CHESS AS A BEHAVIORAL MODEL FOR COGNITIVE SKILL RESEARCH: REVIEW OF BLINDFOLD CHESS *BY ELIOT HEARST AND JOHN KNOTT*

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Hearst and Knott's multifaceted work on chess played without sight of the pieces is not only the definitive compendium on this topic, including a detailed review of the history of blindfold chess, but also a sophisticated psychologist's examination of chess skill. This review builds on the authors' assertion that chess can provide a uniquely revealing model for research on several issues in the area of cognitive skills and visualization. Among these are the relationship between contemporaneous perception and imagery in light of relevant fMRI and other studies, and the formation of larger functional units as a skill increases. It describes a potential research methodology for measuring and quantifying an individual's skill shortfall from a theoretical maximum. This approach, based on a 1951 proposal by Claude Shannon, is applicable in any choice situation in which all the possible choices are known. The proposed measure reflects the time consumed and the equivalent number of "yes-no questions" that would have been required to arrive at a best choice. It has a wide range of applications in cognitive skill research, skill training, and education, and provides a valid way to compare different skills and the effects of different independent variables for a given skill.

Key words: Chess research, visualization, mental imagery, perception, cognitive skills, conceptualization, mental practice, skill measurement and training, creativity, choice research, memory, representations.

Introduction

Perhaps the reason two-player strategy games like chess often fascinate psychologists is that such games, along with mathematics, music, and other arts, have produced displays of virtuosity sometimes viewed as pinnacles of human achievement. One of the more dazzling feats of this sort is blindfold chess—the subject of Hearst and Knott's book. Blindfold chess is played without sight of the chessboard or pieces, with the moves being called out.

Some psychologists have described such feats as "remarkable adaptations to narrowly defined demands," or as a research medium for probing how training can modulate the results of genetic endowment (Ericsson & Charness, 1994; Gobet & Charness, 2006). The authors suggest reasons why this topic should interest behavior researchers, neurobiologists, psychologists, and educators.

Eliot Hearst straddles the worlds of chess and psychology at the highest levels. By age 21 he had already achieved national and international prominence as one of the most talented and promising senior chess masters of his generation. He is pictured in the 1952 photo below with the three other members of the Columbia College chess team of which he was the captain.

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In 1962 he captained the United States Olympic Chess Team. Hearst did his graduate work at Columbia University under Professor W.N. Schoenfeld and then achieved prominence once again, this time as a behavior researcher (Hearst, 1971, 1988; Hearst & Sidman, 1961), while a professor at the University of Missouri, Indiana University, The University of California at Berkeley, Columbia University, and The University of Arizona. The other author, John Knott, is a lifelong researcher and prominent authority on blindfold chess.[1]

The book clearly stands as the definitive compendium on the topic of blindfold chess. Chess players have already expressed admiration for the depth of its scholarship, including the authors' painstaking and masterful analysis of some 444 historically

[1] For more information on the authors, see www.blindfoldchess.net.

significant blindfold chess games, and psychologically flavored biographical sketches of history's greatest blindfold chess masters.[2]

Psychologists will be particularly interested in the chapters "Research on General Chess Skill" and "Psychological Studies and Commentaries on Blindfold Chess" (pp. 151-190),[3] which review much of the salient research literature on those topics, starting with the work of Alfred Binet and continuing with that of Alfred Cleveland, several Russian psychologists, Adrian de Groot, Herbert Simon, William Chase, Dennis Holding, Fernand Gobet, Neil Charness, Christopher Chabris, and many others, including Hearst himself.

Interesting findings

In their review of the literature, the authors document a number of conclusions that may be interesting and sometimes surprising to chess players and non-chess players alike:

- The memory of chess masters, including those able to play many blindfold games simultaneously, is no better than that of the average person, and is specific to chess.
- No other skill, faculty, behavioral attribute, or cognitive ability has yet been found to be predictive of proficiency in chess.
- Highly skilled players can form long-term memories of full-board chess positions within seconds of viewing them.
- High level chess skill (not just blindfold chess) requires a recognition-action repertoire of some 50,000 to 100,000 features of chess positions, with an associated response repertoire, and knowledge applicable to the evaluation of chess positions.

[2] It has been reviewed very favorably in 17 publications and won the Fred Cramer Award for Best Chess Book of 2009.
[3] Page numbers in the citations refer to the book being reviewed.

- Blindfold chess masters consistently report that what they visualize are not pieces or chessboards, but abstractions of these with minimal or no physical features. The typical report is, “I do not visualize real pieces but I know where they are.”
- Some of the strongest masters assert that the sight of actual pieces on a board is often more distracting than helpful in visualizing future positions when thinking ahead during a game.
- Practicing blindfold chess may improve sighted chess skill, presumably by improving the visualization component of sighted chess skill.
- Some of the strongest blindfold chess masters claim that the strength of their blindfold play is similar to that of their sighted play.

Another possible conclusion that some may find surprising—one that the authors do not state explicitly but that a reader may reach—is that the skill of playing many blindfold chess games simultaneously is not different in kind from many more mundane skills.

This conclusion may be made plausible by considering the following imaginary situation: On a long table in front of you sit six telephones, each with someone at the other end of the line. You are rotating among six simultaneous conversations on topics that are familiar to you—for instance a newly opened restaurant, a front page newspaper article you both read this morning, and so forth. As you pick up each phone you hear the last thing the person at the other end said. Clearly, you would have no problem remembering the status of each conversation as you decide what to say next. The verbal behavior, memory, and knowledge you would be exhibiting in each of the six conversations may be no less complex than a chess master’s behavior of playing six simultaneous blindfold chess games, because for a master, a chess game is very much like a conversation. Many of the commonplace multi-tasking activities in which we engage whenever we rotate among several complex tasks place requirements, much as does blindfold chess, on visualization skills and knowledge acquired over a lifetime of learning. The fact that blindfold chess is an arcane activity governed by arbitrary rules can easily lead one to view it, without any scientific justification, as more complex than the many equally intricate commonplace activities we take for granted (Marr, 2003; Weisberg, 1987, 1993), but it may not be.

