Chess Expertise Reflects Domain-specific Perceptual Processing: Evidence from Eye Movements

Journal of Expertise
2023. Vol. 6(1)
ISSN 2573-2773

Eyal M. Reingold[1] and Heather Sheridan[2]

Department of Psychology, University of Toronto, Canada
Department of Psychology, University at Albany, State University of New York, USA

Correspondence: Eyal Reingold, reingold@psych.utoronto.ca; Heather Sheridan, hsheridan@albany.edu

Abstract

The remarkably efficient performance of chess experts reflects extensive practice with domain-related visual configurations. To study the perceptual component of chess expertise, we monitored the eye movements of expert and novice chess players during the performance of a novel double-check detection task. Chess players viewed an array of six minimized chessboards (4 x 4 squares), with each board displaying a king and 2 attackers. Players rapidly searched for the target board containing a double-check among distractor boards which either displayed a single check or displayed no check. During each fixation, chess pieces were only visible within the fixated board, while all other boards were replaced by empty boards. On half the trials, chess pieces were represented using the familiar symbol notation, while on the other half of the trials, pieces were represented using an unfamiliar letter notation. The analysis of overall response times and several fine-grained eye movement measures indicated that in trials using the familiar symbol notation, experts were much faster at identifying the double-check board, and this advantage was substantially attenuated in trials using the unfamiliar letter notation. In addition, an ex-Gaussian distributional analysis documented similar expertise by notation interactions. We discuss the implications of the present findings for theories of visual expertise in general, and skilled performance in chess, in particular.

Keywords

Chess, visual expertise, eye movements, time course, ex-Gaussian analysis, perceptual specificity hypothesis, expert-novice differences, memory, visual search

Introduction

There is a growing body of literature across wide-ranging areas of expertise demonstrating superior perceptual encoding of complex domain-related patterns by experts as compared to their less skilled counterparts (for a review, see Reingold & Sheridan, 2011). The origin of modern expertise research in general, and the study of the perceptual aspects of skilled performance in particular, can be traced back to the pioneering investigation of expertise in chess by de Groot, (1946/1965) and Chase and Simon (1973a, 1973b). Both de Groot, and Chase and Simon, demonstrated that, unlike novices, chess experts displayed a remarkable ability to remember and reproduce briefly presented chess positions. In addition, Chase and Simon (1973a, 1973b) demonstrated that the expert's advantage in encoding and recalling structured chess positions does not generalize to a condition in which chess-related patterns are disrupted by randomly rearranging pieces on the chessboard. Specifically, with such random configurations of chess pieces, Chase and Simon

(1973a, 1973b) documented no difference in performance as a function of expertise. More recently, a very small but reliable expert's advantage was demonstrated with random board positions (Gobet & Simon, 1996c) that is probably attributable to the occasional presence of familiar configurations within random board positions.

Taken together, the powerful effects of skill obtained with actual game positions (i.e., where chess-related patterns were intact), coupled with the weak or absent effects of skill obtained with random chess positions (i.e., where chess-related patterns were broken down), led to two critical insights with far reaching influence on subsequent research on expertise. First, the specificity of the experts' advantage ushered a dramatic theoretical shift in the conceptualization of expertise away from viewing skilled performance as the product of superior general intelligence and innate talent, and toward the recognition that expertise largely reflects domain-related knowledge acquired through extensive practice (for reviews, see Charness, 1992; Ericsson & Charness, 1994; Gobet & Charness, 2018) Second, both de Groot and Chase and Simon concluded that the efficiency of the perceptual encoding processes was a critical determinant of skilled performance. In particular, the specificity of the expert's advantage indicated that when processing complex domain-related displays, the main advantage for experts is not in the identification and localization of individual display elements (i.e., individual chess pieces and board locations; this type of information was available in both structured and random chess boards), but rather in the ability to rapidly encode larger clusters of related display elements (i.e., familiar chess configurations; this type of information was available in structured chess boards and only very infrequently by chance in random chess boards). According to Chase and Simon (1973a, 1973b), through extensive practice, players construct representations in long-term memory of chunks which correspond to recognizable configurations of pieces that are interrelated by type, color, or role (e.g., attacker–defender, etc.). Expert players are able to use this knowledge in long-term memory to encode and manipulate more chess-related information in a given mental operation than do less skilled players, who utilize smaller chunks. The size of an expert's vocabulary of chess related configurations was initially estimated to be 50,000–100,000 chunks (Simon & Gilmartin, 1973). However, a more recent estimate puts the number of chunks at approximately 300,000 (Gobet & Simon, 2000). In addition, small perceptual chunks are most likely supplemented by larger structures termed templates (Gobet & Simon, 1996b, 1998).

The hypothesis advocated by de Groot, and Chase and Simon, that a domain-specific perceptual advantage is a fundamental component of chess skill, received strong empirical support during the past several decades. A comprehensive review of this literature is beyond the scope of the present paper (see Reingold & Charness, 2005; Reingold & Sheridan, 2011 for reviews). Instead, we briefly summarize in Table 1 some of the main findings from studies which demonstrated enhanced perceptual encoding by chess experts. To illustrate better the linkage between these findings and the theoretical frameworks proposed by de Groot, and Chase and Simon, we organize our summary around several interrelated predictions, which implicitly or explicitly motivated the vast majority of previous research on the topic. These predictions were most clearly articulated as part of a research program by Reingold, Charness, and their colleagues (Charness et al., 2001; Reingold, Charness, Pomplun, et al., 2001; Reingold, Charness, Schultetus, et al., 2001; Reingold & Charness, 2005) that focused on testing the hypothesis that the processing of larger chess configurations (such as chunks or templates) mediates at least in part the enhanced perceptual encoding by chess experts. As can be clearly seen by an inspection of Table 1, there is strong empirical support for the idea that when processing structured (but not random) chess configurations, experts encode larger chunks rather than individual chess pieces, resulting in fewer fixations and more fixations between pieces, larger visual spans, parallel and automatic extraction of chess relations, and more rapid access to task-related (i.e., relevant and/or salient) aspects of the display. Furthermore, convergent evidence establishing superior perceptual encoding by chess experts was recently obtained in neuroimaging studies that have uncovered expert/novice differences in brain activation in regions associated with object and pattern recognition (Bilalić et al., 2010, 2012a; Bilalić, Kiesel, et al., 2011; Bilalić, Langner, et al., 2011; Langner et al., 2019; Rennig et al., 2013; Wright et al., 2013; See Bilalić, 2018 for a review). Finally, consistent with the findings summarized in Table 1 (see P4 in particular), chess expertise was shown to modulate ERPs (Event-Related Potentials) to chess-related stimuli as early as 240 ms post-stimulus (Wright et al., 2013).

Table 1. Predictions and evidence related to the frameworks of de Groot and Chase and Simon concerning the perceptual aspect of chess skill.

Prediction	Empirical findings and references
P1 - encoding of chunks rather than individual pieces should result in fewer fixations, and fixations between rather than on individual pieces.	Several early eye movements studies (Ellis, 1973; Jongman, 1968 reanalyzed by de Groot & Gobet, 1996; Tikhomirov & Poznyanskaya, 1966; Winikoff, 1967) provided weak support for this prediction. In contrast, Reingold, Charness, Pomplun, et al. (2001) provided strong support for this prediction in a check detection task, and similarly Charness et al. (2001) clearly demonstrated such a pattern in a choose-a-move task.
P2 - encoding of chunks rather than individual pieces requires a larger segment of the chessboard to be processed during each fixation constituting an increase in the size of the visual span.	Using a gaze-contingent moving window paradigm that manipulated the size of the visible area of the chessboard during each fixation, Reingold, Charness, Pomplun, et al. (2001) demonstrated that while processing structured chess positions experts displayed dramatically larger visual spans than either intermediate or novice players. In marked contrast, for random board positions there was no difference in visual span size as a function of expertise.
P3 – efficient encoding of a particular chunk might be accomplished by using automatic and parallel extraction of some of the chess relations from which it is composed.	Reingold, Charness, Schultetus, et al. (2001) and Reingold & Charness (2005) used a check detection task that contained a king and two potential attackers. When asked to only respond to one of these attackers, which was cued, experts (but not novices) showed no advantage of cuing, even though cuing narrowed the search space, and experts also exhibited Stroop-like interference if a cued non-checking attacker was accompanied by an attacker that was checking. Similar difficulty ignoring familiar chess configurations has been shown in the investigations of the Einstellung (set) effect in chess (Bilalić et al., 2008a, 2008b; Sheridan & Reingold, 2013). In addition, Waters and Gobet (2008) demonstrated a disruption to chunking when chess pieces were shifted to the intersections between squares.
P4 – the expert's advantage in encoding complex chess related patterns should result in faster identification of task relevant aspects of the display.	There is ample support for this prediction in a variety of chess related tasks including a choose-a-move task (Charness et al., 2001; Reingold & Charness, 2005; Sheridan & Reingold, 2013; Simon & Barenfeld, 1969; Tikhomirov & Poznyanskaya, 1966), a memorization task (de Groot & Gobet, 1996), a relevance search task (Bilalić et al., 2010), a threat detection task (Bilalić et al., 2012), and a simplified Knight tour task (Sheridan & Reingold, 2017).

