Supporting Online Material for

The Neural Basis of Intuitive Best Next-Move Generation in Board Game Experts

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Materials and Methods

Subjects

All participants were right-handed Japanese males. Informed consent was obtained in accordance with a protocol approved by the RIKEN Research Ethics Committee. In the Perception experiment, 11 professional players (4 to 7 dan, 30.0 ± 2.1 years old, see Fig. S1B for explanation of rank), 8 high-rank (3 to 5 dan, 30.1 ± 2.8 years old, the amateur ranks are offset from the professional ranks) and 9 low-rank (2 kyu to 1 dan, 31.7 ± 2.0 years old) amateur players participated. In the next-move generation experiment, 17 professional (4 to 9 dan, 30.2 ± 1.5 years old) and 17 high-rank amateur players (2 to 4 dan, 32.5 ± 2.3 years old) participated.

Tasks

The quick generation (Fig. S3) and deliberative search (Fig. S4) tasks were combined in single experiments (Next-move generation experiment). The subject first conducted the quick generation task in four sessions, and then the search task in an additional session. Before entering into the MRI scanner and before the fMRI experiments, the subjects were trained for the task of quick generation of the best next move in several short sessions (5~20 problems in each session). The training started with the shogi board presentation for 2 s, and then the presentation time was shortened to 1 s. The problems presented during the training were different from those used during the fMRI experiments. The perception experiment (Fig. S2) was conducted on different days.

Subjects viewed the images through an optic-fiber goggle system (resolution: 800 x 600; refresh rate, 60 Hz). Corrected-to-normal vision was achieved for each individual subject by adjusting the refractive correction pieces built into the goggles or further by wearing a pair of plastic glasses. All visual stimuli (200 × 200 pixels, gray images) were restricted to within 3 degrees of visual angle. The position of the left eye and its pupil size was monitored during experiments to check the eye movement and general state of the subject.

Perception experiment: The activations during the perception of shogi patterns were compared, by block design, with those during the perception of patterns of other board games as well as of scenes, faces, other objects and scrambled patterns. Twenty-four examples of each stimulus category were presented sequentially (200 ms each followed by a 300 ms blank) in each block of 12 s, which was followed by a fixation-only period of 12 s. The subject conducted a one-back recognition task (Fig. S5F).

Quick generation task: We used spot games of shogi, called checkmate problems (Tsume shogi) and brinkmate problems (Hisshi mondai), which mimic the end phase of games. These spot games are played by one person who has to find a series of moves leading to a checkmate (capturing the opponent’s king) even when the opponent makes optimal counter moves. The subjects only reported the first move in our experiments. The use of the spot games excludes the effects of game context and allows extensive repetitions of the mental procedure within a limited experimental period. To avoid frequent attention shifts, we limited the distribution of pieces to positions in one part of the board, a 5 x 5 square region. Since regular checkmate and brinkmate problems often have arrangements of pieces only in a part of the board, this did not create an unnatural situation for the players.

To emphasize the intuitive generation of the best next move and reduce the amount of search processing, we used a short interval (1 s) for the presentation of board patterns (Fig. S3A). After a 1-s presentation of a fixation point, the board pattern of a problem was superimposed on it. The subject was instructed to fix his gaze at the fixation point throughout the trials. The presentation of the pattern
was followed by presentations of four response choices: two candidate next moves, “a move other than the two candidates”, or “no idea”. The subject reported his answer by pressing one of four buttons within 2 s (Fig. S5A). We instructed the subjects to generate the correct next move during the presentation of the pattern and only make a match between the move in mind and choices once the choices appeared. We confirmed in post-experimental interviews that the time was too short even for professional players to figure out the whole sequence of moves to reach checkmate and that the idea of the best next move popped out largely without conscious reasoning. After reporting the move selection, the subject reported his confidence in the move selection (Yes or No) and then reported whether he recalled the particular problem and answer from a previous experience (Yes or No). The few trials in which the subject recalled the problem from a previous experience (8% in professional players and 3% in amateur players) and those in which the subject did not generate any idea (5% in professional players and 13% in amateur players) were excluded from the analyses (Fig. S3B). The length of each trial was 11 s, and during the remaining part of the trial (3 to 8 s) the subject performed a simple detection task: detecting a ‘Gold’ piece (Fig. S1A) among serially presented shogi pieces (150 ms each interleaved by a mask for 100 ms, thus four pieces per second, Fig. S3A). The subject reported the appearance of the ‘Gold’ piece by pressing a button (Fig. S5B). This detection task served to interrupt thinking about the preceding problem. As a sensory-motor control task without generation of a next move, we presented patterns only composed of the opponent’s pieces at the opening phase of game in 60 trials. The subject reported the king’s position, confidence and memory of the pattern in similar ways as checkmate and brinkmate problems (Fig. S5C). We used 180 problems (112 checkmate and 68 brinkmate problems), each of which appeared only once. The 180 trials of checkmate and brinkmate problems and 60 sensory-motor control trials were randomly intermingled.  

