://www.fide.com/ and http://www.uschess.org/.

The Variables Associated with Chess-Related Experience

Before proceeding in depth into the definition of chess-related experience used in this present study, it is worthwhile to briefly review and discuss the measurement of practice in other studies. Ericsson and Charness (Charness et al., 1996, 2005; Ericsson et al., 1993) measured deliberate practice by asking the participants to estimate how many hours they practiced or studied alone. However, deciding what is and what is not deliberate practice can be complex. For example, studying alone is not necessarily engaging in what Ericsson defined as deliberate practice since it can involve learning chess principles and other aspects of chess theory, studying specific opening positions, and preparing moves to play against opponents whose opening preferences are known. In this article, we side step the question of how deliberate practice is or should be defined and report our results in terms of the following chess-related experiences: time spent studying alone, time spent playing non-tournament games, number of tournament games played, and estimated time spent playing tournament games. The total of these chess-related experience subsumes deliberate practice and represents an upper bound on the amount of time engaged in deliberate practice.

Studying Alone. To obtain the total number of study-alone hours, CS and chess players were asked to estimate how many hours they had studied alone for a typical week at a given age. The total number of study-alone hours was calculated by multiplying the weekly estimated average number of hours by the number of weeks in a year and adding the yearly estimates at and below that age.

Playing Non-Tournament Games. To obtain the total number of hours that CS and chess players had played seriously with opponents, the participants were asked to estimate how many hours they had spent playing with opponents for a typical week at a given age. The total number of study-alone hours was calculated by multiplying the weekly estimated average number of hours by the number of weeks in a year and adding the yearly estimates at and below that age.

Playing Tournament Games. CS's and chess players' number of games played in tournaments were obtained from both USCF and FIDE's official website. If a game appeared in both the USCF and FIDE data bases, it was counted as a FIDE game. Since the duration varies game by game, each game in USCF tournaments was estimated as 4 hours and each game in FIDE tournaments was estimated as 5 hours. The total of number of hours played in USCF and FIDE was used as the total number of hours playing in tournaments.

Chess Experience. Studying alone, playing non-tournament games, and playing tournament games are all considered chess experience. Thus, the total time for chess experience is the sum of the number of hours of these three chess-related activities.

CS's Chess-Related Background

CS is an only child. Her father has played chess and had a USCF rating of about 1550 (79th percentile) at the time of data collection in 2014. The first time CS showed an interest in learning chess was at age of 6, and her father had a USCF rating of about 1050 at that time. She asked her father to teach her the basic rules of chess so that she could join the chess club at school. Her interest in chess appeared to be self-motivated. CS first joined the USCF and started playing chess seriously when she was 7. Even after she started playing chess seriously, she still enjoyed and spent time on other indoor and outdoor activities. Parts of her interview are documented in Chang's (2016) dissertation.

At the time of data collection, CS had received chess instructions both in a group and individually. When she was 7, she participated in a chess club and received training for three months during the summer. From the age of 8 until the interview date (age 10), she met occasionally with a grandmaster over a two to three months period for consultation. In general, CS's chess training was relatively unstructured, not very intensive, and irregular.

Results and Discussion

Chess Experience

CS's Chess Rating History. Figure 2 shows CS's USCF rating history as a function of the number of months that she played chess seriously. Because USCF ratings measure chess expertise on an interval scale (Elo, 1965, 1986; Reingold & Charness, 2005), the functional form of the learning curve is interpretable. As can be seen in Figure 2, although the function is somewhat negatively accelerated, it is very close to linear from 20 months to the time of this writing.

Within 19 months of the time she started playing chess seriously, CS's rating was at the 88th percentile of the USCF population, at the 95th percentile of the junior group (under age 21), and at the 98th percentile of those group age 12 and under (U12). At the time of testing, which was 43 months after she had started playing chess seriously, CS's rating was at the 96th percentile of the UCSF population, the 99th percentile of the junior group, and above the 99th percentile of the U12 group. A few days after the interview, CS defeated an international grandmaster. As of the current writing on March 2017, which is 73 months after she started playing, CS's rating is in the 98.8th percentile of the USCF population, and the 99.7th percentile of the junior group. CS has defeated four international grandmasters and placed second in an international competition. Although it might be a subjective judgment as to whether CS is a chess prodigy, her exceptional achievements clearly indicate she is playing at an international level. This calls into question the claim that "… in well-established domains of expertise even the most 'talented' cannot reach an international level in less than around a decade of experience and intense preparation" (Ericsson, 2007, p.14).

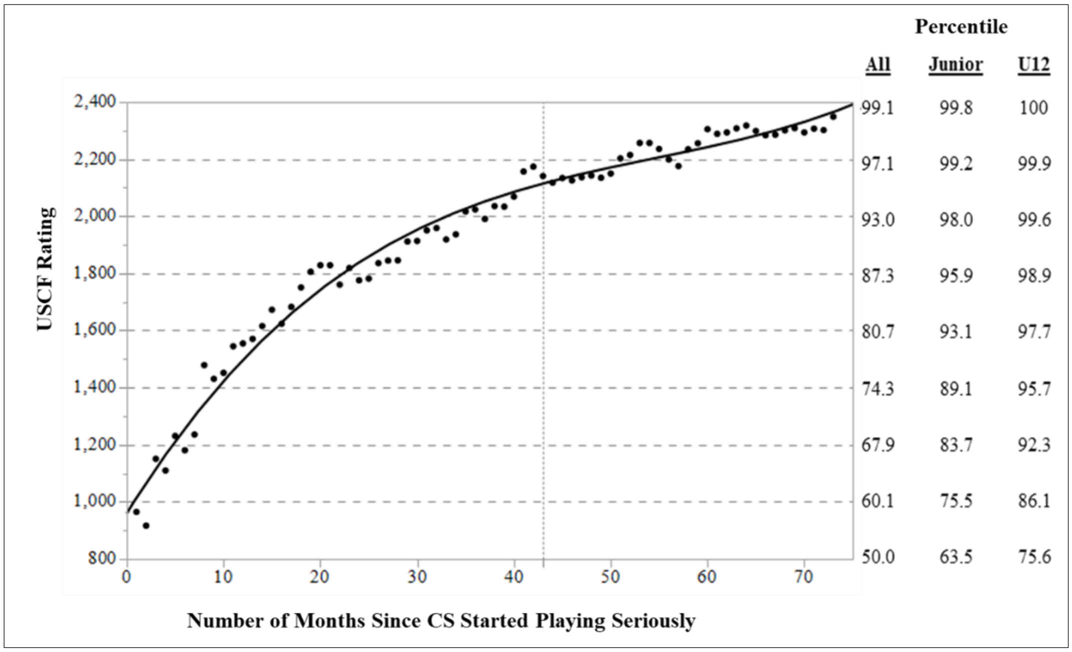

Figure 2. CS's rating history as a function of the number of months since she started playing chess seriously. The vertical dashed line indicates the interview date. She started playing chess seriously when she was 7 years and 5 months old, and at the time of this writing, was 13 years and 5 months old. Three types of percentiles are labeled on the right hand-sided y-axis. "All" indicates the percentiles were calculated based on the entire population of USCF. "Junior" indicates the percentiles were calculated based on all junior members whose ages were under 21. "U12" indicates the percentiles were calculated based on all the child members whose ages were 12 and below. The smooth curve represents a cubic fit: $\text{Rating} = 96.12 + 54.34 \times \text{Month} – 0.868 \times \text{Month}^2 + 0.005 \times \text{Month}^3$.