The main goal of the present study was to explore further differences in encoding efficiency as a function of chess skill. To accomplish this goal, we monitored participants' eye movements during the performance of a novel double-check detection task. Parallel and automatic extraction of chess relations by experts might result in more efficient encoding of complex patterns such as double-check configurations, which by definition depict multiple interconnected chess relations (Reingold, Charness, Schultetus, et al., 2001; Sheridan & Reingold, 2017). Specifically, in the present task, chess players viewed an array of six minimized chessboards (4 x 4 squares), with each board displaying a king and two attackers. Players rapidly searched for the target board containing a double-check (double-check board) among distractor boards which either displayed a single check (single-check board) or displayed no check (no-check board) (See Figure 1).

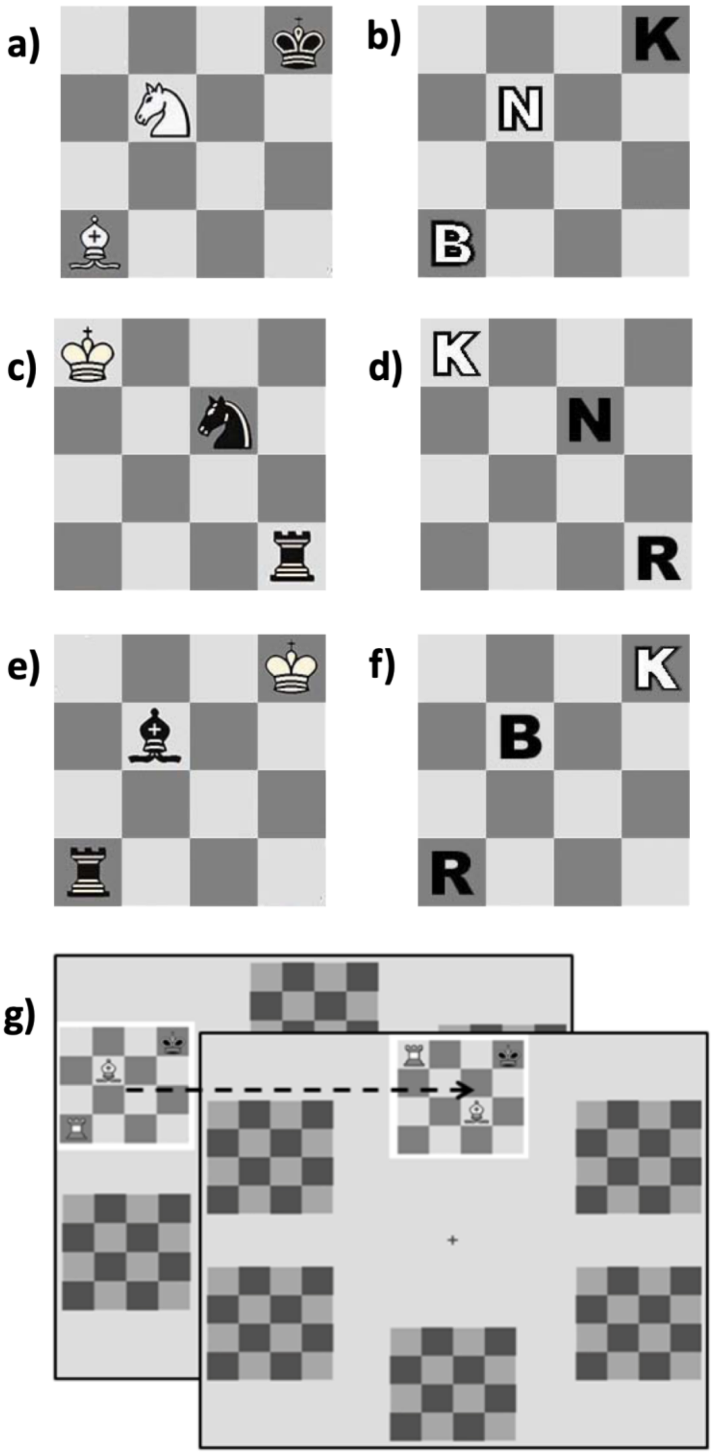

Figure 1. An illustration of the double-check detection task. Chess players were asked to rapidly locate the target miniature chessboard that contained a double check (Panels a, b), among distractor boards which either displayed a single check (Panels c, d) or displayed no check (Panels e, f). Chess pieces were shown using either the familiar symbol notation (Panels a, c, e) or the unfamiliar letter notation (Panels b, d, and f). During each trial, six boards were arranged around a central fixation cross. However, during each fixation, chess pieces were only shown within the fixated board (Panel g illustrates the display change that occurred when the gaze moved from the top-left board to the top-center board). See text for further details.

In Figure 1, note that expert chess players were demonstrated to make extensive use of parafoveal and peripheral processing during each fixation (i.e., resulting in larger visual spans; see Reingold, Charness, Pomplun, et al., 2001). Consequently, in order to obtain an accurate measure of the processing time for a particular board, during each fixation a gaze contingent window restricted processing to the fixated board, while all other boards were replaced by empty boards (See Figure 1, Panel g for an illustration). This ensured that despite their larger visual spans, experts were not able to pre-process a board prior to their first fixation on that board, and they were also not able to use such pre-processing to guide their search (i.e., choose to fixate or skip a board based only on parafoveal or peripheral processing). Given our interest in obtaining a measure of perceptual encoding speed for each of the three board types (double-check, single-check, and no-check), we focused on the analysis of first-dwell duration (defined as the sum of the duration of one or more consecutive fixations during the very first encounter with a particular board type during a trial, prior to the eyes moving to another board).

We also manipulated the familiarity of the notation (symbol vs. letter) that was used to represent the chess pieces. Symbol and letter notations were used to represent identical chess problems. However, the symbol representation is much more familiar to chess players than the letter representation. Consequently, if perceptual encoding efficiency is related to chess experience, then any skill advantage should be more pronounced in trials using the symbol notation than in trials using the letter notation (Reingold, Charness, Pomplun, et al., 2001 used this rationale in introducing this manipulation; see also Chase & Simon, 1973b). The above prediction is predicated on the assumption that long-term memory representations of chess configurations are perceptually specific (i.e., preserve perceptual/surface details such as notation; henceforth, the *perceptual specificity hypothesis*). Thus, obtaining skill-by-notation interactions would demonstrate that the expert's perceptual encoding advantage is due to the acquisition of domain-related representations of chess configurations and that these representations of relational information are at least in part perceptually specific.

Finally, another unique aspect of the present study involved our use of a distributional analysis technique to investigate the effects of chess expertise and notation on the distributions of first-dwell durations. Specifically, in order to study the time course of expertise and notation effects on first-dwell duration, we used an ex-Gaussian fitting method which was previously successfully used to model RT distributions (see Balota & Yap, 2011 for a review), and fixation times in reading (Reingold et al., 2012, 2015; Sheridan et al., 2013; Sheridan & Reingold, 2012b, 2012c; Staub, 2011; Staub et al., 2010). The ex-Gaussian distribution is a convolution (sum) of two stochastically independent random variables, a normally distributed random variable and an exponentially distributed random variable. The ex-Gaussian distribution can be fully specified with three parameters μ (Mu, the mean of the Gaussian component), σ (Sigma, the standard deviation of the Gaussian component), and τ (Tau. the mean and standard deviation of the Exponential component). The sum of the Mu and Tau parameters from the fitted ex-Gaussian distribution equals the mean of the empirically obtained dwell-duration distribution. Importantly, a comparison of the best-fitting Mu and Tau parameters can reveal whether a variable's effect on the mean dwell time is due to an overall shift in the location of the distribution and/or a change in the degree of skew. Whereas a shift effect (i.e., a difference in Mu between conditions) indicates that the variable has an early acting influence on the majority of dwell durations, a skew effect (i.e., a difference in Tau between conditions) indicates that the variable influences long dwell durations. Given the previous findings of enhanced perceptual encoding by chess experts, we would predict that when encoding chess related patterns that are presented using the familiar symbol notation, the distribution of first-dwell durations for novices should be shifted to the right of the expert's distribution. Furthermore, to the extent that experts' memory representations for chess configuration are perceptually specific, such a shift effect should be weaker or even absent when the letter notation is used.