Chess as a unique research model

The book draws attention to a number of theoretical issues, mostly in the realm of cognitive behavior, that have received little attention in the behavior analytic literature and which behavior analysts have largely abandoned to others, possibly for lack of a methodology with which to address them (Staddon, 2001; Marr, 2003; Foxx & Faw, 2000). One objective of this review is to propose a quantitative research methodology that may enable behavior analysts to address such issues and thus continue to reclaim this important domain.

The features that should make chess interesting to behavior analysts as a uniquely useful model for cognitive behavior research are these: the choices (chess moves) are discrete, all in the same modality, involve purely cognitive behavior, are suitable for registration and quantitative evaluation by computer, and the number of available choices in a given position (supposedly 37 on average) is convenient. Furthermore, the skill levels of chess players are quantitatively scalable and span a range that is wide enough to provide a useful independent variable for most research purposes.

Those may be some of the reasons why the authors state (pp. 150-151), as does former world chess champion Garry Kasparov (2010), that chess can serve as a useful laboratory model for research in skill areas even beyond chess. Chess has, in fact, been dubbed “the drosophila of cognition research and psychometrics” (Chase & Simon, 1973; Van der Maas & Wagenmakers, 2005; p.150). This review will attempt to show how the above-listed features of the chess model make available a research methodology applicable to a wide variety of problems that require quantitative measurement of skill and knowledge.

The experimental study of skill outliers (“creativity?”)

The terms “creativity,” “originality,” and “imagination” have been applied mainly in realms like music, art, literature, and mathematics, where the behavioral phenomena involved and their controlling variables tend to be elusive. The laboratory study of such phenomena would require a methodology that offers plausible definitions of these phenomena in terms of scalable and measurable variables. This review attempts to show how the chess model makes such a methodology available.

Chess players can often agree fairly well on the degree to which chess moves are “brilliant,” “creative,” “imaginative,” “original,” or “beautiful” (Margulies, 1977). Grandmaster tournaments often award a special “brilliancy prize” for the game that contained the most “brilliant,” “imaginative,” or “creative” move or combination of moves. Games described in these terms generally achieved the win by sacrificing material for an advantage that was difficult to foresee, or by violating standard heuristics and algorithms.

The ways in which the research-relevant features of chess discussed in the preceding section hold out the promise of a methodology for studying such behavior will be discussed in greater detail in the later section titled “A model for the study of creativity and imagination.”

Seeing and Visualizing

One of the theoretical issues to which the book draws attention is the relationship (similarities and differences) between contemporaneous perception of external stimuli that involve light falling on the retina, (which we will call “Seeing”[4]), and visualizing, or imaging, where there is no contemporaneously present external stimulus or retinal involvement (which we will call Visualizing or Visualization[5]). To address this issue, we need to determine what the behaviors of Visualizing and Seeing have in common and how they differ.[6] The radical behaviorist conceptualization of Visualizing as “internal seeing” or “seeing a stimulus in its absence” (Moore, 2008; Skinner, 1953, 1974), does not speak to what behavior is involved in either Seeing or Visualizing, or to how Seeing and Visualizing differ from each other.

It must be noted at the outset that Visualizing is not simply a delayed (non-contemporaneous) perceptual response. Most chess positions visualized in blindfold play or when thinking ahead in sighted play (chess players usually call this “calculating”) have not been seen before. Similarly, we can easily imagine novel sentences, melodies, or scenes that we have never actually heard or seen. One explanation for this is that visualizations or imagings

[4] When the terms “seeing” and “visualizing” are used as defined technical terms, as here, they will be shown capitalized.
[5] The terms most often used in the psychological literature are “mental imagery” and “visual mental imaging” but this review will continue to use the authors’ term “Visualizing” and “Visualization.” The internal hearing counterpart of visualizing has been termed “auditory imagery,” (Smith, Reisberg, & Wilson, 1992).
[6] This discussion of Seeing bypasses the extensive vision literature (e.g., Bruce, Georgeson & Green, 2003; Marr, 1982, Noë, 2004) which deals with issues that are not directly relevant here.

can consist of recombinations, rearrangements, or syntheses of parts, features, components, or other attributes of previous perceptions—visual, auditory, conceptual, relational, or abstract ones.[7]

Differences between Seeing and Visualizing

- Seeing involves the retina while Visualizing does not.
- Seeing is associated with a contemporaneous stimulus while Visualizing is not, nor with a stimulus that has necessarily *ever* been perceived.
- In Seeing, one can scan and interrogate the stimulus to answer questions (which can be self-generated) regarding minor details, while in Visualizing, where there no source of reflected light and no visible scene that can be scanned and interrogated for minor details, one cannot. In the case of Seeing a chess position, for instance, one can readily answer questions regarding the color, shape, surface characteristics, or sizes of the chess pieces or chessboard, or the source of the illumination, while in Visualizing one cannot.[8]

Seeing also usually involves behavior often referred to as "recognizing" or "noticing" various features of the stimulus. However such behavior is defined, it is always based on a history of concept learning. We will refer to these types of responses as Conceptualization. Examples of Conceptualization responses are, "I recognize this," "I know what or who that is, it is X," and, "It is not Y," but the concepts "recognized" can be as different as the face of a person or the truth of a written statement.