CS's Chess-Related Experience. According to Ericsson et al.'s (1993) description of deliberate practice, deliberate practice activities are not inherently enjoyable and motivating, but aim at improving one's level of performance. During the interview, CS was asked to rate her enjoyment of various chess-related activities. She rated her experience in analyzing positions, participating in chess tournaments, and solving chess problems as highly enjoyable (7 out of 7 on 7-point Likert scale) and rated receiving formal instruction 6 out of 7. Moreover, she reported that even if she went a long time without improving her rating, she still enjoyed studying chess. She also reported that she enjoyed chess because of the opportunities for friendships that it provides and also the opportunities to compete at a high level. Overall, CS's engagement in chess-related activities was deemed very enjoyable.

Figure 3 shows CS's cumulative number of hours of studying alone, non-tournament playing, tournament playing, and overall chess-related experience as a function of her age as of the interview date. As Figure 3 shows, at the age of 10, CS had engaged in 156 hours of studying alone, 1,196 hours playing non-tournament games, and 2,417 hours playing in tournaments. Overall, at the age of 10, CS had engaged in a total of 3,769 hours of chess-related experience.

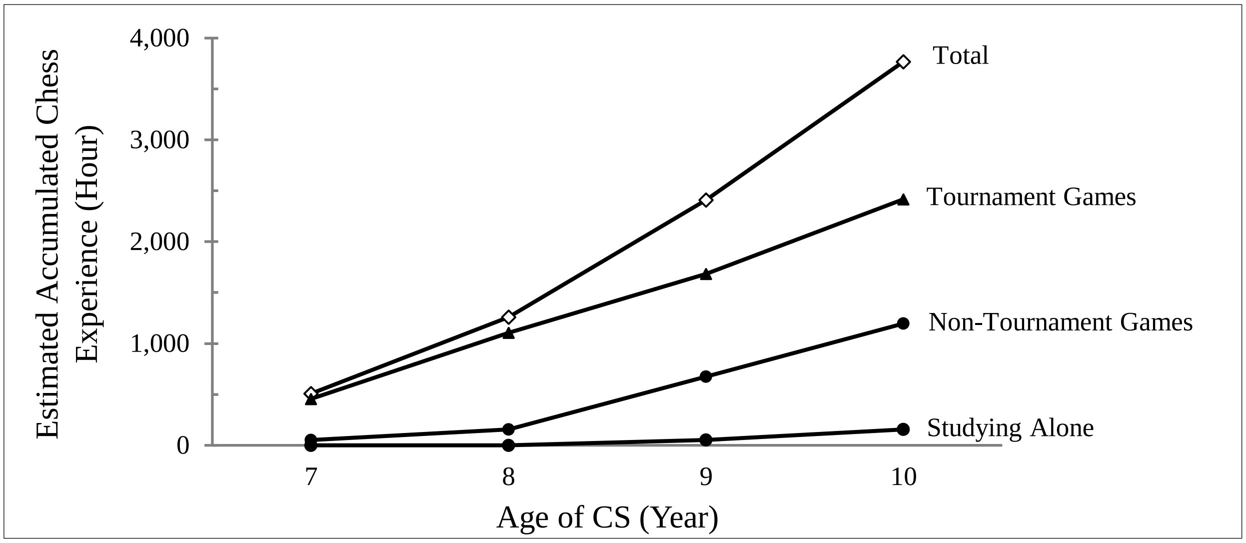

Figure 3. CS's estimated accumulated amount of time engaging in chess-related experience by age. "Total" indicates overall chess-related experience.

CS's rating history and the percentiles as functions of her amount of chess-related experience are plotted in Figure 4. Since CS continued to play and study, it is not surprising that the shape of the function relating experience to rating was very similar to the shape of the function relating age to rating: slightly negatively accelerated and close to linear after 1,500 hours of experience.

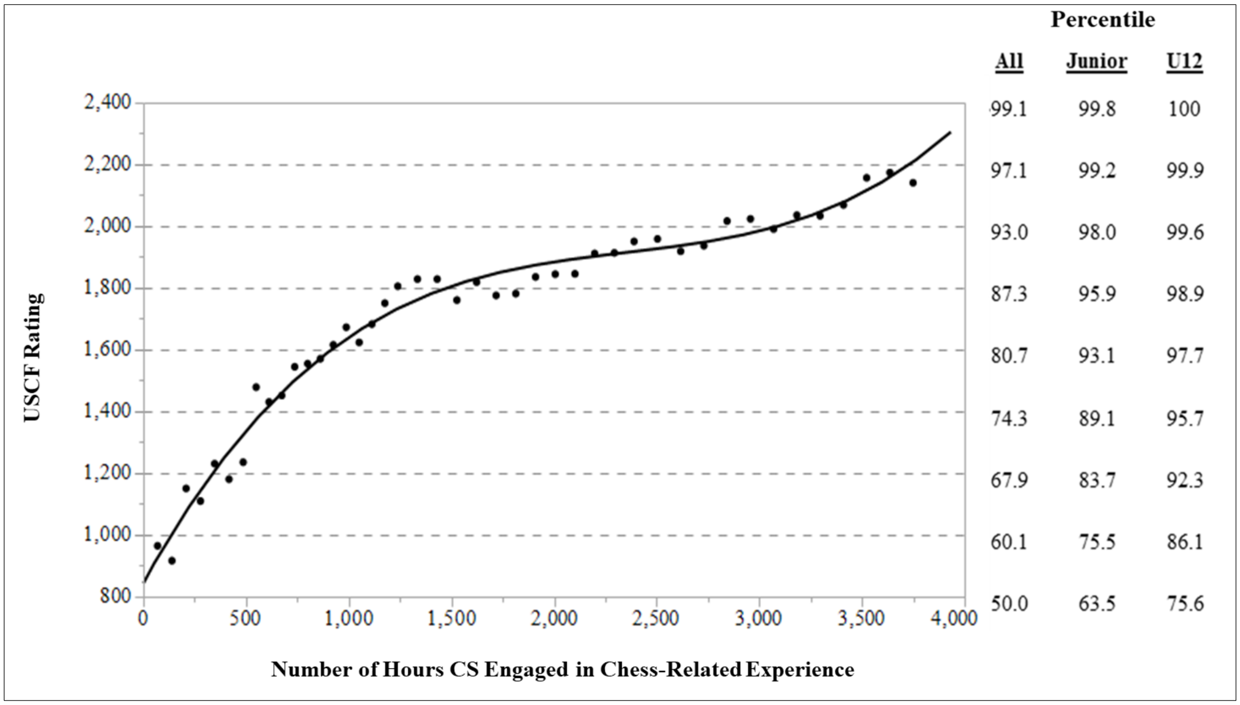

Figure 4. CS's rating history and percentile as a function of the number of chess-related experience hours. The dashed circle indicates CS's rating reached the 96th percentile in the entire USCF population until the interview date, which was the same day indicated by the vertical dashed line in Figure 2. The smooth curve represents a cubic fit: $\text{Rating} = 846.6 + 1.2 \times \text{Hour} - 4.79e^{-4} \times \text{Hour}^2 + 6.77e^{-8} \times \text{Hour}^3$.