**Deliberative search task:** To compare the activations during the quick generation of the best next move with those during deliberative search, we conducted an additional experiment on each subject (Fig. S4). We randomly selected 30 problems from the problems for which the subject failed to report the correct move (either no idea or wrong answers) in the preceding quick generation experiment. The pattern of a problem was shown for a longer time (up to 8 s). The subject pressed a button when he found the correct move, and then four choices appeared in the same format as that used in the quick generation experiment. If the subject did not press the button within 8 s, the presentation of the pattern was automatically replaced by four choices. The average period of the problem presentation was 5.9 s and 7.3 s for professional and amateur players, respectively (Figs. S5D and S5E). The length of each trial was 16 s, and during the remaining part of the trial (5 to 13 s), the subject performed the ‘Gold’-piece detection task.

**MRI specifications**

All MRI experiments were conducted using a 4 T MRI system with a head gradient coil. A bird-cage radio-frequency (RF) transmit-receive coil was used for the fMRI experiments. A combination of a bird-cage RF transmit coil and a whole-brain “Duyn” phase-array receive coil system coupled with 4 surface coils was used for high-resolution anatomical structure scanning.

**Perception experiment:** Functional images were acquired with a four-segment centric-ordered, gradient echo T2* echo-planar imaging (EPI) sequence with volume TR of 2.5 s, TE of 25 ms, slice thickness of 3.75 mm and in-plane resolution of 3.75 x 3.75 mm² (FOV: 24 x 24 cm², FA: 40 degrees). Fifteen slices with interleaved acquisition were collected in an oblique orientation at 30 degrees tilted from the AC-PC line, almost parallel to the parieto-occipital sulcus. The scanned area covered most of occipital visual cortex, all of the temporal cortex, parietal cortex, hippocampus and thalamus, most of cerebellum and basal ganglia.
**Next-move generation experiment:** Functional images were acquired with a two-segment centric-ordered, gradient echo T2* EPI sequence with volume repetition time (TR) of 2 s, echo time (TE) of 15 ms, slice thickness of 5.5 mm and in-plane resolution of 3.75 x 3.75 mm² (field of view [FOV]: 24 x 24 cm², flip angle [FA]: 40 degrees). Twenty-one axial slices with interleaved acquisition were taken parallel to the AC-PC line.

In both experiments, longitudinal magnetization was allowed to reach steady state before EPI images were collected (5 volumes). A full volume without phase encoding was taken at the beginning of each scan and used to correct the phase artifacts (1). The first three echoes in each segment were navigator echoes, which were used to correct phase errors and inter-segment amplitude variations (2). Heartbeat and respiration were recorded along with the timing of RF pulses for later corrections for physiological fluctuations. In-plane 2D anatomical images were also collected with a four-segment T1-weighted inversion recovery FLASH sequence. Accompanying low-resolution 3D T1-weighted anatomical images (resolution: 1.72 x 1.72 x 1.72 mm³) in each experiment were also scanned in the same slice orientation as in the corresponding functional scan. High-resolution T1-weighted anatomical images (resolution: 1.00 x 1.00 x 1.00 mm³) were acquired on different days.

**Data analyses**

After EPI image reconstruction, cardiac and respiratory artifacts were reduced using a retrospective estimation and correction method in the k-space (3). The further image processing and analyses were performed using BrainVoyager. First, the slice scan acquisition timing was corrected. To correct for the rigid head motion, all EPI images were realigned to the first volume of the first scan. Data sets in which the translation motions were larger than 1.0 mm or the rotation motions were larger than 1.0 degree were discarded. Functional EPI images were then registered, first on the 2D anatomical MR images, then on the low-resolution 3D T1 images, and finally on the high-resolution 3D T1 images. They were spatially transformed into Talairach space (4) by resampling the data with a resolution of 3 x 3 x 3 mm³. A spatial smoothing with a 4-mm gaussian kernel (full width at half-maximum) was applied to the data of the next-move generation experiment, whereas no spatial filtering was applied to the data of the perception experiment. A high-pass temporal filtering with a cutoff of 0.005 Hz was applied to all fMRI data.