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[7] Much of what we call thinking, too, may consist of covert recombination and reassembly of such components into novel configurations (Bar, 2007; Mechner, 1992, pp. 10-11).

[8] One might speculate that this scanning-interrogation feature is responsible for the subjective experience of "seeing" a visual scene with all its richness of detail and complexity.

Chess masters' protocols regarding their Visualizations

Non-chess players may be surprised to learn that blindfold chess masters report that they definitely do not visualize images of actual chess pieces or of chess boards when they play blindfold chess. Various top masters describe what they do in such terms as "no mental pictures," "abstract knowledge," "I know where the pieces are," "no real picture," "only an abstract type of representation," "relationships," "the significance of a piece," "knowing which combination or plan is in progress," "lines of force," "pieces are only friend or foe, carriers of particular actions," "sort of formless visions of the positions," and so forth Many of these masters reported that they have no visual image at all (p.151).[9]

Such introspective reports and protocols, being unverifiable by objective measurement, generally tend to be accorded low status as behavioral data.[10] It is, however, striking that almost all chess masters describe what they do in very similar terms, and this consistency, in conjunction with the relative inaccessibility of the underlying events, suggests that here may be an instance where such "introspections" should be considered.[11]

The Traditional View

The reason the masters' protocols may be surprising to some is that they contradict the widespread traditional (but

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[9] This reviewer, who himself once had a chess master rating and has played simultaneous blindfold chess, would describe his Visualizings in the same terms as those reported above, and can corroborate from personal knowledge that most chess masters who can play blindfold chess (and most can) would report likewise.

[10] For an analysis of the conceptual issues concerning the status of introspective verbal reports, see Locke (2009).

[11] The authors quote Chabris' (1999) explanation of these protocols as follows: "Expertise in visual-spatial domains such as chess is based on the development of cartoon-like representations of the domain's important properties… cartoons highlight important information and obscure unimportant information." (p.177)

unfounded) view that what is Visualized is an image or copy of a visual stimulus, in the sense of an isomorphic (point-for-point) reproduction, retrieval, or reconstitution (Kosslyn, Thompson & Ganis, 2006). When applied to blindfold chess, this view would hold that what is visualized is the "image" (in the sense of a copy or visual reproduction) of a chess position.

The masters' protocols clearly support the interpretation that what is visualized or recalled is not a visual image or mental copy at all, but rather Conceptualizations—the same *learning-history-based conceptual responses to the stimulus* that also occur in Seeing, and that these Conceptualization responses do not include any copy or reproduction—they are *the very same* responses. Examples of such Conceptualization responses might be, "I know which square each piece occupies" and "I know the relationships of the pieces in this situation." [12]

Status of the copy/reproduction conjecture

It is important to note that the traditional copy/reproduction view is nothing more than a conjecture about subjective experiences or private events of others, and may be based largely on the fallacious reasoning that the retinal image, when "transmitted" to the brain, will be "seen"[13] (Bennett & Hacker, 2003; Noë, 2004). This copy/reproduction conjecture and the chess masters' protocols, which contradict it, are both reports

[12] The fact that in Visualizing, certain types of questions and answers are linked to spatial/geometric aspects of the stimulus and may involve the eye muscles (e.g., Donahoe & Palmer, 1994, pp. 253-256) cannot be interpreted to mean that what is visualized is a copy or reproduction of an image, as Conceptualizations too can be linked to or associated with spatial/geometric properties and eye movement. Similarly, the studies discussed by the authors on pp. 168-169, in which the dependent variable is time needed to accomplish tasks involving mental manipulation of shapes or reading a recalled map, cannot be interpreted as differentiating between (a) a visualized reproduction or copy of images and (b) the operation of history-based abstract or conceptual processes.
[13] By whom? This is the "homunculus/infinite regress" issue.

regarding internal events, but the chess masters' protocols are direct and consistent first-hand reports by the subjects themselves, while the traditional copy/reproduction conjecture is second-hand—a speculative attribution to others of presumed experiences.

In the following discussions, what the chess masters say they do will continue to be referred to as "Conceptualization." A more cumbersome expression might be "Non-representational abstract visualization."[14] Another possibility would be "abstraction," but Conceptualization has the advantage of referencing our knowledge of concept learning and learning histories, while the term "abstraction," though more widely used, has its roots in other disciplines.

Similarities between Seeing and Visualizing

The differences discussed above between Seeing and Visualizing are fairly obvious, but the fMRI research findings that Seeing and Visualizing activate the same or very similar brain areas (Kosslyn, 1980, 1994; Borst & Kosslyn, 2008; Mechner, 1994, pp. 28-29; Richardson, 1999; Wheeler, Peterson & Buckner, 2000)[15] suggest that Seeing and Visualizing must have some behavior in common. For that behavior, we need look no further than Conceptualization—the learning-history-based conceptual behavior that occurs in both Seeing and Visualizing. Much the same Conceptualization behavior reported by the blindfold chess masters when they describe their Visualization also occurs when