Method

Participants

Forty-two chess players (18 experts and 24 novices) were recruited from online chess forums and from local chess clubs in Toronto and Mississauga (Ontario, Canada). The mean age was 30 in the expert group, and 27 in the novice group. There was one female player in the expert group, and there were six female players in the novice group. For the expert players, the average Elo rating ranged from 1876 to 2580 (*M* = 2231)[1]. All the novice players were unrated club players who were familiar with the rules of chess but had never participated in a rated chess tournament. All the participants had normal or corrected-to-normal vision.

Materials and Design

As shown in Figure 1, the experimental stimuli consisted of minimized 4 X 4 chessboards. Each of these chess boards contained a king that was always located in one of the four corner squares, and two potential checking pieces (from the combinations of rook, bishop, and knight). As discussed earlier, these chessboards were used to examine three different conditions. For the “Double Check” condition (see Figure 1, Panels a and b), both of the pieces were attacking the king. For the “Single Check” condition (see Figure 1, Panels c and d), only one of the two pieces was attacking the king. For the “No Check” condition (see Figure 1, Panels e and f), neither one of the two pieces was attacking the king. Each trial in the experiment contained six of the miniature chessboards, such that three of the boards were in the “No Check” condition, two boards were in the “Single Check” condition, and the remaining board was in the “Double Check” condition. These six boards were arranged around a central fixation cross (as shown in Figure 1, Panel g).

In addition, we manipulated the familiarity of the notation (symbol vs. letter). For the symbol notation condition (see Figure 1, Panels a, c, and e), all of the chessboards in a trial contained chess symbols that were created using standard chess software (Chessbase 11). For the letter condition (see Figure 1, Panels b, d, and f), all of the chessboards in a trial contained capital letters instead of symbols (i.e., B = bishop, K = king, N = knight, or R = rook).

Across trials, there were equal numbers of boards containing each type of attacker (rook, bishop, and knight), and each color of king (white, black). The locations of the six boards were randomly varied across trials such that the “Double Check” condition board had an equal chance of occurring in each of the six locations, and there was variation in the spatial layout of the boards (i.e., the positioning of the king and the two potential checking pieces). For more detailed information see OSF (https://osf.io/wdcjv/?view_only=87957b174ac8412e94150ac5395b947f).

Apparatus and Procedure

Eye movements were measured with an SR Research Eyelink 1000 system with high spatial resolution and a sampling rate of 1000 Hz. The experiment was programmed and analyzed using SR Research Experiment Builder and Data Viewer software. Viewing was binocular, but only the right eye was monitored. A chin rest and forehead rest were used to minimize head movements. Following calibration, gaze-position error was less than 0.5º. The miniature chessboards were presented using images (212×212 pixels). These images were displayed on a 21 in. ViewSonic monitor with a refresh rate of 150 Hz and a screen resolution of 1024 × 768 pixels. Participants were seated 60 cm from the monitor. The width of one square on the chessboards equaled approximately 2.1 degrees of visual angle, and the interest areas surrounding each of the four chessboards extended slightly beyond the edge of each board (by 0.80 of a degree of visual angle on all four sides of each board). The distance between the center of each of the chessboards and the central fixation cross varied slightly depending on the board’s location in the array (as shown in Figure 1, Panel g); Specifically, this distance was 10.6 degrees of visual angle for the two boards located directly above and below the fixation cross, and 13.7 degrees of visual angle for the four boards located on either side of the fixation cross.

Prior to the experiment, the participants were instructed to select the Double Check board in which two pieces were checking the king. They were asked to respond as quickly and accurately as possible. At the start of each trial, the participants were required to look at a fixation point in the center of the screen and to press a button to initiate the presentation of the six miniature chessboards. When the participant had reached a decision, they looked at a gray fixation cross located at the center of the screen and pressed a button on the response pad. This caused the fixation cross to turn green, which signaled the participant to then fixate the chessboard they had chosen in order to select it. Upon fixating the chessboard to be selected, a chime sounded, and the trial ended. We recorded the participants' gaze location to determine which board they had selected. We used this procedure for collecting responses to ensure that any delays and eye movements associated with providing a response did not impact the data that was collected during the trial (see Glaholt & Reingold, 2012 for a similar gaze selection procedure).

The experiment contained a total of 384 trials (i.e., 96 practice trials, which were followed by 288 experimental trials), and the experiment was approximately 45 minutes in duration. These trials were divided into blocks (with 24 trials per block), and the participants were encouraged to take a short break between each block of trials. As previously mentioned, during the experimental trials, the participants viewed the chessboards through a gaze-contingent moving window that was continuously centered on the participant's current point of fixation. This window allowed the participants to view only one of the six chessboards at a time, because the chess boards outside of the window contained blank squares (as shown in Figure 1, Panel g). To allow the participants to become familiar with the content of the chessboards, the gaze contingent window was not used during the practice trials (i.e., all six chess boards were always visible during the 96 practice trials). Finally, the same notation (i.e., symbol or letter) was used for all 24 trials within each block, and notation type alternated across blocks (i.e., Blocks 1, 3, 5, etc. vs. Blocks 2, 4, 6, etc.).

Before beginning the practice trials, the participants were informed about the letter and symbol manipulation (They were told that "On some trials, the chess symbols have been replaced with letters. For example, the bishop has been replaced with the capital letter B."). The participants were also told to locate the board that depicted the king in a double check situation "as quickly as you can." After the practice blocks were completed, and prior to beginning the experimental trials, the participants were informed about the gaze-contingent moving window (They were told that "you will be viewing the chess displays through a window that will continuously be centered at the point at which you are looking. This window will effectively allow you to view only one chess display at a time; chess displays outside of the window will be blank.")

Results

To test our prediction that chess expertise entails a rapid perceptually-specific advantage, our analyses focused on contrasting expertise effects in the symbol versus the letter notation conditions. We will begin by analyzing the global performance measures of accuracy and response time (RT) using a 2 x 2 analysis of variance (*ANOVA*), with notation (symbol, letter), and level of expertise (novice, expert) as independent variables. We will then examine three eye movement measures that provided an index of the early perceptual processing of chessboards (first-dwell duration, first-fixation duration, and the probability of a single-fixation dwell). These dependent measures were analyzed using a 2 x 2 x 3 ANOVA, with notation, level of expertise, and board type (double check, single check, no check) as independent variables. Finally, we employed Ex-Gaussian fitting to model individual participants' first-dwell durations. Ex-Gaussian fitting provides fine-grained time course information that is useful for exploring the influences of expertise and notation on rapid perceptual processing.

Accuracy

The percentage of incorrect trials was extremely small for the experts (Symbol condition: *M* =0.6%, *SE* = 0.15%; Letter Condition: *M* = 0.7%, *SE* = 0.16%) and for the novices (Symbol Condition: *M* = 0.5%, *SE* = 0.13%; Letter condition: *M* = 0.8%, *SE* = 0.14%). The interaction and main effects were not significant for accuracy (all *F*s < 2.4, all *p*s > .13). For all the remaining analyses reported below, we excluded the small proportion of inaccurate trials (less than 1% of the data).