**Identification of activations associated with the perception of shogi patterns:** Statistical modeling was performed using a box-car function (12 s) for each stimulus category convolved with a canonical, two-gamma haemodynamic response function (HRF). Board-game-relevant ROIs were defined in each subject by comparing the board game categories with the other stimulus categories in voxel-wise statistics. ROIs were defined in individual subjects, but not on the group, because the exact position of the precuneus activation varied among the subjects. The time course of activation in each ROI (10 mm box centered at the maximum of hot spot) in each subject was then calculated. Statistical tests of response selectivity for shogi patterns were carried out on the mean fMRI responses averaged over the third, fourth and fifth time points (7.5, 10 and 12.5 s after the stimulus-series presentation onset). The mean responses were compared between each pair of stimulus categories.

**Identification of activations associated with quick generation of the best next move:** Statistical parametric maps were created using multiple regression analysis. Each trial was modeled with three regressors defined for the three phases, respectively: 1) presentation of the shogi patterns plus the response time difference in each trial, which was regarded as the time of quick generation of the best next move, 2) the period of questions and answers about the confidence and memory and 3) the period of ‘Gold’-piece detection. The response time difference is the time obtained by subtracting the response time in individual trials by the averaged response time that the subject spent in the sensory-motor control task. These regressors were then convolved with a canonical, two-gamma HRF.
Activations associated with the sensory-motor control task were analyzed in the same way. The regression beta coefficients were computed in each individual subject and then put into a group random effect analysis of variance. We used a family-wise error rate for multiple comparison correction, namely, minimum cluster size threshold. The thresholds were determined referring to the AlphaSim tool from AFNI (5) to acquire the overall significance level of $\alpha < 0.001$. Unless otherwise noted, $p < 0.001$ and 15 voxels were used as thresholds.

For the correlation analysis of the strength of activity in the caudate head with the percentage of correct responses in the quick generation task (Fig. 3B), all the trials including those where the subjects had no ideas or no responses, but excluding those where the subject recalled the prior experience of the given pattern and the best next move for the pattern from memory, were collapsed together to estimate the parameters for both fMRI activity and behavioral responses. For each subject, the percentage of correct responses was calculated, and the mean beta coefficient was averaged from the anatomical caudate head ROI.

**Region of interest (ROI) definition:** For the quantification of activation, the anatomical caudate head ROI was defined by the structural image in individual subjects for both professional and amateur players. The DLPFC, PMd, preSMA and precuneus ROIs were defined by the voxels activated during the quick generation of the best next move compared with the activity during ‘Gold’-piece detection in the quick generation task using conjunction analysis across the professional and amateur groups ($p < 0.001$, uncorrected).

**Identification of activations associated with deliberative search:** Two regressors were used to model each trial, one for search during the shogi-pattern presentation and the other for detecting a ‘Gold’ piece. The ‘Gold’-piece detection phase was used as the control condition.

**Functional connectivity analysis:** 1) ROIs were defined as described above. 2) Mean response of each subject in each trial in each ROI was calculated by averaging fMRI signals over voxels in the ROI and summing along time with weights of the two-gamma haemodynamic response function locked to the phase of pattern presentation. 3) In each subject, the responses in individual trials were sorted according to the subject’s response type, and the mean response averaged over trials was subtracted from the individual-trial responses to calculate deviations of responses from the mean in individual trials. 4) In each subject, linear regressions were calculated between pairs of ROIs. 5) The mean correlation coefficients were averaged across subjects in either subject group. 6) The correlation coefficients were converted to a normal distribution by Fisher’s transformation (6). The statistical significance of the correlation coefficient differences across the conditions and groups were calculated by Z-test. Because the individual time points of fMRI signals in each trial are not independent, the degrees of freedom were modified by Bartlett correction factor (6).