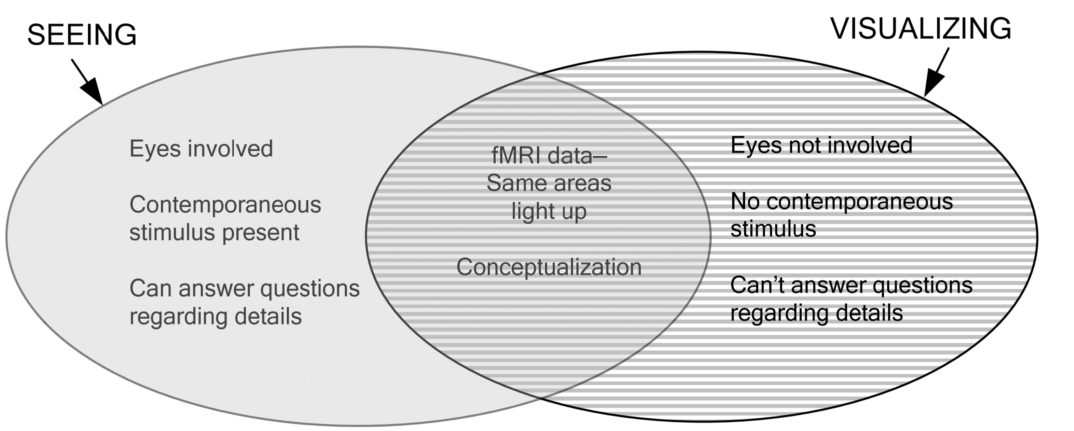
[14] The term "representation" is being avoided here because it has been used in such a multiplicity of senses in cognitive neuroscience that it has lost its usefulness (Bennett & Hacker, 2003). It has been used in the senses of isomorphic mappings (copies) of visual images, the reproduction or retrieval of an image (Huk, 2008), and conceptual or abstract responses (Martin, 2007). The term confounds these meanings, while our purpose here is to distinguish between them.

[15] The same findings have also been reported for audition (Reisberg, 1992; Intons-Petersen, 1992; Naatanen, 1985; Smith, Reisberg, & Wilson, 1992), and for olfaction (Bensafi et al., 2003.)

they have sight of a board and pieces. We may infer that the same is true in domains other than chess that also involve Seeing and Visualizing.

The results of the fMRI studies have sometimes been misinterpreted as evidence for a possible neural reproduction, retrieval, or mapping of the physical features of the stimulus image (Edelman, Grill-Spector, Kushnir & Malach, 1998; Kourtzi & Kanwisher, 2001)—a sort of reconstitution of the retinal image to form a copy. But the chess masters say that they don't have such an image or copy, nor is there a need to postulate one. The fMRI findings can be fully explained by postulating that both Seeing and Visualizing include similar Conceptualization responses without image or copy attributes. Functions like the scanning and interrogating behavior that can occur in Seeing but not in Visualizing might be reflected in other parts of the fMRI image.

This view of the relationship between Seeing and Visualizing can be represented by a Venn diagram, like this:



It would seem to predict that the degree of fMRI similarity or overlap between Seeing and Visualizing would be a function of the *amount* of Conceptualization, which could be defined as the player's skill level as measured by the method described later.

Charness' findings

Seemingly relevant to this issue is Charness' finding (p.159) that most experienced chess players can form robust long-term memories of chess positions they viewed for only a few seconds. They can recreate the positions much later after having spent the intervening time in unrelated chess or non-chess activities. But in interpreting this finding it is important to note that the masters did not necessarily retain or retrieve visual images or copies of the positions, just the ability to reconstruct them—an ability that can be based entirely on Conceptualization. When Conceptualization responses occur in Seeing, they may or may not then form long-term memories—that is, become susceptible to long-term recall. In this case the circumstances on which the formation of long-term memories depends include stimulus features (concepts) recognized as important based on prior experience, as well as contemporaneous cues that focus special attention on certain stimulus features (Charness, 1976). In the experiment reported by Charness, the contemporaneous cue was, presumably, an instruction to focus on the features relevant to reconstruction of the position, and these features would have been concepts.

Visualizing in normal chess

When the term Visualization is used from this point forward, it will refer to the Conceptualization behavior. Thus, a "visualized" chess piece would be a piece whose placement on the chessboard is "known," in the conceptual sense, not a visual image of the piece.

Visualization skill is evidently an important component of both blindfold and sighted chess skill (p.9, 91, 127, 190), but somewhat surprising are the reports of many strong chess masters, and other evidence, that it can actually be helpful to look away from the board when thinking ahead ("calculating") (p.9, 127, 151, pp. 189-190). How come? Because when considering a move in normal over-the-board chess, the player typically tries to visualize some aspects of the position that will ensue after the move is made. Prior to actually moving the piece, the player still sees it in its original position—a stimulus that conflicts with the (visualized) position that would exist after the piece is moved. This type of conflict is compounded when more than one move or even piece captures are involved. We might expect such conflicting stimuli to interfere with Visualizing. By looking away from the board and relying on pure Visualization, the player can avoid such interference.

But why would this effect depend on the player's strength? The explanation could be that when looking away from the board the player relinquishes the sight not these interference effects, stimuli but also of all the sight of all the other pieces that would *not* be moved and would remain on their squares. Being able to see these pieces can be helpful, but only to the extent that the player, when looking away, would have some uncertainty as to their placement. The more experienced the player, the smaller that uncertainty, the less help is therefore derived from the sight of them, and the greater the extent to which the interference effects outweigh the value of seeing all of the pieces. This can be a reason why the stronger the player, the smaller the benefit derived from sight of the pieces and their placements.

The "recognition-action" repertoire

We know that what we perceive is largely a function of what we have learned to perceive (Graham, 1951, pp. 911-915; Skinner, 1953; Woodworth & Schlosberg, 1955, pp. 403-491). In general, perception is so strongly dependent on history that history will often even override contemporaneous perception (Brown, 1973; Carter & Werner, 1978; Cumming, Berryman, & Cohen, 1965; Mechner 1994, pp. 33-34; Schoenfeld & Cumming, 1963; Wright & Cumming, 1971).