Response Times

As shown in Panel a of Figure 2, response times (in milliseconds) were faster for the experts (Symbol condition: *M* = 3629, *SE* = 181; Letter Condition: *M* = 4754, *SE* = 254) than the novices (Symbol condition: *M* = 4929, *SE* = 302; Letter Condition: *M* = 5539, *SE* = 284), $F(1, 40) = 7.73$, $p < .01$, $\eta^2_p = .16$. Also, response times were faster for the symbol condition relative to the letter condition, $F(1, 40) = 67.39$, $p < .001$, $\eta^2_p = .63$. More importantly, in support of our perceptual specificity hypothesis, the symbol condition elicited larger expertise effects than the letter condition, as shown by a significant interaction between expertise and notation, $F(1, 40) = 5.93$, $p < .05$, $\eta^2_p = .13$.

First-dwell Duration

To provide an index of the time required to perceptually encode the chess boards, we analyzed the duration of the very first dwell on the chessboard (i.e., *first-dwell duration*). A dwell was defined as one or more consecutive fixations on the chessboard, prior to the eyes moving to another board. As shown by the pattern of means in Panel a of Figure 3, first-dwell durations were faster for the experts than the novices, $F(1, 40) = 7.70$, $p < .01$, $\eta^2_p = .16$, and for the symbol condition relative to the letter condition, $F(1, 40) = 86.81$, $p < .001$, $\eta^2_p = .69$. First-dwells were faster for the “no check” condition relative to the “single check condition”, and both of these board conditions were faster than the “double check condition”, as reflected in a main effect of board condition, $F(2, 80) = 108.44$, $p < .001$, $\eta^2_p = .73$. As further support of our hypothesis that the advantage of expertise is perceptually specific, the symbol condition elicited larger expertise effects than the letter condition, as shown by a significant interaction between expertise and notation, $F(1, 40) = 10.59$, $p < .01$, $\eta^2_p = .21$. This pattern of expertise by notation interaction was separately significant for each board type condition (double check: $F(1, 40) = 9.60$, $p < .01$, $\eta^2_p = .19$; single check: $F(1, 40) = 8.94$, $p < .01$, $\eta^2_p = .18$; no check: $F(1, 40) = 7.36$, $p < .01$, $\eta^2_p = .16$), and the three way interaction was not significant (i.e., Expertise X Notation X Board type, $F < 1$).

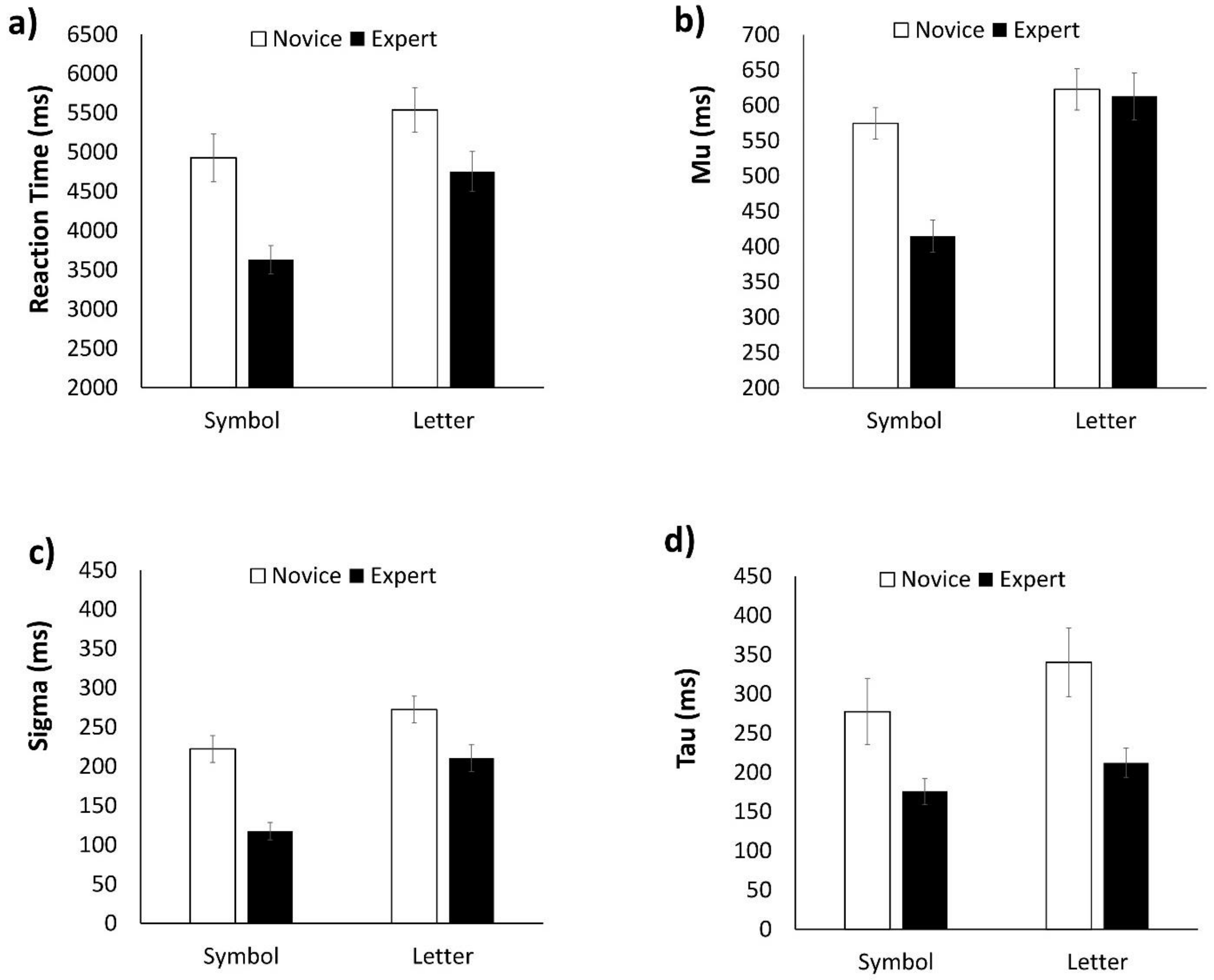

Figure 2. Expertise by notation effects for response time (Panel a) and for the best-fitting ex-Gaussian parameters, Mu (Panel b), Sigma (Panel c) and Tau (Panel d). The error bars represent the standard error of the means.