**Post-experimental interview**

On separate days after the experiments, we interviewed seven professional and seven amateur players, who participated in the next-move generation experiment.
Fig. S1. Overview of shogi. (A) Eight types of shogi pieces and their movability. Many of the pieces have corresponding types in chess with identical movability, whereas some are unique to shogi, such as Gold, Silver and Lance. In shogi, the Knight can only move to one of two forward positions, and the Pawn can take the opponent’s piece at the position one square directly forward (oblique forward in chess). There is no analog of the chess Queen. (B) Starting setup. Only the own side is shown. There is only one Rook on the right side and one Bishop on the left side (two Rooks and two Bishops in chess). (C) Three examples of typical arrangements of pieces to protect the king. From the left to the right, examples of Yagura gakoi, Mino gakoi and Anaguma gakoi. (D) Ranking system of shogi players. The professional rank is offset from the amateur rank. Amateur rankings range from 15 kyu (the lowest) up to 1 kyu and then 1 dan to 6 dan (the highest). Professional rankings start from 6 kyu (the lowest) and go up to 1 kyu and then 1 dan to 9 dan (the highest). Players with ranks up to 3 dan on the professional scale are not yet fully professional, but in the preparatory step to become professional.
Legend of Fig. S1 continued

Other differences between shogi and chess

Shogi is a board game native to Japan. It is similar to chess in several aspects including the game objective, which is to take the opponent’s king (checkmate). However, shogi is different from chess in the following points.
1) The board is composed of 9 by 9 positions (8 by 8 in chess).
2) There are eight types of pieces (six in chess).
3) Six types of pieces can be promoted to be stronger types (with wider movability) when they enter the bottom three rows in the opponent’s side.
4) The opponent’s pieces taken from the board stay in reserve for later use. When the player wishes, instead of moving an existing piece, the player can drop any reserve piece to any empty position of the board as an ally piece. This is called the “drop rule.”

Promotion provides the Rook and Bishop with the movability of King in addition to their original movability, and converts Silver, Knight, Lance and Pawn to Gold. When promoted pieces are taken by the opponent, they return to their original types.

The drop rule (4th point above) provides shogi games several characteristics different from chess games. First, it is much more popular to sacrifice pieces for strategic purposes, because comparable pieces may be later recovered. Secondly, the number of possible moves is larger, because any piece in the reserve can be dropped to any empty position (but more than one pawn in a vertical line are not allowed). Thirdly, the number of pieces on the board does not decrease toward the end of game.