This is also true for perception and Visualization in chess. Chase and Simon (1973) (pp.157-158) have estimated that a "recognition-action" repertoire of 50,000 to 100,000 piece configurations (also called "chunks," "templates," or "patterns") that the player has learned to recognize[16] constitutes an important component of chess skill, for both sighted and blindfold play.[17]

"Recognition-action" is an apt term because recognition implies Conceptualization. The "action" in this recognition-action thesis can be a single move or a whole sequence of moves, a plan, an algorithm to be invoked, a strategy to be adopted, or presumably even just the recall of a similar previously-encountered position-action episode involving the action of another player; of the player himself when previously faced with a similar position; or of writings regarding actions appropriate to such a position. The masters' protocols, (e.g., "knowing which combination or plan is in progress") suggest that the action often consists of a sequence of moves as a unit (Chase and Simon, Cleveland (pp. 151-152), Holding, (p.162), and others (pp.162-166)).

[16] Behavior analysts would conceptualize it as a multiple discrimination repertoire of that magnitude.

[17] For examples of such piece configurations and position features, see Fischer, Margulies, & Mosenfelder (1966), which teaches a number of these to beginners by means of programmed instruction. Since most of the configurations are parts of integrated sequences that may be logically nested and/or intertwined and are rarely discrete, the numerical estimates of how many there are should not be taken too seriously.

Relationship to matching internal models

Potentially relevant to the authors' discussion of the Chase & Simon conjectures is this reviewer's suggestion that skilled performances (of which chess is an example) are normally practiced and honed by matching an internal visualized model (rather than a contemporaneous external one) of the desired performance (Mechner, 1994, pp. 29-34). For instance, musical performers, especially when practicing, try to match their internal model of what the music should sound like, and a golfer may try to match his Visualization of Tiger Woods' swing.

Do chess players, too, when considering possible actions, sometimes strive to match Visualized model behavior? This could take the form of covertly asking, "What would Bobby Fischer, (or my coach) do in this position?" or "What did I do in a similar position in a previous game?"

Coordinative structures and degrees of freedom

The authors report de Groot's 1965 conclusion (p.54), later supported by others, that stronger players consider roughly the same number of moves as weaker players, but consider better ones, and faster. The explanation for this may be the same one that has been proposed in the motor performance literature for the changes that occur as a performance progresses from novice to expert: the performance's behavioral components become linked and assembled into increasingly efficient and effective functionally integrated larger units. The performance's degrees of freedom—the number of functional units that can move separately—does not change significantly as expertise increases, but what does change is the internal structure and elaborateness of these units—the number of elements (concepts or actions) that become linked *within* each unit. This process does not depend on whether the component elements are motor or non-motor, and appropriate practice can automatize the behavioral elements within functional units by strengthening their linkages (Mechner, 1994, p. 39-47). As skill develops, elements that initially functioned independently fuse and become linked, thereby forming larger units whose number remains more or less the same (Belen'kii, Gurfinkel & Pal'tsev, 1967; Bernshtein, 1967; Normand, LaGasse, & Rouillard, 1982; Turvey, Fitch, & Tuller, 1982; Turvey, Schmidt, Rosenblum, & Kugler, 1988). That is how expertise develops not only in motor skills like tennis or marksmanship but also in non-motor skills whose key components are covert or cognitive, like chess (Gobet & Charness, 2006),[18] problem solving, and language proficiency.

"Mental practice" and the benefits of blindfold play

The benefits of motor skill practice accrue to the practiced motor skills, and the benefits of covert practice accrue to the practiced covert skills (Mechner, 1994, p.39). That is why covert practice is most beneficial in performances that have significant covert or Visualization components, and least beneficial in performances for which overt motor components are key (p.170, Heuer, 1985; Ross, 1985; Ryan, Blakeslee, & Furst, 1986; Ryan & Simons, 1983; Van Gog et al., 2009). Because sighted chess is at the cognitive extreme of the motor-cognitive range and depends heavily on Visualization skill, it should be expected to benefit significantly from playing blindfold chess, which amounts to pure

[18] Experienced chess players can cite numerous examples of such larger units and linked actions. Examples: When the configuration is a queen's side pawn majority, consider strategies that will convert that majority into a passed pawn; in certain positions, assign high priority to the placement of a rook on an open file or on the seventh rank, especially when doing so includes a threat. For expert players, such algorithms are unitary concepts perceived in a split second. The authors cite studies that discuss the thousands of hours of study needed to acquire the necessary number of such unitary concepts and linked elements.

Visualization practice. This analysis would explain and support the claim by grandmasters and the authors that blindfold play improves sighted play.

A SKILL MEASUREMENT METHOD

The authors suggest that "…analyzing the methods used by blindfold champions to achieve their feats could reveal novel and specific ways to improve the memories of people engaged in non-chess activities requiring exceptional or merely better-than-average memory skills," and "The skills that play a role in blindfold chess can be valuable in a practical sense, in everyday life" (pp. 1-2, p.11, 147). They cite, as an example, holding in memory a map when driving from one unfamiliar location to another, and they mention problem solving in mathematics, physics, architecture, music, sports, and financial decision making, all of which involve Visualization or consideration of alternatives (p.149).

Any efforts to realize or evaluate such possibilities would require appropriate training methods. But the development and evaluation of such training methods requires tools that permit skill levels to be measured and compared. Accordingly, this review proposes a procedure that can generate a quantitative, non-arbitrary way to measure and rate any skill that, like chess, involves choices among known alternatives. Such a procedure would be usable in skill research generally to determine the nature and location of a deficit in relation to a theoretical maximum for each particular skill component, as a function of such independent variables as training method, sleep, or practice techniques.