CS's rate of acquiring chess is exceptional compared to chess players in other studies. For example, Gobet and Campitelli's (2007) found that 13 players with a mean national rating of 2165 (about 2161 in USCF rating) had practiced alone for a mean of 8,012 hours. CS reached that level of play after approximately 3,500 hours of chess related experience of which practicing alone was a small portion.

In sample 1 of Charness et al.'s (2005) study, the players had a mean rating of 2,032 and had practiced alone for a mean $\log_{10}$ time of 3.4 hours (2512 hours approximately) with a standard deviation of 0.5. CS reached a comparable level of play after 156 hours which is 2.4 standard deviations below Charness et al.'s (2005) mean. Similarly, in Howard's (2012) study, the players had a mean rating of 2,122 and had practiced alone for a mean of 3981 hours with a standard deviation of 0.5. CS's hours practicing alone was 2.8 standard deviation below the mean of Howard's participants.

CS had engaged in approximately 156 hours of studying alone and engaged in a total of approximately 3,769 hours of chess experience when she defeated a grandmaster and achieved a rating that placed her in the 96th percentile of the entire USCF population. Thus, CS's engagement in chess-related experience was substantially less than 10,000 hours or 10 years of practice claimed to be necessary to reach an international level of play.

The following section compares CS's performance with that of Dan McLaughlin who sought to determine whether extensive deliberate practice can lead to a high level of expertise in golf. Although CS and McLaughlin acquired different types of skills, it is informative to compare their skill acquisition rates because a vast difference would suggest that natural ability plays an important role in the development of expertise. Moreover, Ericsson (1998) implied that the growth of expertise is gradual and continuous regardless of the field and argues that the amount of practice necessary to reach an international level is similar across fields. Specifically, Ericsson and Lehmann (1996) stated that "in *chess, sports,* and many other domains with thousands of active participants, individuals attain internationally recognized levels of exceptional performance only after spending about 10 years in intense preparation" (p. 296, emphasis added). Similarly, Ericsson, Roring & Nandagopal (2007) stated that their findings on the development of expertise applied to adult competitions in sports, sciences, and the arts.

Inspired by Ericsson et al.'s (1993) theory of deliberate practice, at age 30 McLaughlin quit his job as a commercial photographer with the goal of becoming a professional golfer. He was not a competitive athlete and had never played a full 18 holes of golf prior to starting his experiment, which he refers to as "the Dan Plan." Before undertaking his "journey," McLaughlin consulted Ericsson and Len Hill, who gave him detailed information about deliberate practice and helped him learn how to obtain the maxim effect of deliberate practice. In April 2010, McLaughlin began engaging in deliberate practice and hired a coach to get the most out of each hour of practice and to meet Ericsson's deliberate practice criteria[1]. In August 2011, McLaughlin played his first full round of golf, and starting in May 2012 he recorded detailed statistics about his performance (http://thedanplan.com/). In April 2015, after completing 6,003 hours of deliberate practice, he ended his experiment due, in part, to back injuries and financial frustrations. His performance in golf is presented in terms of his handicap index. This index is calculated by using the average of a golfer's best 10 handicap differentials in his or her last 20 rounds and multiplying it by 0.96. The handicap index is calculated based on the score that the golfer obtained in each round and is adjusted to account for differences golf courses. Smaller handicaps indicate better performance. McLaughlin's last handicap index was 5.5, placing him in the 85th percentile of the men's population of the United States Golf Association (USGA). His best handicap index was 2.6, which placed him in the 93rd percentile. However, he was unable to maintain that level of performance very long.

After engaging in about 6,000 hours of intensive deliberate practice, McLaughlin reached around the 90th percentile of the USGA population but was still far away from the level required to play at an international level. Based on McLaughlin's performance, it appears that not everyone can compete at an international level even after considerable deliberate practice.

Figure 5 presents McLaughlin's percentile as a function of the number of deliberate practice hours and CS's percentile as a function of the number of studying alone hours and chess-related experience. As argued previously, if there is any deliberate practice involved in CS's chess experience, it would be included in the studying alone time. CS and McLaughlin had substantially different improvement rates illustrated by the fact that CS was able to reach the 80th percentile without engaging in any deliberate practice as compared to McLaughlin, who engaged in approximately 3,000 hours of deliberate practice to reach the same percentile. To be conservative and compare McLaughlin's trajectory based on his practice time with CS's trajectory based on her chess-related experience, CS reached the 80th percentile after approximately 900 hours of chess-related experience compared to McLaughlin's 3,000 hours. Similarly, CS reached 90th percentile with much less practice and experience than did McLaughlin. After CS had studied chess alone for approximately 156 hours and had 3,749 hours of chess experience, she was in the 96th percentile of the USCF population and had defeated a grandmaster. McLaughlin's performance was far lower than this even after he had engaged in 6,003 hours of practice and his best score never came anywhere near the level of the low-end performance of the golfing equivalent of a grandmaster. Moreover, his performance appeared to asymptote at the 90th percentile and does not show the continuous gradual improvement expected based on Ericsson's theory. As noted previously, the direct comparison between CS and McLaughlin is difficult because they were acquiring different types of skills. However, it is worth noting that CS and McLaughlin's began at different ages, a variable found by Gobet and Campitelli (2007) to be related to skill development.

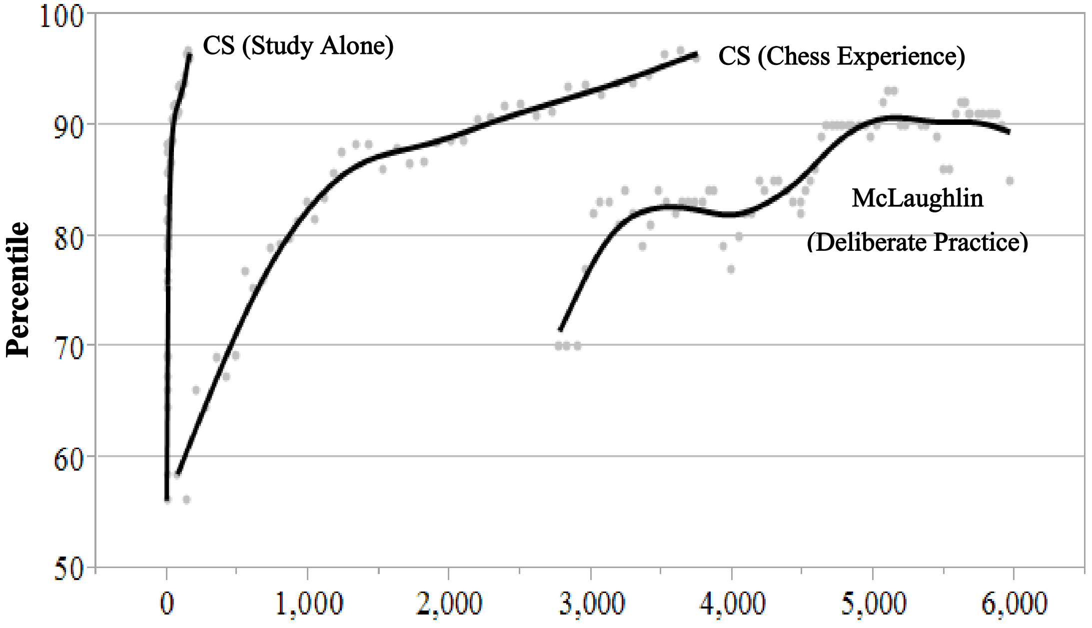

Figure 5. CS's percentiles as a function of hours spent studying alone and chess experience, and McLaughlin's percentile as a functions of hours of deliberate practice. This is graphically presented using a smoothing spline with λ, = 0.07.