The opening phase of a shogi game is usually used to make an arrangement of pieces circumscribing the king for defensive purposes (kakoi). Fig. S1C shows three examples of such defense arrangements representing three popular types (Yagura gakoi, Mino gakoi and Anaguma gakoi, “kakoi” is changed to “gakoi” for the easiness of pronunciation). There are no such large-scaled defense arrangements in chess games. The total number of moves in an average game is larger (140 moves in shogi; 80 moves in chess, in an average game among top players). Computer programs for playing shogi have not yet won games with top-level professional players, unlike chess (a computer chess program defeated the world champion in 1997).
Fig. S2. Perception experiment. (A) Time sequence. Twelve-second blocks of stimulus presentation were alternated with 12 s periods of fixation only. In each block of stimulus presentation, 24 examples of one stimulus category were presented sequentially (200 ms each, followed by a 300 ms blank). Each subject went through four sessions, each of which had 22 or 23 stimulus presentation blocks (90 blocks altogether). Each stimulus category was presented in 10 blocks, which were distributed randomly throughout the four sessions. The subjects conducted one-back recognition task during the stimulus presentation: they reported an immediate repetition of a stimulus by pressing a button. During the fixation-only period, the fixation cross occasionally changed color, at which time the subject had to press a button. (B) Examples of 9 stimulus categories. The opening and endgame patterns were randomly taken from the database of professional players’ tournament games (http://wiki.optus.nu/shogi/). The random patterns were generated by randomly shuffling piece positions of realistic patterns within the constraints of shogi rules. The chess and Chinese chess patterns were also randomly taken from tournament games. The patterns were limited to 5 x 5 squares for all the board game patterns. In separate experiments, area MT was localized in 6 subjects (3 professional and 3 amateur players), by comparing a random dot motion (white dots on black background; visual angle, 10 degrees; 1% density; dot radius, 0.1 degree; 12 s) with a stationary dot pattern (12 s).
**Fig. S3.** Quick generation and sensory-motor control tasks. (A) Sequence of events in a trial. After 1 s of initial cue presentation, a shogi pattern (checkmate or brinkmate problem) was presented for 1 s, during which the subject generated the best next move. After reporting their move choice, confidence level and whether or not that problem had been encountered before, the subject engaged in ‘Gold’-piece detection during the remaining time left in the trial (roughly 3-8 s). In the sensory-motor control task, an opening shogi pattern only composed of the opponent’s pieces was presented, and the subject reported the king’s position. (B) Proportions of responses in professional (left) and amateur (right) players in the quick generation task. “No idea” represents the trials in which the subject selected “No idea” or made no responses in the first report. “Memory” represents those in which the subject selected “Yes” in the memory report. The data from “no idea” or “memory” trials were not included in the activation analyses. The other trials were categorized as “Confident” or “Unconfident” according to their confidence report, and “correct” or “error” according to the correctness of the move chosen.
Fig. S4. Deliberative search task. The sequence of events in a trial is shown. After 1 s of initial cue presentation, a shogi pattern (checkmate or brinkmate problem) was presented. The pattern was replaced by four choices either when the subject had found a correct next move and pressed a button or when 8 s had passed. After reporting his move choice, the subject engaged in ‘Gold’-piece detection during the remaining time left in the trial. The total length of each trial was 16 s.
**Fig. S5.** Behavioral data. (A) Mean response time in the quick generation task. (B) Percentage of correct responses in the ‘Gold’-piece detection in the quick generation task. (C) Percentage of correct responses in reporting the position of the opponent’s king in the sensory-motor control task. (D) Mean time from the onset of the board pattern to the button press in the deliberative search task. The board pattern was automatically replaced with the response choices when 8 s had passed. (E) Percentage of correct responses in the deliberative search task. (F) Percentage of correct responses in detection of repetitive presentation of the same image in the perceptual experiment. The error bars indicate SEM across subjects. Type 1, correct responses with confidence; Type 2, correct responses without confidence; Type 3, erroneous responses without confidence; Type 4, memory; Control, opponent’s king detection (sensory-motor control). Pro: professional group; Ama1: high-rank amateur group; Ama2: low-rank amateur group. OS: opening shogi; ES: endgame shogi; RS: random shogi; CH: chess; CC: Chinese chess; SC: scene; FA: face; OB: object; SR: scrambled image.
Fig. S6. Activations associated with perception of board-game patterns in amateur players. (A) Cortical regions that responded more strongly to board game patterns than to other non-game stimuli shown on the flattened cortical map by yellow and orange ($p < 1.0 \times 10^{-8}$ corrected and $p < 0.001$ corrected, respectively), shown for two subjects representing a high-rank amateur player (amateur 4 dan, Ama1) and low-rank amateur player (amateur 1 dan, Ama2), respectively. For comparison, the fusiform face area (FFA) in the ventral temporal cortex that responded more strongly to faces than to scrambled images, the parahippocampal place area (PPA) in the parahippocampal cortex that responded more strongly to scenes than to scrambled images, and MT in the posterior bank of the inferotemporal sulcus that responded more strongly to moving than stationary random dot stimuli ($p < 0.005$ by t-test) are shown by different colors. POS, parieto-occipital sulcus. (B) Activations in the posterior precuneus in the same two amateur subjects as those in (A).
Fig. S7. The time courses of caudate head activations during the quick generation of the best next move in the professional (upper) and amateur players (lower). Gray bars above the abscissae indicate the shogi board presentation period, and error bars indicate SEM across subjects. Blue lines, trials with confidence; Red lines, trials without confidence; Gray lines, sensory-motor control trials in which the subject reported the position of the opponent’s king.
**Figure S8.** Activations associated with quick generation of the best next move and deliberative search in amateur players. (A) Activations associated with quick generation of the best next move. There was no significant activation in the caudate head. (B) There was no activation when the activations during the quick generation of the best next move was contrasted to the activity during the sensory-motor control task ($p > 0.01$). (C) Activations associated with deliberative search.
Table S1. Brain activations in the professional group associated with the quick generation of the best next move and deliberative search as contrasted with the ‘Gold’-piece detection ($p < 0.001$ with cluster-size threshold of 15)

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Table S2. Brain activations in the amateur group associated with the quick generation of the best next move and deliberative search as contrasted with the ‘Gold’-piece detection ($p < 0.001$ with cluster-size threshold of 15)