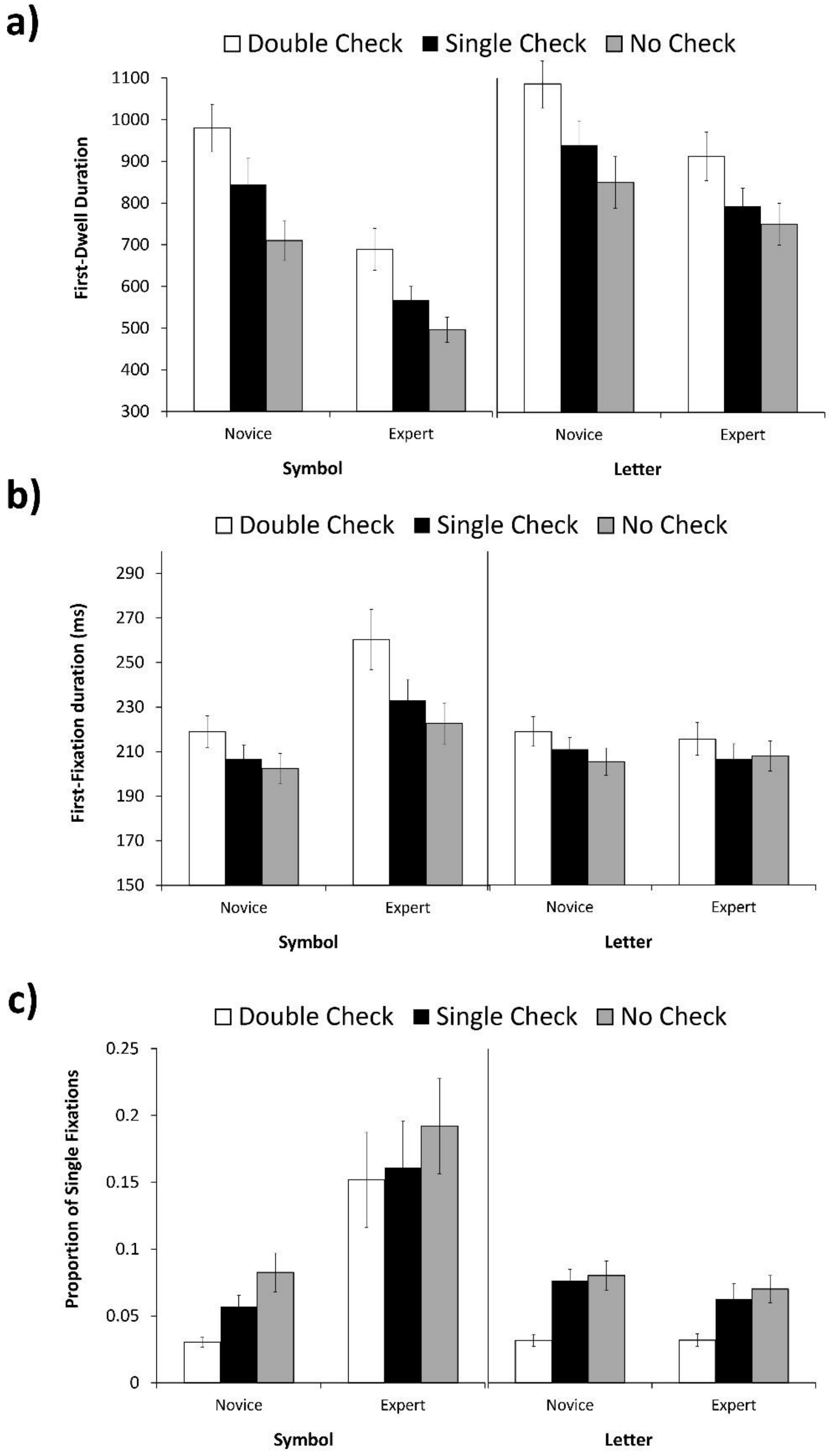

Figure 3. Expertise by notation by board type effects for first-dwell duration (Panel a), for first-fixation duration (Panel b), and for the proportion of single-fixation dwells (Panel c). The error bars represent the standard error of the means.

First-fixation Duration

Although the first-dwell duration variable constitutes the primary measure of perceptual encoding speed in the present study, we also analyzed first-fixation duration (i.e., the duration of the very first fixation on the chessboard) as an indicator of early perceptual processing of board information. As can be clearly seen in Panel b of Figure 3, the pattern of first-fixation duration differed dramatically between experts and novices. Specifically, for novices, notation did not influence first-fixation duration (i.e., there was no main effect of notation or an interaction between notation and board type, both *F*s < 1.24, both *p*s > .27). The main effect of board type on first-fixation duration for novices was significant, $F(2, 46) = 16.57$, $p < .001$, $\eta^2_p = .42$, reflecting longer first fixations on double check boards than on either single check boards (both *t*s > 2.20, both *p*s < .05) or no check boards (both *t*s > 3.12, both *p*s < .01). In marked contrast, for experts, there was a main effect of notation reflecting longer first fixations for the symbol notation than for the letter notation, $F(1, 17) = 23.01$, $p < .001$, $\eta^2_p = .58$), and a significant interaction between notation and board type, $F(2, 34) = 13.48$, $p < .001$, $\eta^2_p = .44$, reflecting much larger differences as a function of board type for the symbol notation than the letter notation. The above differences between novices and experts in the pattern of first-fixation durations resulted in a significant three way interaction (i.e., expertise x notation x board type, $F(2, 80) = 7.738$, $p < .001$, $\eta^2_p = .16$). Importantly, consistent with the perceptual specificity hypothesis, there was a significant interaction between expertise and notation reflecting an influence of expertise for the symbol notation but not for the letter notation, $F(1, 40) = 29.47$, $p < .001$, $\eta^2_p = .42$, and this interaction was separately significant for each board type condition (double check: $F(1, 40) = 24.61$, $p < .001$, $\eta^2_p = .38$; single check: $F(1, 40) = 27.68$, $p < .001$, $\eta^2_p = .41$; no check: $F(1, 40) = 10.38$, $p < .01$, $\eta^2_p = .21$).

Probability of a Single-fixation Dwell

As summarized in Table 1, when encoding chess configurations, experts were demonstrated to make extensive use of parafoveal processing during each fixation resulting in fewer fixations, and larger visual spans (e.g., Reingold, Charness, Pomplun, et al., 2001). Consequently, we predicted that experts would be more likely than novices to demonstrate a single fixation on a board prior to moving to a different board (henceforth, *single-fixation dwell*). In addition, as part of our perceptual specificity hypothesis, we predicted that the pattern of a greater probability of single-fixation dwells for experts than novices would primarily occur in the symbol notation condition, and that such an effect would be diminished or even absent in the letter notation condition (i.e., expertise by notation interaction). As shown in Panel c of Figure 3, the pattern of findings for the probability of single-fixation dwells was consistent with our predictions. Specifically, the probability of single-fixation dwells was larger for experts than the novices, $F(1, 40) = 12.66$, $p < .001$, $\eta^2_p = .24$, and for the symbol condition relative to the letter condition, $F(1, 40) = 18.32$, $p < .001$, $\eta^2_p = .31$. The probability of single-fixation dwells was larger for the “no check” condition relative to the “single check condition”, and both of these board conditions demonstrated larger probabilities than the “double check condition”, as reflected in a main effect of board type, $F(2, 80) = 31.99$, $p < .001$, $\eta^2_p = .44$. Most importantly, consistent with our hypothesis that the advantage of expertise is perceptually specific, there was a significant influence of expertise for the symbol notation but not for the letter notation, as reflected by a significant interaction between expertise and notation, $F(1, 40) = 20.37$, $p < .001$, $\eta^2_p = .34$. The pattern of expertise by notation interactions was very similar across all board type conditions (double check: $F(1, 40) = 16.04$, $p < .001$, $\eta^2_p = .29$; single check: $F(1, 40) = 18.35$, $p < .001$, $\eta^2_p = .31$; no check: $F(1, 40) = 20.21$, $p < .001$, $\eta^2_p = .13$), and the three-way interaction was not significant (i.e., Expertise X Notation X Board type, $F < 1$).

Distributional Analysis of First-dwell Duration

To further test our hypothesis that the experts’ encoding advantage was driven by rapid perceptually specific processing, we used the Ex-Gaussian distributional analysis technique. The ex-Gaussian distribution is the convolution of the Gaussian normal distribution and an exponential distribution, and the shape of the ex-Gaussian distribution can be specified with three parameters: μ (Mu, the mean of the Gaussian normal distribution), σ (Sigma, the standard deviation of the Gaussian normal distribution) and τ (Tau, the mean and standard deviation of the exponential function). We fitted the ex-Gaussian distribution to the first-dwell duration data using an algorithm known as *quantile maximum likelihood estimation* (*QMPE*; Cousineau et al., 2004; Heathcote et al., 2002). The first-dwell duration data was fitted separately for each participant and for each condition.

Importantly, ex-Gaussian fitting allows us to clarify whether the influence of expertise on mean first-dwell duration, which was discussed earlier, is due to a shift in the location of the distribution (a shift effect indicates a rapid influence on both short and long dwells) or due to a change in the degree of skew (a skew effect indicates an influence that is primarily restricted to long dwells). Accordingly, if the influence of expertise is due to rapid processing, then such an influence should be reflected in a shift effect (i.e., a difference in Mu as a function of expertise). Furthermore, the perceptual specificity hypothesis predicts that the magnitude of the shift effect should be greater in the symbol notation condition than in the letter notation condition. Consistent with these predictions, Figure 4 illustrates the dramatic pattern of the expertise by notation influence on the distribution of first-dwell duration. Specifically, in the symbol condition, in both the histograms (Panel a) and in the density functions generated from the best-fitting ex-Gaussian parameters (Panel c), the Novices' distribution is shifted to the right of the experts' distribution. In marked contrast, such a shift effect is not visible in the letter condition (Panels b, d).