Two main conclusions can be drawn from these data. First, since CS was able to reach the 96th percentile of the UCSF population after she started seriously playing chess for 3 years and 7 months, her exceptional chess performance calls into question Ericsson's assertion that 10 years of deliberate practice are required to be an expert. Second, CS violated the 10,000-hour rule by playing at an international level after fewer than 4,000 hours of chess experience demonstrating that her exceptional performance in chess was not due to practice alone. Her performance in chess provides a strong evidence to support the view that there are individual differences in the rate of reaching expertise (e.g., Campitelli & Gobet, 2011; Gobet & Campitelli, 2007; Hambrick, Oswald, et al., 2014)

Cognitive Abilities and Chess Knowledge

CS scored 81% on the chess memory task and 78% on the chess knowledge task. As Figure 6 shows, these scores were both much higher than the scores of most of the adult chess sample described in detail in Study 2, with only four adult chess players scoring higher than CS on the chess knowledge task. For the entire sample, both chess memory, $r(75) = .73$, $p < .001$, 95% CI [.60, .82], and chess knowledge, $r(75) = .67$, $p < .001$, 95% CI [.52, .78] correlated highly with chess rating.

Accuracy on the chess knowledge test and its relation with hours spent studying alone and hours of chess experience are presented in Figure 7. A few players, including CS were able to obtain high scores on the chess knowledge task after spending very little time studying chess or engaging in chess-related experiences. At the time of testing, CS had studied chess alone for only 156 hours. As Figure 7 shows, very few chess players who had studied as little as CS had, or who had as little chess experience as CS, performed as well CS in the chess knowledge test. It is unclear how CS and these few others were able to do so well with so little study and experience.

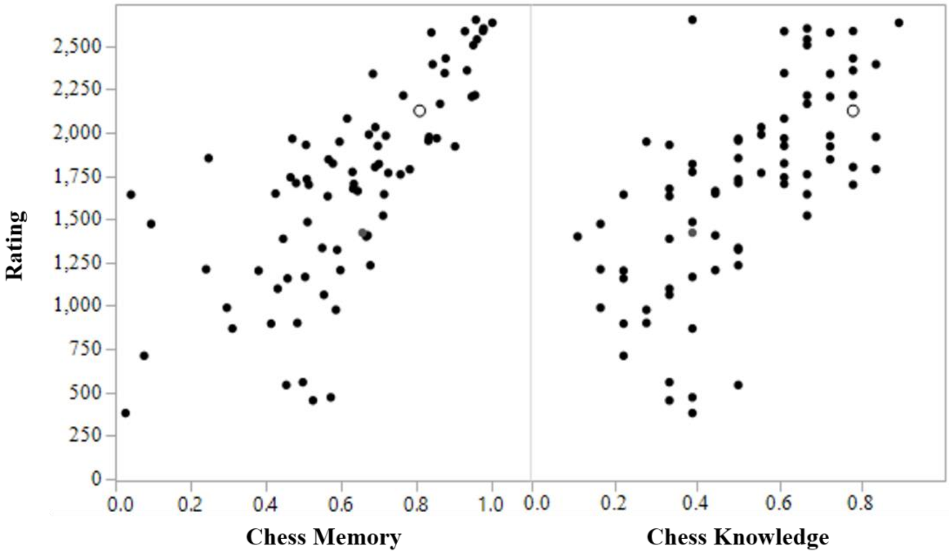

Figure 6. The scatterplot of CS and other chess players' USCF ratings and their accuracy in chess knowledge task. CS's data is indicated by an empty circle.

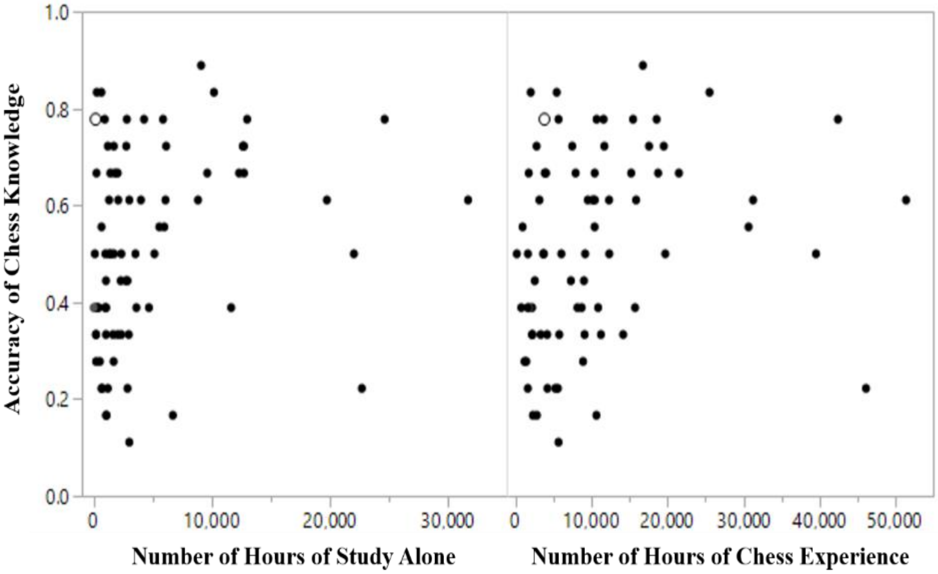

Figure 7. The scatterplots of CS and other chess players' accuracy in chess knowledge and the number of hours studying alone and chess-related experience. CS's data is indicated by an empty circle.

CS's rankings among the 35 children studied here are as follows: 1st in visual short-term memory, 3rd in backward visuo-spatial memory span, 4th in backward digit span, 6th in forward visuo-spatial memory span, 9th in approximate number system, 23rd in automated symmetry span, and 26th in forward digit span. As can be seen in the left-most graph in Figure 8, her score of 2.41 on the visual short-term memory task was substantially higher than the score of the next highest child. Descriptive statistics on these children (excluding CS) and CS in the seven cognitive tasks are presented in Table 1.

Table 1. Descriptive Statistics of Seven Cognitive Tasks.

	M	*SD*	*Min*	*Max*	CS
Visual STM	1.38	0.43	0.27	2.10	2.41
Block Tapping Backward	5.35	0.92	3	8	6
Digit Span Backward	4.59	1.05	3	8	5
Block Tapping Forward	5.53	0.96	4	8	6
Approximate Number System	0.35	0.31	0.11	1.43	0.15
Auto Symmetry Span	24.79	7.01	15	40	21
Digit Span Forward	7.91	1.36	5	10	7

Note. The lower scores in approximate number system task represent better performance.