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<td>L -22</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>R 22</td>
<td>-7</td>
</tr>
<tr>
<td>precuneus</td>
<td>L -12</td>
<td>-69</td>
</tr>
<tr>
<td></td>
<td>R 14</td>
<td>-70</td>
</tr>
<tr>
<td>middle temporal gyrus</td>
<td>L -28</td>
<td>-77</td>
</tr>
<tr>
<td></td>
<td>R 27</td>
<td>-70</td>
</tr>
<tr>
<td>parahippocampal gyrus</td>
<td>L -28</td>
<td>-35</td>
</tr>
<tr>
<td></td>
<td>R 26</td>
<td>-34</td>
</tr>
</tbody>
</table>
**Table S3.** Logistic regression of the probability of correct next-move generation in professional and amateur players

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>Standard error of mean</th>
<th>T value</th>
<th>Significance (P)*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Professional</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>0.5960</td>
<td>0.1937</td>
<td>3.08</td>
<td>0.004</td>
</tr>
<tr>
<td>$\beta_{\text{steps}}$</td>
<td>-0.0319</td>
<td>0.0220</td>
<td>1.45</td>
<td>0.083</td>
</tr>
<tr>
<td>$\beta_{\text{moves}}$</td>
<td>-0.0087</td>
<td>0.0068</td>
<td>1.28</td>
<td>0.109</td>
</tr>
<tr>
<td>$\beta_{\text{RT}}$</td>
<td>-2.1374</td>
<td>0.4147</td>
<td>5.15</td>
<td>4.84e-05</td>
</tr>
<tr>
<td>$\beta_{\text{Type}}$</td>
<td>-0.0778</td>
<td>0.1651</td>
<td>0.47</td>
<td>0.322</td>
</tr>
<tr>
<td><strong>Amateur</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>-0.0724</td>
<td>0.1280</td>
<td>-0.56</td>
<td>0.290</td>
</tr>
<tr>
<td>$\beta_{\text{steps}}$</td>
<td>-0.0434</td>
<td>0.0296</td>
<td>1.47</td>
<td>0.080</td>
</tr>
<tr>
<td>$\beta_{\text{moves}}$</td>
<td>-0.0041</td>
<td>0.0039</td>
<td>1.05</td>
<td>0.155</td>
</tr>
<tr>
<td>$\beta_{\text{RT}}$</td>
<td>-1.0748</td>
<td>0.2936</td>
<td>3.66</td>
<td>0.001</td>
</tr>
<tr>
<td>$\beta_{\text{Type}}$</td>
<td>0.1464</td>
<td>0.1436</td>
<td>1.02</td>
<td>0.162</td>
</tr>
</tbody>
</table>

*Probability of false alarm of the conclusion that the difference of mean from 0 was significant.

**Methods:** We used the multiple logistic regression to analyze the factors that modulated the probability of the correct next-move generation. The probability was represented by

$$ z = \beta_0 + \beta_{\text{steps}}N_{\text{steps}} + \beta_{\text{moves}}N_{\text{moves}} + \beta_{\text{RT}} RT + \beta_{\text{Type}} Type + \epsilon \quad (1) $$

$$ p = \frac{1}{1 + \exp^{-z}} \quad (2) $$

where $N_{\text{steps}}$ represents the number of steps to reach the final checkmate, $N_{\text{moves}}$ the number of possible next moves, RT the response time and Type the type of problem (checkmate or brinkmate). The regressors ($\beta_0$, $\beta_{\text{steps}}$, $\beta_{\text{moves}}$, $\beta_{\text{RT}}$, $\beta_{\text{Type}}$) were estimated by fitting the probability distribution of the model with the distribution of real choices across trials in each subject. Then, the random effect statistical analysis across subjects in either professional or amateur group showed that the probability of correct responses was only significantly modulated by the response time ($p<0.00005$ for the professional group and $p<0.001$ for the amateur group). The mutual correlation between $N_{\text{steps}}$, $N_{\text{moves}}$, RT and Type was very weak ($r^2 < 0.07$), which is a necessary condition for this analysis. These covariates were orthonormalized by Gram-Schmidt method before regression. Only $\beta_{\text{RT}}$ was significantly different from 0, which means that the probability of correct responses depended only on the reaction time among the four variables.
References