Dependent variables in skill research

Many types of quantitative skill research require a dependent variable that provides a measure of a choice's shortfall from best and of the speed with which the choice was made. The proposed technology, which uses the chess model to illustrate its implementation, assigns operational meaning to the concept of a skill shortfall in relation to a theoretical maximum. It relies on the availability of chess computers that can be used to define maximum skill level.

Such computers can now play at top grandmaster level and can thus identify best moves[19] in given positions. The authors (pp. 163-164, 189-190) describe the use of this approach by Chabris and Hearst (2003). They used the chess computer Fritz 5 to rate the magnitude of errors made by masters. The computer generated numerical indices for a move's shortfall from "best" using pawn-equivalents as the arbitrary units. Chabris and Hearst used these indices to compare blindfold and sighted play for the frequency and magnitude of mistakes (there was no significant difference), defining "mistake" as a 1.5 "pawn" shortfall[20] from best, and "blunder" as significantly larger shortfalls.

The issue of a measure's arbitrariness

In view of the fact that every chess position must theoretically result in a win, a loss, or a draw when it is played out to the end of the game, any rating of the strength of a move or the magnitude of a mistake is necessarily arbitrary. Such computer-generated ratings reflect the computer's evaluation of the position after it has calculated ahead a certain number of moves. But how

[19] The sense in which the term "best" is used here is simply that the moves are so strong that even in the occasional instances where there may exist one or more still stronger moves, little would be gained by including them, even if they could be found. When there are several moves for which no better ones can be found in a given position, any such move would qualify as "best."
[20] Pawn shortfall from best can be thought of as a measure of the degree to which a particular move makes the position better or worse, using the value of a pawn as the unit of measurement.

many moves ahead and moves of what strength? Because the answers to these questions are necessarily arbitrary, so are such move ratings.[21] But for a measure to enable valid comparisons among different values of an independent variable within as well as between skill areas, it cannot be arbitrary. Its units must have the same meaning regardless of the independent variable used and the skill area involved.

Traditional skill rating methods and their limitations

Skill or knowledge involving choice behavior (henceforth referred to simply as “Skill”) is often studied with “right or wrong” items (Chase & Ericsson, 1982). Problems of the type “What's the best move?”—widely used in game magazines and instructional books—generate either a "percent correct" score or someone’s subjective rating of the quality of the answers chosen. But a wrong choice does not provide information about the nature or magnitude of the responsible Skill deficit, and an average or total score does not identify the particular items that presented problems.

Hearst and Knoll make frequent reference to Skill ratings based on the system that generates formula-based numerical ratings for players' past competitive performance results against each other. Such ratings, which are widely used in competitive games like chess (p.143, 163)[22] and go,[23] are numerically

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[21] It might be noted, incidentally, that the information such a rating conveys to a particular player depends on the player’s skill level. For instance, a top grandmaster might interpret an advantage of 1.6 pawn-equivalents as an easy win, and a relatively inexperienced player might interpret it as a minor edge.

[22] The competitive-performance-based rating formula internationally used in chess, devised by the Hungarian physicist Arpad Elo (1978), arbitrarily assigns a rating somewhat below 1,000 to beginners, while players of world championship strength would usually achieve ratings in the vicinity of 2,800.

[23] In go, the competitive-performance-based rating scale used by the American Go Association for amateur players assigns a rating of around -350 (35 kyu) to

arbitrary and have no anchorage points—they float and drift. If all rated chess or go players were to become stronger or weaker to the same degree at the same time, their respective ratings would not change.

Requirements of a useful skill measure

To be useful in the measurement of chess skill, a measure should be applicable to the performance of an individual player confronting a particular chess position or series of positions (as opposed to a measure that describes the player's past competitive performance against live opponents). The measure should also permit specific Skill deficits to be identified and pinpointed. Chess players usually differ in their Skill for different phases of the game—the opening, middle, and end game—and for different types of positions—skill differences that cannot be isolated in competitive play. But the proposed measurement procedure can be applied separately to each game phase or type of position, and can thus pinpoint the magnitude and nature of Skill deficiencies.

A measure of this sort would be applicable not only to chess Skill but also to the measurement of any other type of cognitive Skill in which a number of plausible alternative choice responses are available and the best answer, or set of best answers, is known (e.g., spelling, geography questions). That is one of the reasons why chess, where every move is a choice among a manageable number of known alternatives, offers a good research model for studying this type of choice behavior in general.

Measuring Skill shortfall from a theoretical maximum

Claude Shannon, in his 1951 paper "The Prediction and

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rank beginners and +800 (8 dan) to the strongest amateurs. Professional players are rated internationally on a separate scale from 1 to 9.

Entropy of Printed English" showed how various statistical approximations to the letter sequences in normal English text can be quantified in terms of "entropy"[24] by using a normal speaker of English as the human measuring instrument. He proposed the entropy measure as a way to quantify an individual's information deficit for each successive letter in such sequences, explaining that the $\log_2$ of the number of tries needed to identify the letter, expressed as bits of "information," corresponds to the number of yes-no questions the individual would have needed to ask in order to identify the letter if such a questioning strategy had been used.

The present paper shows how the entropy measure generated by Shannon's procedure can be flipped around to provide a measure of an individual's Skill deficit for a given stimulus situation, rather than merely to measure the entropy attribute of the stimulus situation. The same procedure is obviously applicable to any multiple-choice situation in which all the possible choices are known and can be made available, and in which successive tries can lead to a known optimal choice.