Although CS's performance on the visual short-term memory task is impressive, her performance was compared to only 34 other children. To see if we could further support the conclusion that she is exceptional on this task, we tested an additional 28 10-year-olds using the same procedure as used for the first 34 children. These children, none of whom had played chess, consisted of 13 boys and 15 girls. As can be seen in the middle graph in Figure 8, none of these children did as well as CS on the visual short-term memory task. Descriptive statistics for all 62 children are as follows: *M* = 1.24, *SD* = 0.51, *Min* = 0.08, *Max* = 2.1. The right-most graph in Figure 8 shows that CS's performance was higher than all but three of the adult chess players. Overall, CS's performance in the visual short-term memory task was exceptional.

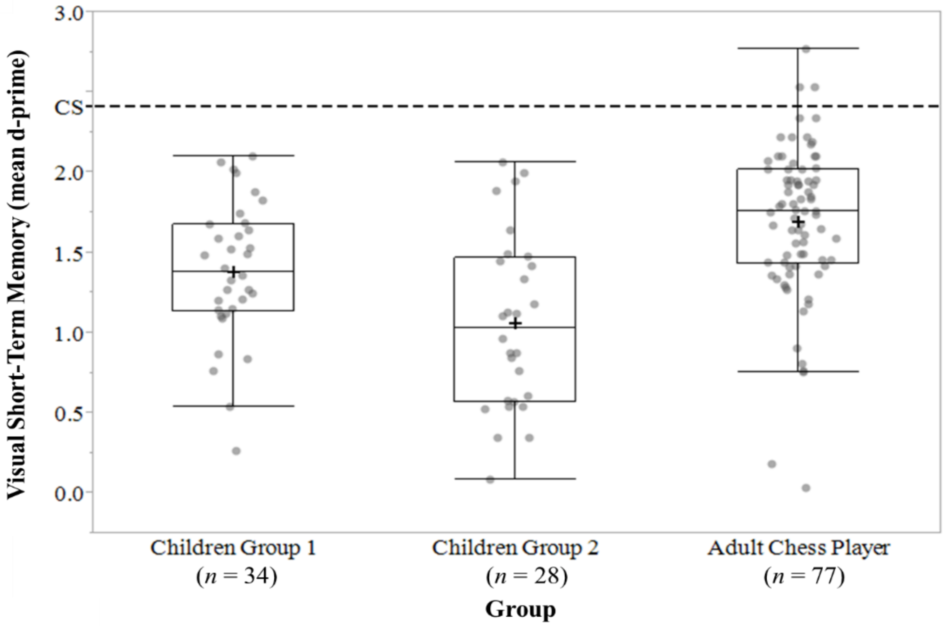

Figure 8. Quantile plots of the performance of the three groups in the visual short-term memory task. The "+" sign represents the mean, the "box" extends from the 25th percentile to the 75th percentile, the horizontal line within the box represents the median, the two other horizontal lines represent the inner fences as normally defined in a box plot, and the horizontal dashed line represents CS's performance.

It is intriguing that both CS and Sammy Reshevsky performed extremely well on tests of visual short-term memory and suggests that this ability may play a role in their exceptional chess ability. It would seem likely that if this were true then there would be a relationship between visual short-term memory and chess skill for adult chess players. Testing the correlation in the sample of adult chess players revealed no evidence of a relationship, $r(75) = -.07$, $p = .55$. This finding is consistent with Waters, Gobet, and Leyden's (2002) study, which did not find any correlations between visual memory and chess skills. The correlation in the present study was found to be affected by the fact that there was a small negative but non-significant correlation between experience (after a square root transformation to reduce skew) and visual short-term memory, $r(75) = -0.18$, $p = .12$. A multiple regression controlling for chess-related experience revealed evidence for a weak but non-zero relationship between visual short-term memory and rating (incremental $R^2 = .03$, $F(1, 74) = 4.26$, $p = .043$). The weakness of this relationship between visual short-term memory and chess skill leaves open the possibility that Reshevsky and CS's extraordinary visual short-term memory may be unrelated to their chess expertise. We explored the possibility that there was an interaction between visual short-term memory and the other variables we measured. However, none of the interactions were significant (minimum p uncorrected for multiple tests = .056). However, this does not rule out the possibility CS was exceptional in some ability we did not measure and the combination of being exceptional on that ability and visual short-term memory played an important role in her chess expertise. It is also possible that visual short-term memory is important for the speed with which chess expertise develops but is not a major factor in the level one reaches after thousands of hours of experience. This is consistent with Ericsson's argument that factors important for the early stages of acquisition are not the same as those for the later stages (Ericsson, Roring, & Nandagopal, 2007). In summary, among the possible explanations for the fact that CS has an exceptional short-term visual memory and unusual chess expertise are (1) it may be a coincidence, (2) it may be due to the combination of her short-term visual memory and an ability of hers we did not measure, and (3) her visual short-term memory may be responsible for her early acquisition of chess expertise but will not be important for the final level she achieves. However, the fact that she and Sammy Reschevsky both had exceptional visual short-term memories and quickly became very strong chess players makes it difficult to dismiss visual short-term memory as being unimportant for the acquisition of chess expertise. Future research on the possible role of visual short-term memory in chess expertise, especially in young players, is needed before these puzzling findings can be understood.

Study 2

In this study, we investigated the role of practice in the development of expertise by examining whether practice is sufficient to explain all individual differences in the skill acquisition and, if not, what proportion of the variance can be explained by practice. Chase and Simon's (1973) recognition action theory postulates that practice is the most important variable to explain variance in chess expertise. Ericsson et al.'s (1993) theory of deliberate practice predicts that practice would explain all or almost all of the reliable variance. If there is a substantial amount of variance not explained by practice, then the question arises as to what other factors play a role. In Study 2, we examined the roles of cognitive ability (domain-general fluid intelligence), chess-specific crystallized intelligence, and chess-specific fluid intelligence played in the individual differences in chess skills. Of course, the latter two factors are likely influenced by practice and other chess experiences, so we considered the contributions of these factors after controlling for practice.

One view of the development of expertise is Ericsson's deliberate practice theory which holds that there are no factors other than deliberate practice that have more than trivial effects on chess skill. The time spent at deliberate practice has typically been measured by asking players to report the amount of time they have studied alone. Therefore, according to Ericsson's theory, the amount of time players studied alone should be the only variable related to chess expertise. Alternatively, individual differences in chess skill could be a function of the degree of engagement in chess activities. In this study, we estimated the amount of time chess players spent studying alone, the time they spent playing chess informally, and determined the number of games they played chess in tournaments. Finally, it may be that deliberate practice and other chess related experience are not sufficient to explain all or even almost all of the individual differences in chess skill. Other factors may include cognitive ability (domain-general fluid intelligence), chess-specific crystallized intelligence, and chess-specific fluid intelligence. If both natural ability and chess experience are important, then some or all of the intelligence variables would predict chess rating even after controlling for time studying alone and other chess playing experience.

Method

In Study 2, only adult chess players' data were analyzed. The descriptions of the participants, procedure, and materials of all the tasks and survey were described in Study 1.