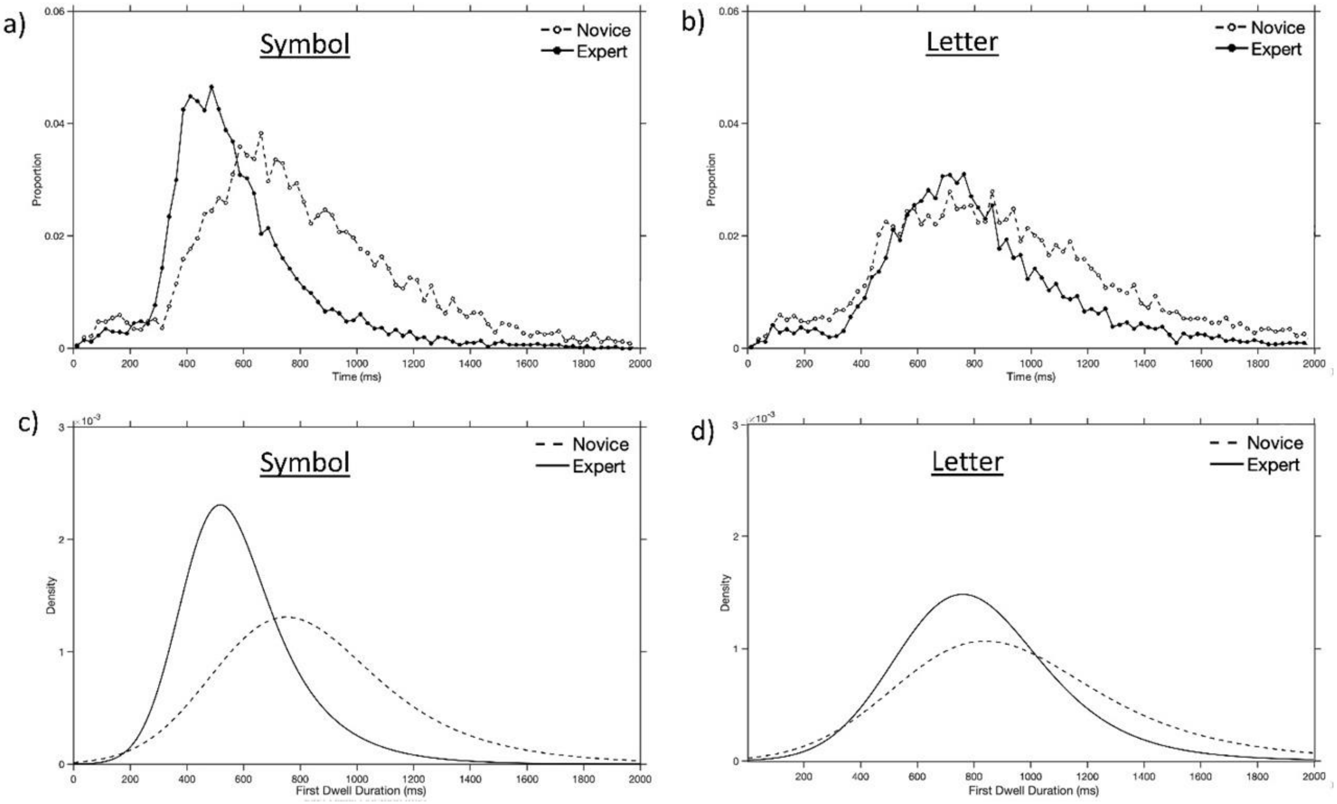

Figure 4. Histograms (Panels a, b) and density functions generated from the best-fitting ex-Gaussian parameters (Panels c, d), demonstrating the influence of expertise for symbol notation trials (Panels a, c) and letter notation trials (Panels b, d).

In addition, we analyzed each of the ex-Gaussian parameters (Mu, Sigma, Tau) using a 2 x 2 ANOVA, with notation (symbol, letter), and level of expertise (novice, expert) as independent variables. Consistent with the pattern seen in the histograms and density functions, the expertise by notation interaction was significant for Mu, $F(1, 40) = 25.27$, $p < .001$, $\eta^2_p = .63$ (see Panel b of Figure 2), reflecting a large expertise effect (i.e., shift effect) in the symbol condition, $t(40) = 4.89$, $p < .001$, $d = 1.52$, and no expertise effect in the letter condition ($t < 1$). A similar expertise by notation interaction was obtained for the Sigma parameter, $F(1, 40) = 6.79$, $p < .05$, $\eta^2_p = .15$ (see Panel c of Figure 2), demonstrating that in the symbol condition, the variability of first-dwell durations was larger for novices than experts, $t(40) = 4.75$, $p < .001$, $d = 1.48$, and there was no difference in variability as a function of expertise in the letter condition ($t < 1$). In contrast to the analyses of Mu and Sigma, which demonstrated large expertise effects in the symbol condition and no influence of expertise in the letter condition, for Tau, there was no such effect (see Panel d of Figure 2). In fact, for the Tau parameter there was a small numerical difference in the direction of a larger expertise effect in the letter condition than in the symbol condition, but the expertise by notation interaction did not reach significance, $F(1, 40) = 1.88$, $p = .178$, $\eta^2_p = .05$). The differential pattern of results for Mu and Sigma versus Tau is consistent with our interpretation that the experts' advantage in the symbol condition reflects, at least in part, rapid perceptually specific processing that impacts the entire distribution of dwell durations. Our findings also suggest that the effect of expertise on skew is mediated by a different mechanism that is not impacted by the notation manipulation (i.e., is not perceptually specific), and which primarily influences long dwells.

Discussion

The present study builds upon a growing body of literature (see Table 1), which convincingly demonstrated enhanced perceptual encoding of chess configurations by expert players in comparison to their less skilled counterparts. Replicating the pattern reported by Reingold, Charness, Pomplun, et al. (2001), and consistent with the perceptual specificity hypothesis, robust expertise by notation interactions were demonstrated for overall response times and for the fine-grained eye movement measures (first-dwell duration, first-fixation duration, and the probability of a single-fixation dwell). Specifically, in trials using the familiar symbol notation, experts were considerably faster at identifying the double-check configurations, and this advantage was substantially attenuated or even eliminated in trials using the unfamiliar letter notation. In addition, for the symbol notation there was a very dramatic experts' advantage that occurred within an extremely rapid time course (i.e., affecting both short- and long-dwell durations), while for the letter notation there was a much smaller and delayed effect of expertise (i.e., that was confined to long-dwell durations).

In order to examine the implications of the present findings, it is instructive to compare the notation manipulation to the configuration-type manipulation (chess configuration vs. random configuration). Note that in random configurations, the symbols used to represent individual pieces are preserved, but both the appearance and semantics of chess configurations are irrevocably altered. In other words, in the case of random configurations, chess knowledge is rendered largely irrelevant because such configurations are both perceptually unfamiliar and semantically incoherent. In contrast, the influence of the notation manipulation is much more selective. Specifically, the letter notation disrupts the perceptual/surface familiarity of chess configurations, but the semantics of the configurations remain intact and chess comprehension and problem solving can proceed. Despite this difference between the notation manipulation and the configuration-type manipulation, both were shown to strongly interact with expertise, and these interactions were used as the basis for the conclusion that experts' superior encoding of chess configurations was due at least in part to their chess experience, rather than to a general perceptual superiority (see discussion by Reingold, Charness, Pomplun, et al., 2001).

However, the interaction between notation and expertise can be used to further pinpoint a mechanism which might underlie visual expertise in general, and skilled performance in chess, in particular. This is the case because the expertise-by-notation interaction suggests that experts' rapid encoding processes are at least in part reliant on memory representations of chess configurations (or chunks), which preserve perceptual/surface details such as notation. In other words, there is evidence for the perceptual specificity of the memory representations which are involved in the encoding of chess configurations by experts, and when there is a mismatch between such representations and the notation used to represent chess pieces (i.e., as is the case with the letter notation), pattern recognition processes are impeded, and the experts' advantage is substantially reduced and delayed. If memory representations contained only conceptual information concerning the meaning of chess configurations (i.e., perceptual features such as notation are discarded) then we would not expect experts to be differentially affected by the notation manipulation, and the magnitude of the influence of expertise should not have been reduced when the letter notation was used instead of the familiar symbol notation.

Therefore, the expertise-by-notation interaction provides strong support for the argument by Chase and Simon (1973a) "that the most important processes underlying chess mastery are these immediate visual-perceptual processes rather than the subsequent logical-deductive thinking processes" (p. 215). Thus, in a radical departure from previous conceptualizations of skilled performance, de Groot, and Chase and Simon, hypothesized that chess grandmasters use efficient perceptual encoding of chess configurations to generate the most promising candidate moves and to restrict their reliance on the effortful and slow serial search through the space of possible moves. In other words, expert-novice differences were hypothesized to reflect qualitative rather than merely quantitative differences. Specifically, the frameworks of de Groot, and Chase and Simon, suggest greater reliance on fast and automatic perceptual pattern recognition processes by top chess experts than by less skilled players that tend to depend more on slow and effortful problem solving and search and evaluation processes.