The Uncertainty measure applied to choice situations

The underlying concept of the proposed procedure is that for a particular individual, the difficulty of any question or problem involving choice can be expressed as a shortfall from a theoretical maximum, or "uncertainty" (we will call it "**U**"). **U** corresponds to the number of yes-no questions the individual would need to ask to get the answer if a question-asking procedure were applicable, and is measured by the $\log_2$ of number of tries rather than by an actual number of yes-no questions (bits of information). For example, if 32 tries were needed, **U** would be

[24] or information deficit, disorganization, disorder, or unpredictability, or its inverse: negentropy, degree of organization, or predictability (Wiener, 1948, 1950).

five bits, because the $\log_2$ of 32 is five. Here is the underlying reasoning: Suppose you knew that a coin was tossed three times but not how it landed on those three tosses. To find out, you would need to ask three yes-no questions: (1) "Did it land heads on the first toss?" (2) "Did it land heads on the second toss?" and (3) "Did it land heads on the third toss?" That makes eight possible outcomes, and the $\log_2$ of eight is three. Thus, your uncertainty **U** was three bits.

The unique property of the **U** measure is that it is non-arbitrary in the sense that it is applicable to a wide variety and range of skills, knowledge, and choice situations, and therefore enables comparisons among these. Arbitrary measures, in contrast, do not permit valid comparisons of the type we normally wish to make in scientific research.

The U measure applied to chess skill

One of the reasons chess provides a useful laboratory model of choice behavior is that the Shannon procedure described above is readily applicable to it. As stated earlier, chess permits the maximum Skill level to be defined operationally by using the strongest available chess programs,[25] which can generate a satisfactory approximation to the best move (or to the set of best moves when there is more than one) for any position.

This is the procedure: the individual is presented with a chess position on a computer screen and is instructed to indicate what he or she believes might be the best move. After each try, the computer responds “correct” or “try again,” based its

[25] In 2009, a computer chess program named Rybka, reputedly the strongest then in existence, played close to the strength level of the strongest human grandmasters, and programs reputed to be even stronger have more recently been made available on the internet as free downloads. In the case of standard 19x19 go, on the other hand, there are as yet no computer programs that can generate sets of moves beyond the level of weak players. However, there are now computer programs that can generate best moves for 9x9 go.

determination of the one or more best moves for that position. The player keeps trying until the computer responds "correct." This procedure can be applied to individual positions or series of positions, including those that would comprise an entire game.

For the hypothetical player who would always be "correct" on the first try, **U** would be zero bits because the log of 1 is zero. This corresponds to a Skill level at which a player would have zero uncertainty, i.e., would need to ask zero yes-no questions. A less skilled player, who might need, say, 8 tries,[26] would have a **U** of three bits (i.e., corresponding to three yes-no questions). So, the greater the Skill deficit, the greater the **U**.[27]

The measurement of power

The proposed Power measure considers not just **U** but also the time consumed for each try, and calculates "Power" as a joint function of the two for each position. This Power measure can serve as the dependent variable in research studies in which the independent variable might be various types of training exercises and procedures, test conditions, types of positions, the player's experience or Elo rating, fatigue, ingested substances, age, and so forth.

In short, Power, as defined here, is a pure measure of ability to find best moves. The effects of occasional mistakes or oversights are small. The Power of a player who always finds the best move (or one of the best moves) instantly (i.e., in zero

[26] Since there are, on average, approximately 37 legal moves in any given position, random choices would find a best move after around 18 tries, and a typical non-master might need an average of 4-12 tries. The U measure could be refined by redefining its zero value as the chance level, which would be half of $\log_2$ of the number of choices available in every position.

[27] A possible refinement of this procedure would give "partial credit" for trying moves that are second-best, third-best, etc. Such tries could, for instance, be counted as fractional rather than whole tries, with the amount of partial credit based on the computer's evaluation of move rankings, although any evaluation function is inevitably arbitrary.

seconds) is 1.00, which represents maximum Power. The Power rating would decrease toward zero as the number of tries and the time consumed increases. The formula is

$$\textbf{Power} = \mathbf{1/(U+T)}$$

where $\mathbf{U = \log_2 N}$, and **N** is the number of tries needed to find one of the best moves. $\mathbf{T = k\sqrt{\mathit{t}}}$, where ***t*** is the time consumed in finding it,[28] and the constant **k** is the weight assigned to the time component relative to the **U** component.

This formula permits the player to trade off number of tries against thinking time in a way that leaves the Power score relatively unaffected. The player can achieve the same Power score by thinking longer so as to require fewer tries, or by trying more choices more quickly and using less thinking time. Such tradeoffs mean that a player's Power score for each position need not be strongly affected by the amount of time spent. Terms like "Power constancy" or "complementarity" describe this tradeoff between thinking time and number of tries. This Power constancy feature may be able to accommodate stylistic differences between players in the way they use time and in the way a given player may use different tradeoffs at different times.

Power constancy and the time factor k

The degree of Power constancy will depend on the value of the time factor **k** selected. If **k** is set at zero, time plays no role at all, and players would then be able to maximize their Power score by thinking as long as possible on each try so as to minimize **N**. On the other hand, if **k** is set at an extremely high value, the

[28] The computer software would automatically subtract out the time consumed by the physical act of keying in each try. Keying-in time could be defined as the time between the first and last keystrokes, minus any excessively long inter-keystroke pauses, and minus the time taken for extra keystrokes.

way to maximize the Power score would be to minimize thinking time by trying every reasonable move as quickly as possible, as number of tries would then have almost no effect at all.[29]

In both of these cases, there would be no Power constancy. Therefore, Power constancy is maximized at some intermediate value of **k**. The **k** setting could also be used when the goal is to simulate tournament conditions with long time limits, in which **k** would be set low, or rapid play conditions in which **k** would be set high.