Measurements

Domain-General Fluid Intelligence. The domain-general fluid intelligence measure was based on performance on seven cognitive tasks: Digit Span Forward, Digit Span Backward, Approximate Number System, Block Tapping Forward, Block Tapping Backward, Auto Symmetry Span, and Visual Short-Term Memory. The principal components on these tasks were used as the measure of domain-general fluid intelligence.

Chess-Related Fluid and Crystalized Intelligence. It was measured by van der Maas and Wagenmakers' (2005) Verbal Knowledge Test. The chess-related crystalized intelligence measure was based on performance on fifteen conceptual knowledge questions, and the chess-related fluid intelligence measure was based on three visualization questions.

Variables Associated with Chess-Related Experience. Three chess-related experiences—studying alone, playing non-tournament games, and playing tournament games—were described in Study 1.

Analysis Plan

We planned *a priori* to conduct a principal components analysis to reduce the number of cognitive ability variables to avoid the possibility of inflating the Type I error rate due to performing multiple tests or to reduce power by having to correct for performing multiple tests. The number of retained was determined based on the percent of variance explained by each component and, as will be seen, ended up being one.

Given that cognitive ability and chess experience may interact, the existence of an interaction between cognitive ability and chess-related experience to chess skill was first tested. The assumption normality of residuals in the multiple regression model was then tested.

A hierarchical multiple regression was used to test the predictions of the three views of individual differences in chess skill: deliberate practice, chess experience, and natural ability with previous chess experience. This analytical approach is similar to the one adopted in the analyses conducted in Lane and Chang's (2018). However, Lane and Chang used this approach to assess how much chess knowledge contributes to chess memory after controlling for chess experience, whereas this study assessed how much chess knowledge, chess-related fluid intelligence, and domain general fluid intelligence contribute to chess skills after controlling for chess experience.

Results and Discussion

Data were examined carefully to ensure the quality of the data prior to further statistical analyses. The analyses were conducted based on the raw data and on estimates using corrections for unreliability (Cohen & Cohen, 1983). The corrected estimates were included for two reasons: First, it is not possible to accurately test the magnitude of a correlation between two variables without controlling for the potential distorting effect of measurement error variance (see Schmidt & Hunter, 1999, for review); second, the analysis based on corrected estimates avoids potential inaccurate estimation in a multiple regression due to the predictors differing in their reliability.

Chess Rating. Chess rating is the dependent variable in the analysis. All the participants had a USCF rating, and all their current ratings were obtained from USCF's website to avoid potential inaccuracies caused by misremembering or due to the rating's being from a different organization. The reliability coefficient used for the chess rating was .91, following Hambrick, Oswald, et al. (2014).

Chess-Related Experience. Both the distributions of the number of study alone hours and playing in non-tournaments were extremely skewed, and both variables had one player with a value of 0. A $\log_{10}(x+1)$ transformation was used to reduce the skew. The reliability coefficient used for the self-reported studying alone time was .80, following Hambrick, Oswald, et al. (2014). Since playing chess with opponents was also assessed by self-report, it was estimated to have a reliability of .8. Playing in tournaments was measured by using the number of tournament games that the chess players have played historically. The total number of games is the sum of the number of games played in USCF tournaments and the number of games played in FIDE tournaments. Because the original distribution of this variable was extremely skewed, a log transformation was used to reduce the skewness. Since the number of games played in tournaments was directly obtained from the records of chess official websites, the reliability of this measure was assumed to be 1.

Cognitive Ability/Domain-General Fluid Intelligence. As stated in the analysis plan, we planned *a priori* to begin with a principal component analysis to see whether the data on these tasks could be analyzed more parsimoniously. The results showed that the first principal component accounted for 53% of the variance whereas the second factor accounted for only 13% of the variance. In addition, all seven of the tasks had high loadings on the first factor, ranged from 0.66 to 0.81 (see Table 2).

These findings suggested that a one-factor solution provided a good summary of the seven cognitive tasks. It allowed us to do subsequent analyses using this first factor rather than the individual measures. We believed that "fluid intelligence" would be an appropriate name for this factor because the nature of these tasks had been defined, although we recognize it weighs memory tasks more heavily than most measures of fluid intelligence.

Since this domain-general fluid intelligence was computed by using the principal component of the seven cognitive abilities, it was assumed to have high reliability and was estimated to be 0.9. The second principal component accounted for only 13% of the variance and was not analyzed in the subsequent analyses.

Table 2. Loadings of the Seven Cognitive Abilities on the First Principal Component.

	First Principal Component
Digit Span Forward	.66
Digit Span Backward	.77
Approximate Number System	.70
Block Tapping Forward	.72
Block Tapping Backward	.75
Auto Symmetry Span	.81
Visual STM	.67

Chess-Specific Fluid Intelligence and Crystalized Intelligence. The item reliability (Cronbach's α) for the three chess fluid-knowledge questions was .45, and the item reliability for the fifteen chess crystallized-knowledge questions was.72.

Table 3 presents descriptive statistics and a descriptive correlation matrix for all these variables, including chess rating, seven cognitive abilities, domain-general fluid intelligence, chess-specific memory, chess-specific fluid intelligence, chess-specific crystallized intelligence, Log time studying alone, Log time playing in non-tournaments, and Log games playing in tournament.

Two analyses were performed to assess the appropriateness of the model. The first was to test whether cognitive ability and chess-related experience interacted. None of the three interactions were significant with the *p* values for Log time studying alone x Domain-general fluid intelligence, Log time playing non-tournaments x Domain-general fluid intelligence, and Log games playing in tournament x Domain-general fluid intelligence interactions being .08, .997, and .39, respectively. Although there was a slight hint of a Log time studying alone x Domain-general fluid intelligence interaction, these results are generally consistent with Hambrick and Oswald's (2005) conclusion that the relationship between domain-general fluid intelligence and amount of time spent on relevant experiences is additive.

The interactions were subsequently not included in the model leaving a multiple regression analysis with six predictors. The distribution of the residuals for this regression model showed a slight positive skew. However, multiple regression is robust when the residuals are much more positively skewed than they were here (Lumley, Diehr, Emerson & Chen, 2002).