Methodologically, investigating such predictions of qualitative expert-novice differences require going beyond the ubiquitous (albeit impressive) main effects of expertise, and instead focusing on experimental manipulations that might differentially affect (i.e., dissociate between) the performance of experts versus novices. As explained above, due to the disruption of perceptual encoding processes, the letter notation condition exerted a much greater effect on the performance of experts than novices, resulting in a substantial attenuation of the influence of expertise on task performance. However, establishing qualitative differences as a function of expertise also requires demonstrating the opposite pattern in which a manipulation affects novices to a much greater extent than experts. Precisely such a pattern was obtained in investigations of the influence of severe time pressure on chess performance. Time pressure would be expected to be very detrimental to the slow and effortful serial search processes that are characteristic of novices' performance. In contrast, the fast and effortless perceptual pattern recognition processes that largely determine experts' performance should be much less affected by time pressure. Consistent with this prediction, several investigations reported little effect of extreme time pressure on the performance of top chess players, and a substantial effect on the performance of weaker players (e.g., Burns, 2004; Calderwood et al., 1988; Chabris & Hearst, 2003; Gobet & Simon, 1996a). For example, Burns (2004) conducted an extensive investigation of archival data on blitz chess. In blitz chess tournaments players are afforded less than 5% of the time available during regular chess tournaments. Burns (2004) demonstrated that among weaker players, skill differences were attenuated by playing blitz chess, thereby demonstrating the importance of problem solving and search processes for less skilled performers. In contrast, this effect all but disappeared for top players (with ratings > 2200). Thus, the investigation of the influence of severe time pressure on chess performance provided important convergent evidence in support of the hypothesis of greater reliance on fast perceptual pattern recognition processes by top chess experts than by their less skilled counterparts.

Finally, the increasing theoretical and empirical emphasis on the crucial role of domain-specific perceptual processes in determining skilled performance in chess is reminiscent of a similar trend in the memory literature. Specifically, the memory literature has undergone a shift from a primary focus on conceptual and semantic influences on memory performance in the 1970s, towards a growing acknowledgment of the role of perceptual influences (for a review see Reingold, 2002). Of particular relevance for the present study is the work by Paul Kolers (e.g., Kolers, 1976) using the transformed text paradigm. In order to study the perceptual specificity of memory representations, Kolers applied geometrical transformations to normal text such as inversion or mirror reflection. Similar to the notation manipulation in chess, the transformed text manipulation selectively disrupted perceptual familiarity but preserved the semantics. Using this paradigm, Kolers (1976) provided a dramatic demonstration of long-term retention of superficial perceptual details (i.e., typography) supporting the existence of perceptually specific memory representations (see also Reingold, 2002; Sheridan & Reingold, 2012a, for eye movements studies using similar paradigms). Thus, we would argue that an important goal for empirical investigations of visual expertise would be to study further the perceptual specificity of memory representation that might underlie the experts' advantage, and to consider related paradigms that were developed for that purpose in the memory literature.

Endnote

1. We used the chess players' CFC (Canadian Chess Federation) ratings in these calculations, with the exception that one of the expert players did not have a CFC rating; In this case, we used this chess player's FIDE (Federation Internationale des Echecs) rating in lieu of the CFC rating.

Acknowledgements

We are especially grateful to all the chess players who participated in the experiment. This research was supported by an NSERC grant to Eyal Reingold.

Authors' Declarations

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 authors declare that they are not able to make the dataset publicly available but are able to provide it upon request.

ORCID iDs

Eyal Reingold
https://orcid.org/0000-0001-8941-0644

Heather Sheridan
https://orcid.org/0000-0001-8486-644X

References

Balota, D. A., & Yap, M. J. (2011). Moving beyond the mean in studies of mental chronometry: The power of response time distributional analyses. *Current Directions in Psychological Science*, *20*(3), 160–166. https://doi.org/10.1177/0963721411408885

Bilalić, M. (2018). The double take of expertise: Neural expansion is associated with outstanding performance. *Current Directions in Psychological Science*, *27*(6), 462–469. https://doi.org/10.1177/0963721418793133

Bilalić, M., Kiesel, A., Pohl, C., Erb, M., & Grodd, W. (2011). It takes two-skilled recognition of objects engages lateral areas in both hemispheres. *PloS One*, *6*, e16202. https://doi.org/10.1371/journal.pone.0016202

Bilalić, M., Langner, R., Erb, M., & Grodd, W. (2010). Mechanisms and neural basis of object and pattern recognition: A study with chess experts. *Journal of Experimental Psychology: General*, *139*, 728–742. http://psycnet.apa.org/journals/xge/139/4/728/

Bilalić, M., Langner, R., Ulrich, R., & Grodd, W. (2011). Many faces of expertise: Fusiform face area in chess experts and novices. *The Journal of Neuroscience*, *31*, 10206–10214. https://doi.org/10.1523/JNEUROSCI.5727-10.2011

Bilalić, M., McLeod, P., & Gobet, F. (2008a). Inflexibility of experts - reality or myth? Quantifying the Einstellung effect in chess masters. *Cognitive Psychology*, *56*(2), 73–102. https://doi.org/10.1016/j.cogpsych.2007.02.001

Bilalić, M., McLeod, P., & Gobet, F. (2008b). Why good thoughts block better ones: The mechanism of the pernicious Einstellung (set) effect. *Cognition*, *108*(3), 652–661. https://doi.org/10.1016/j.cognition.2008.05.005

Bilalić, M., Turella, L., Campitelli, G., Erb, M., & Grodd, W. (2012). Expertise modulates the neural basis of context dependent recognition of objects and their relations. *Human Brain Mapping*, *33*, 2728–2740. https://doi.org/10.1002/hbm.21396

Burns, B. D. (2004). The effects of speed on skilled chess performance. *Psychological Science*, *15*, 442–447.

Calderwood, R., Klein, G. A., & Crandall, B. W. (1988). Time pressure, skill, and move quality in chess. *American Journal of Psychology*, *101*, 481–493.

Chabris, C. F., & Hearst, E. S. (2003). Visualization, pattern recognition, and forward search: Effects of playing speed and sight of the position on grandmaster chess errors. *Cognitive Science*, *27*, 637–648.

Charness, N. (1992). The impact of chess research on cognitive science. *Psychological Research*, *54*, 4–9. http://link.springer.com/article/10.1007/BF01359217

Charness, N., Reingold, E. M., Pomplun, M., & Stampe, D. M. M. (2001). The perceptual aspect of skilled performance in chess: Evidence from eye movements. *Memory & Cognition*, *29*(8), 1146–1152. http://www.ncbi.nlm.nih.gov/pubmed/11913751

Chase, W. G., & Simon, H. A. (1973a). Perception in chess. *Cognitive Psychology*, *4*, 55–81. http://www.sciencedirect.com/science/article/pii/0010028573900042

Chase, W. G., & Simon, H. A. (1973b). The mind’s eye in chess. In W. G. Chase (Ed.), *Visual information processing* (pp. 215–281). Academic Press.

Cousineau, D., Brown, S., & Heathcote, A. (2004). Fitting distributions using maximum likelihood: methods and packages. *Behavior Research Methods, Instruments, & Computers*, *36*(4), 742–756. http://www.ncbi.nlm.nih.gov/pubmed/15641420

de Groot, A. D. (1965). *Thought and choice in chess*. Mouton.

de Groot, A. D., & Gobet, F. (1996). *Perception and memory in chess*. Van Gorcum.

Ellis, S. H. (1973). *Structure and experience in the matching and reproduction of chess patterns* (Vol. 34, Issue 5B). Dissertation Abstracts International (University Microfilms No. AAG73-26954).

Ericsson, K. A., & Charness, N. (1994). Expert performance: Its structure and acquisition. *American Psychologist*, *49*, 725–747. http://psycnet.apa.org/journals/amp/49/8/725/

Glaholt, M. G., & Reingold, E. M. (2012). Direct control of fixation times in scene viewing: Evidence from analysis of the distribution of first-fixation duration. *Visual Cognition*, *20*(6), 605–626.