Table 3. The Mean, Standard Deviation, and Correlation Matrix for All Variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Chess Rating	1	.07	.27	.13	.28	.21	.28	.07	.27	.73	.47	.65	.55	.39	.65
Cognitive Ability															
2. Digit Span Forward	.07	1	.67	.35	.36	.37	.35	.32	.66	.15	.11	.14	-.15	-.17	-.08
3. Digit Span Backward	.27	.67	1	.49	.45	.44	.54	.28	.77	.40	.32	.30	.03	.07	.04
4. Approximate Number System	.13	.35	.49	1	.32	.45	.50	.47	.70	.44	.29	.27	-.05	-.02	.03
5. Block Tapping Forward	.28	.36	.45	.32	1	.49	.56	.47	.72	.46	.23	.28	.07	.09	.28
6. Block Tapping Backward	.21	.37	.44	.45	.49	1	.60	.41	.75	.45	.20	.29	-.03	-.13	.22
7. Auto Symmetry Span	.28	.35	.54	.50	.56	.60	1	.49	.81	.59	.31	.34	-.05	-.03	.27
8. Visual Short-Term Memory	.07	.32	.28	.47	.47	.41	.49	1	.67	.37	.30	.23	-.24	-.06	.26
9. Domain-General Fluid Intelligence	.27	.66	.77	.70	.72	.75	.81	.67	1	.57	.35	.37	-.07	-.05	.21
Domain-Specific Ability															
10. Chess Memory	.73	.15	.40	.44	.46	.45	.59	.37	.57	1	.53	.67	.31	.09	.59
11. Chess-Specific Fluid Intelligence	.47	.11	.32	.29	.23	.20	.31	.30	.35	.53	1	.52	.18	.10	.44
12. Chess-Specific Crystallized Intelligence	.65	.14	.30	.27	.28	.29	.34	.23	.37	.67	.52	1	.29	.11	.53
Chess-Related Experience															
13. Log Time Studying Alone	.55	-.15	.03	-.05	.07	-.03	-.05	-.24	-.07	.31	.18	.29	1	.49	.43
14. Log Time Playing in Non-Tournaments	.39	-.17	.07	-.02	.09	-.13	-.03	-.06	-.05	.09	.10	.11	.49	1	.35
15. Log Games Playing in Tournament	.65	-.08	.04	.03	.28	.22	.27	.26	.21	.59	.44	.53	.43	.35	1
M	1683	7.14	6.08	0.14	6.75	6.13	31.36	1.70		0.62	0.48	0.52	3.31	3.35	2.09
SD	574	1.46	1.80	0.05	1.51	1.30	10.01	0.47		0.23	0.32	0.20	0.68	0.63	0.77

Note. The approximate number system score was rescaled to be positive. The higher scores represent better performance. *r's* > .37 are significant with *p*'s < .001; *r's* > .29 are significant with *p*'s < .01, and *r's* > .22 are significant with *p*'s < .05.

Analyses were conducted both with and without correcting for unreliability (measurement error). Spearman's (1904) disattenuation formula was used to adjust for measurement error (unreliability) from a correlation coefficient (Hunter & Schmidt, 1990). The corrected and uncorrected correlation coefficients among seven variables are presented in Table 4.

Table 4. Correlations Among Six Tasks and Chess Rating

	1	2	3	4	5	6	7
1. Chess Rating	.91	.55	.39	.65	.27	.47	.65
2. Log Time Studying Alone	.65	.80	.49	.43	-.07	.18	.29
3. Log Time Playing in Non-Tournaments	.46	.61	.80	.35	-.05	.10	.11
4. Log Games Playing in Tournaments	.68	.48	.39	1	.21	.44	.53
5. Domain-General Fluid Intelligence	.29	-.09	-.06	.22	.90	.35	.37
6. Chess-Specific Fluid Intelligence	.73	.30	.17	.66	.55	.45	.52
7. Chess-Specific Crystallized Intelligence	.81	.39	.14	.62	.46	.92	.72

Note. The reliabilities are shown on the diagonal. The lower triangle contains the correlations corrected for unreliability and the upper triangle contains the uncorrected correlations.

Hierarchical Regression Analysis. A multiple regression analysis was performed in order to test whether deliberate practice as measured by studying alone is the only factor explaining individual difference in attaining chess skills and to investigate other factors that may play a role in chess skill.

In the regression analysis, chess rating was regressed on the other six variables shown in Table 4. These six variables accounted for 66% of the variance (adjusted $R^2 = .63$) and 82% of variance (adjusted $R^2 = .80$) after controlling for unreliability. This model accounts for more variance than models in previous studies. For example, Charness et al.'s (2005) model accounted for a total of 38% of chess skill variance whereas Gobet and Campitelli's (2007) model accounted for 41% of chess skill variance. One possible explanation for this difference is that this study used a wider range of chess ratings than previous ones. The standard deviations of the participants' chess rating were 267 in Charness et al.'s (2005) study, 222 in Gobet and Campitelli's (2007) study, and 574 in the current study. The standard deviation for chess rating is 609 for the entire USCF population. The standard deviation for chess rating in the present study was not quite as high as the population, but it was close.

Table 5. The Results of the Hierarchical Regression of Chess Rating on the Six Variables

	Uncorrected			Corrected		
Variable	R^2	Min	Max	R^2	Min	Max
Time Studying Alone	.31	.05	.31	.42	.03	.42
Playing Chess Informally	.33	.01	.15	.43	.02	.21
Playing Chess in Tournaments	.52	.04	.43	.60	.06	.47
Domain-General Fluid Intelligence	.56	.01	.07	.66	.002	.09
Chess-Specific Fluid Intelligence	.59	.01	.22	.76	.002	.54
Chess-Specific Crystallized Intelligence	.66	.07	.43	.82	.06	.65

Note. The uncorrected columns are based on the actual data and the corrected columns correct for unreliability. The column R^2 represents the R^2 as each variable is entered into the regression model. The column “Min” shows the proportions of variance explained if the variable is entered last so that none of the common variance is attributed it. The column “Max” shows the proportions of variance explained if the variable is entered first so that all of the common variance is attributed to the variable.

A hierarchical regression analysis was used to assess the contributions of various factors to the prediction of chess skills. The results of this hierarchical regression are presented in Table 5. In the following discussion, the results without correcting for unreliability are presented first, and the results after correcting the correlation coefficients for unreliability are presented in parenthesis.

Table 5 shows the variance explained by each variable individually but does not show the combined contribution of the experience variables (i.e., study alone, informal play, and tournament play). To be most favorable to these experience variables, Log time studying alone, Log time playing in non-tournaments, and Log games played in tournament variables into the regression model. In this analysis, any variance common among chess experience and other factors is attributed to chess experience. The three chess experience variables together accounted for 52% (60%) of the variance ($p < .001$).

Sequentially adding domain-general fluid intelligence accounted for an additional 4% (6%) of variance ($p = .014$), adding chess-specific fluid intelligence accounted for an additional 3% (10%) of variance ($p = .041$), and adding chess-specific crystallized intelligence accounted for an additional 7% (6%) of variance ($p < .001$). Table 5 also shows that the variance accounted for by each variable when none of the common variance is attributed to and when all of the common variance is attributed to it.

These findings support the view that chess players’ domain-general cognitive ability, chess-specific fluid intelligence, and chess-specific crystallized intelligence all contribute meaningfully to individual differences in chess skill even after controlling for chess experience.

Although the importance of practice has been well established (Ericsson et al., 1993), these results contradict the claim that deliberate practice is sufficient to explain individual differences in chess skill. In the analysis in which all variance common to the study alone time and other variables was apportioned to the study alone variable, this variable explained only 31% (42%) of the variance. In the analysis in which all variance common between the chess experience variables and other variables is attributed to the experience variables, these three variables taken together explained 52% (60%) of the variance. Thus, domain-specific deliberate practice and/or domain-specific experience are not sufficient to explain all or even the vast majority of individual differences in chess performance.

Domain-general fluid intelligence, chess-specific fluid intelligence, and chess-specific crystallized intelligence contributed to chess skill independently of practice. Ericsson et al. (1993) argued that the high association between chess knowledge and chess skill is due to the amount of deliberate practice and that this association is the evidence for deliberate practice. At first glance, this argument seems compelling. However, chess-specific crystallized intelligence substantially improved the prediction of chess ratings even after controlling for our three measured of chess experience. Thus, deliberate practice as measured by time studying alone or even very liberally as any chess experience does not fully explain the high association between chess knowledge and chess skills. Therefore, the results of this current study, consistent with the findings of Pfau and Murphy (1988), show that chess knowledge is an important predictor of chess skill.