Gobet, F., & Charness, N. (2018). Expertise in Chess. In K. A. Ericsson, R. R. Hoffman, A. Kozbelt, & A. M. Williams (Eds.), *The Cambridge handbook of expertise and expert performance* (pp. 597–615). Cambridge University Press. https://doi.org/10.1017/9781316480748.031

Gobet, F., & Simon, H. A. (1996a). The roles of recognition processes and look-ahead search in time-constrained expert problem solving: Evidence from grandmaster level chess. *Psychological Science*, *7,* 52–55.

Gobet, F., & Simon, H. A. (1996b). Templates in chess memory: A mechanism for recalling several boards. *Cognitive Psychology*, *31,* 1–40. https://doi.org/10.1006/cogp.1996.0011

Gobet, F., & Simon, H. A. (1996c). Recall of rapidly presented random chess positions is a function of skill. *Psychonomic Bulletin and Review*, *3,* 159–163. https://doi.org/10.1207/s15516709cog2404_4

Gobet, F., & Simon, H. A. (1998). Expert chess memory: Revisiting the chunking hypothesis. *Memory*, *6,* 225–255.

Gobet, F., & Simon, H. A. (2000). Five seconds or sixty? Presentation time in expert memory. *Cognitive Science*, *24*, 651–682. https://doi.org/10.1207/s15516709cog2404_4

Heathcote, A., Brown, S., & Mewhort, D. J. K. (2002). Quantile maximum likelihood estimation of response time distributions. *Psychonomic Bulletin & Review*, *9*(2), 394–401. http://www.springerlink.com/index/p7241345l444446n.pdf

Jongman, R. W. (1968). *Het oog van de meester (The eye of the master).* Van Gorcum.

Kolers, P. A. (1976). Reading a year later. *Journal of Experimental Psychology: Human Learning and Memory*, *2*, 554–565.

Langner, R., Eickhoff, S. B., & Bilalić, M. (2019). A network view on brain regions involved in experts' object and pattern recognition: Implications for the neural mechanisms of skilled visual perception. *Brain and Cognition*, *131*, 74–86. https://doi.org/10.1016/j.bandc.2018.09.007

Reingold, E. M. (2002). On the perceptual specificity of memory representations. *Memory*, *10*(5–6), 365–379. https://doi.org/10.1080/09658210244000199

Reingold, E. M., & Charness, N. (2005). Perception in chess: Evidence from eye movements. In G. Underwood (Ed.), *Cognitive processes in eye guidance* (pp. 325–354). Oxford University Press. http://books.google.com/books?hl=en&lr=&id=PcIsFXd0d3YC&oi=fnd&pg=PA325&dq=Perception+in+chess+:+Evidence+from+eye+movements&ots=1JA2xRvqPk&sig=CYfYwqyhLasofxwOP5bXUiz1PoU

Reingold, E. M., Charness, N., Pomplun, M., & Stampe, D. M. (2001). Visual span in expert chess players: Evidence from eye movements. *Psychological Science*, *12*(1), 48. https://doi.org/10.1111/1467-9280.00309

Reingold, E. M., Charness, N., Schultetus, R. S. S., & Stampe, D. M. M. (2001). Perceptual automaticity in expert chess players: Parallel encoding of chess relations. *Psychonomic Bulletin & Review*, *8*(3), 504–510. http://link.springer.com/article/10.3758/BF03196185

Reingold, E. M., Reichle, E. D., Glaholt, M. G., & Sheridan, H. (2012). Direct lexical control of eye movements in reading: Evidence from a survival analysis of fixation durations. *Cognitive Psychology*, *65*(2), 177–206. https://doi.org/10.1016/j.cogpsych.2012.03.00

Reingold, E. M., & Sheridan, H. (2011). Eye movements and visual expertise in chess and medicine. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *Oxford Handbook on Eye Movements* (pp. 528–550). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199539789.013.0029

Reingold, E. M., Sheridan, H., & Reichle, E. D. (2015). Direct lexical and nonlexical control of fixation euration in reading. In A. Pollatsek & R. Treiman (Eds.), *The Oxford Handbook of Reading* (pp. 261–276). Oxford University Press.

Rennig, J., Bilalić, M., Huberle, E., Karnath, H.-O., & Himmelbach, M. (2013). The temporo-parietal junction contributes to global gestalt perception-evidence from studies in chess experts. *Frontiers in Human Neuroscience*, *7*(August), 513. https://doi.org/10.3389/fnhum.2013.00513

Sheridan, H., Rayner, K., & Reingold, E. M. (2013). Unsegmented text delays word identification: Evidence from a survival analysis of fixation durations. *Visual Cognition*, *21*(1), 38–60. https://doi.org/10.1080/13506285.2013.767296

Sheridan, H., & Reingold, E. M. (2012a). Perceptual specificity effects in rereading: Evidence from eye movements. *Journal of Memory and Language*, *67*(2), 255–269. https://doi.org/10.1016/j.jml.2012.05.005

Sheridan, H., & Reingold, E. M. (2012b). The time course of predictability effects in reading: Evidence from a survival analysis of fixation durations. *Visual Cognition*, *20*(7), 733–745. https://doi.org/10.1080/13506285.2012.693548

Sheridan, H., & Reingold, E. M. (2012c). The time course of contextual influences during lexical ambiguity resolution: Evidence from distributional analyses of fixation durations. *Memory & Cognition*, *40*(7), 1122–1131. https://doi.org/10.3758/s13421-012-0216-2

Sheridan, H., & Reingold, E. M. (2013). The mechanisms and boundary conditions of the Einstellung effect in chess: Evidence from eye movements. *PloS One*, *8*(10), e75796. https://doi.org/10.1371/journal.pone.0075796

Sheridan, H., & Reingold, E. M. (2017). Chess players' eye movements reveal rapid recognition of complex visual patterns: Evidence from a chess-related visual search task. *Journal of Vision*, *17*(3). https://doi.org/10.1167/17.3.4

Simon, H. A., & Barenfeld, M. (1969). Information-processing analysis of perceptual processes in problem solving. *Psychological Review*, *76*, 473–483. http://www.ncbi.nlm.nih.gov/pubmed/5351854

Simon, H. A., & Gilmartin, K. (1973). A simulation of memory for chess positions. *Cognitive Psychology*, *5*, 29–46.

Staub, A. (2011). The effect of lexical predictability on distributions of eye fixation durations. *Psychonomic Bulletin and Review*, *18*(2), 371–376. https://doi.org/10.3758/s13423-010-0046-9

Staub, A., White, S. J., Drieghe, D., Hollway, E. C., & Rayner, K. (2010). Distributional effects of word frequency on eye fixation durations. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(5), 1280–1293. https://doi.org/10.1037/a0016896

Tikhomirov, O. K., & Poznyanskaya, E. (1966). An investigation of visual search as a means of analyzing heuristics. *Soviet Psychology*, *5*, 2–15.

Waters, A. J., & Gobet, F. (2008). Mental imagery and chunks: Empirical and computational findings. *Memory & Cognition*, *36*(3), 505–517. https://doi.org/10.3758/MC.36.3.505

Winikoff, A. W. (1967). *Eye movements as an aid to protocol analysis of problem solving behavior*. Unpublished doctoral dissertation.

Wright, M. J., Gobet, F., Chassy, P., & Ramchandani, P. N. (2013). ERP to chess stimuli reveal expert-novice differences in the amplitudes of N2 and P3 components. *Psychophysiology*, *50*, 1023–1033. https://doi.org/10.1111/psyp.12084

Vaci, N., Edelsbrunner, P., Stern, E., Neubauer, A., Bilalić, M., & Grabner, R. H. (2019). The joint influence of intelligence and practice on skill development throughout the life span. *Proceedings of the National Academy of Sciences*, *116*(37), 18363–18369. https://doi.org/10.1073/pnas.1819086116

Van der Maas, H. L. J., & Wagenmakers, E.-J. (2005). A psychometric analysis of chess expertise. *The American Journal of Psychology*, *118*(1), 29–60. https://doi.org/10.2307/30039042

Wang, F., Hou, X., Duan, Z., Liu, H., & Li, H. (2016). The perceptual differences between experienced Chinese chess players and novices: Evidence from eye movement. *Acta Psychologica Sinica*, *48*(5), 457–471. https://doi.org/10.3724/SP.J.1041.2016.00457

Received: 15 August 2022
Resubmission received: 23 January 2023
Accepted: 9 February 2023