Taken together, these results show that deliberate practice even when taken together with other chess experience does not explain close to all the individual differences in chess ratings. These results are in agreement with Campitelli and Gobet’s (2011) conclusion that the role of practice in achieving high levels of expertise is necessary but not sufficient.

General Discussion

In 1973, Simon and Chase argued that after 10,000 to 50,000 hours of practice, chess players are able to reach master-level performance by learning thousands of patterns (or chunks) and storing them in long-term memory. Twenty year later, Ericsson and his colleagues (1993) emphasized the importance of practice in acquiring a skill, and also described a special kind of practice called "deliberate practice" that involves guidance by teachers or coaches. This theory also holds that deliberate practice is the primary source of the individual differences in chess skill. The importance of deliberate practice in acquiring a skill has been frequently cited and discussed in many popular books, and extensively cited in scholarly journals and textbooks to emphasize the importance of deliberate practice.

Most studies estimate deliberate practice time by asking the participants to report how many hours per week they had seriously studied chess alone. Few studies have asked the participants to report on other potentially important chess experiences: how many hours they had seriously played chess. However, playing chess does not meet Ericsson's criterion for deliberate practice, and it involves a bit of circular reasoning to justify it as deliberate practice simply because it predicts expertise. Therefore, in this study, deliberate practice is considered a subset of studying alone, and studying alone, playing chess informally, and playing chess in tournaments are all considered as part of chess-related experience. Since no clear definition of practice was provided by Simon and Chase (1973), if any practice is involved in players' chess-related activities, it would be involved in chess-related experience.

As reported in Study 1, CS reached 96th percentile in US population after playing chess seriously for only 3 years and 7 months and having studied chess for approximately 156 hours and engaged in a total of only 3,749 hours of chess-related experiences. We cannot be certain how much time she spent on deliberate practice, as defined by Ericsson, but it would necessarily be less than or equal to 156 hours and possibly as low as 0 hours since it is not clear if any of her studying alone time meets Ericsson's definition of deliberate practice. The short amount of time she spent studying alone, along with her exceptional achievement in chess, is particularly difficult to reconcile with Ericsson's (1993) 10-year practice rule and Ericsson, Prietula, and Cokely (2007)'s 10,000-hour rule. Moreover, the comparison between CS's performance and McLaughlin's golf performance shows that CS and McLaughlin's skill acquisition rates were very different. These results are consistent with the conclusions of several previous studies (Campitelli & Gobet, 2011; Gobet & Campitelli, 2007; Hambrick, Oswald, et al., 2014) and contradict the argument that pure deliberate practice or any types of practice is sufficient to explain individual differences in the development of expertise. CS's performance in one cognitive task, visual short-term memory, was exceptional. She performed better than all of the 62 children and was better than all but three of the 77 adult chess players. However, the finding that the relationship between visual short-term memory and chess skill in adults is weak leaves open the possibility that her extraordinary visual short-term memory is not related to her chess skills. However, the fact that both CS and Reschevsky showed exceptional visual short-term memory as children makes further study of the role of visual short-term memory in chess expertise a potentially fruitful topic.

Study 2 provides evidence that chess experience including time studying alone is necessary but not sufficient to develop expertise in chess. Domain-general fluid intelligence, domain-specific fluid intelligence, and domain-specific crystallized intelligence all contributed to chess skill independently of chess experience. Of these variables, chess-specific crystallized intelligence explained the most variance.

The results of domain-general fluid intelligence contributed significantly to the variance of individual difference in chess skills are consistent with the findings of meta-analyses in the recent studies. Both Burgoyne et al. (2016) and Sala et al. (2017) found that chess players outperformed non-chess players in intelligence-related abilities and these abilities contributed meaningfully to the individual differences in chess skill. The results of this study are also consistent with Pfau and Murphy's (1988) claim that chess knowledge is an important determinant of chess skill. The multiple regression analysis showed that chess knowledge was strongly related to chess ratings even after controlling for chess experience. An unanswered question is how CS and a few chess players in Study 2 were able to obtain a high level of chess knowledge after spending relatively little time studying chess.

A limitation of this study is that it relied on self-report measures of the amount of time spent studying chess alone and playing chess informally. However, self-reporting is a standard method used to measure the amount of time spent on deliberate practice (Charness et al., 1996, 2005; Ericsson et al., 1993; Gobet & Campitelli, 2007). Even though Charness et al.'s (2005) survey was adopted in this study and has been used frequently in the studies of chess expertise, it is always possible that these types of retrospective self-reports are inaccurate. However, since this experiment was conducted when CS had been playing chess seriously for only 3 years and 7 months, her retrospective estimates may be more accurate than others simply because there was a shorter time between the events and her reports of the events.

In summary, both studies provide evidence for the assertion that there are factors in addition to practice and chess experience that are important to the development of chess expertise. These findings call into question the 10-year rule or 10,000-hour rule, and provide evidence challenging the view that chess expertise is solely a function of practice (Ericsson, 2006; Simon & Chase, 1973). Nonetheless, Study 2 shows that practice is very important in acquiring chess expertise. It appears that recognition action theory which assumes that the development of chess expertise is based solely on the automatic building up of thousands of patterns of chess pieces is not sufficient. This theory has particular difficulty explaining how chess knowledge can be still so highly correlated with chess skill even after chess-related experiences are statistically controlled.

It is likely that factors other than knowledge such as the ability to search deeply, plan strategically, and apply positional principles are critical determinants of a player's skill level. However, it is not yet known whether these factors are related to expertise after controlling for chess experience. Overall, our results are in agreement with Campitelli and Gobet's (2011) conclusion that practice is necessary but not sufficient for achieving high levels of expertise.

Footnote

1. According to McLaughlin's diary/blog, he counted tournaments played as part of deliberate practice. He counted each tournament game as having played 2 hours of deliberate practice. It might violate the criteria of Ericsson's deliberate practice, but he justified it by stating: "When I play a tournament round like the one I participated in today I can make the same number of swings and theoretically spend the same amount of time learning or practicing the game but the round took about 6 hours. I can't exactly say that I spent 6 hours 'practicing' today as a lot of the time was just waiting. But, there are certain things you can only learn on the course so I have to count it for something. I decided from the beginning that 18 holes was going to be counted as 2 hours. Everything else is the exact time spent" (retrieved from http://thedanplan.com/5000-of-10000-practice-hours-completed-half-way/).

Authors' Declarations

The data in this article were collected for the first author's dissertation (Chang, 2016) to investigate issues related to individual differences in chess skill. These data were also analyzed and published in another article (Lane & Chang, 2018) to investigate issues related to the basis of the expertise effect in memory for chess positions.

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The authors declare that there are no personal or financial conflicts of interest regarding the research in this article.

The authors declare that they conducted the research reported in this article in accordance with the Ethical Principles of the Journal of Expertise.

The data from Study 1 and Study 2 are available at https://osf.io/gc5q6/. The individual raw data and CS's dataset are not publicly available, but the authors are able to provide them upon request.

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