The player can be provided with computer-generated feedback to help maximize the Power score by adjusting thinking time to that **k** setting. Such assistance could take the form of beep signals at meaningful points, possibly combined with a visual display in a corner of the screen to "optimize" **k** from time to time (i.e., the optimum would be variable, as is explained in the next paragraph), bearing in mind that a wide range of values of **k** yield valid and useful Power measures. It is likely that the value of **k** that maximizes Power will be different for different players and for the same player at different times. Whatever value or function of **k** is used, the player can be given some latitude in choosing it to suit his or her style at any particular time, type of chess position, or mood. In any case, the choice of **k** is very forgiving—any semi-arbitrary choice of **k** close to the middle of the range can be expected to yield relatively reliable and valid Power measures.

Why chess provides a useful model for skill research

The general applicability of the above-described

[29] In developing the required software, a mathematically inclined programmer might consider using calculus of variations in programming the speed-accuracy trade-offs, and Lagrangian multiplier methods for the "optimality with constraints" problem—an optimization function that has been used in economics in connection with "utility functions," in operations research, and in solving optimization problems in control engineering.

methodology for measuring Power is one of the reasons why chess is a useful research model for the measurement and study of any game or Skill domain that can be defined by discrete time-constrained choices or decisions for which the best answer is known, as in certain types of military, business, legal, counseling, and social situations. The measure can also be used for testing knowledge in certain academic subjects like mathematics, the sciences, certain verbal skills, literature, social studies, geography, and so on.

A model for the study of creativity and imagination

As was mentioned earlier, experienced chess players tend to agree on the extent to which chess moves have attributes they variously term "creative," "imaginative," or "original" (we will refer to these collectively as "Creative").[30] An experimental approach to Creativity research would require, as a first step, a laboratory model that corresponds in some way to how these terms are used. Stuart Margulies (1977) showed, in a controlled study, that one of the attributes of a chess move that leads experts to describe it as "beautiful" was *the degree to which it violated accepted heuristics and algorithms of chess play*.[31] A conclusion similar to Margulies' was stated in Mechner (2008, p.244), namely that "contrariness"—the disposition to "swim against the tide of current thinking" was one of the traits seen in virtually all of history's great achievers and creative geniuses.

Margulies' study quantified the independent variable "degree of violation of accepted heuristics and algorithms" on a rank-order scale. The computer approach proposed here would

30 When such adjectives are applied to a chess move, they are evidently intended to describe the behavior that produced the move.
31 While chess players apply the term "creative" to moves less often than "beautiful," they would rarely dispute that the "violation" attribute would be applicable to both.

permit it to be measured on an interval scale ranging from zero to a maximum. For instance, it could be defined quantitatively as the depth of search needed to find the move, in conjunction with amount of material sacrificed or degree to which certain standard positional or strategic principles are violated. In conjunction with the Power measure, such an approach may offer a practical methodology for studying the effects of a wide range of variables on chess Creativity, with possible extrapolation of the findings to realms other than chess.

Another set of parameters in Margulies' definition of "move beauty" (as distinct from Creativity) were some that could be summarized as the economy of means used to achieve a result. The chess model permits such parameters to be quantified and scaled, thereby opening the possibility of investigating which if any independent variables might cause the player to consider the beauty of a move in making a choice when all of the move's other effects are equal, again, with the possibility of extrapolating the findings to other realms.[32]

Addressing questions specific to chess

Once the required software system for measuring Power is available, even non-psychologists would be able to use it privately, without opponents, and without great preparation. Serious chess players would be able to use it to obtain frequent quantitative readings regarding their personal progress and the idiosyncratic effects on them of such factors as substances like alcohol or caffeine, jet lag, time of day, amount of sleep, and so forth.

[32] Using a laboratory model to define a commonly used terms operationally always raises the issue of extrapolability to other realms in which such attributes are considered to be involved. The multiple usages of such terms are generally matched by as many views of the model's "validity." That is why any proposed laboratory model of entities that have such a multiplicity of definitions as "creativity," "imaginativeness, or "beauty" must also be able to stand on its own.

There are many chess-specific research questions that can be asked and answered with the Power measure. For example, is the well-documented peaking of chess playing strength in players' mid thirties (Elo, 1965) correlated with a peaking of Power? In general, what is the relationship between playing strength (Elo rating) and Power?

The Power measure also provides a standardized way to compare players from different countries, cities, or clubs whose standards may differ or may have drifted apart over time. When used over very long periods of time, the Power measure would also enable comparisons of the skills of players at different stages of their careers, or of players who may not even have been alive at the same time.

Finally, the Power measure can be used to investigate experimentally some of the claims and hypotheses cited by the authors. Examples: Some very strong masters assert that the sight of an actual board and pieces is often more of a hindrance than a help in trying to visualize positions when thinking ahead. How is this effect correlated with the player's Power? Some masters claim that the strength of their blindfold play is similar to that of their sighted play. How similar, and does the similarity depend on their Power? A related question is whether blindfold play improves sighted play. This question is closely related to the findings that "mental practice" can improve overt performance for certain other performance skills (see the earlier section titled "Coordinative structures and degrees of freedom"), and can be answered with the proposed procedure.

Applications in Skill training generally

As mentioned earlier, a key component of Skill in games like chess or go is the ability to think ahead ("calculate"), which requires Visualization of positions that may occur several moves later. Visualization skill must therefore be a contributing component of Power, and any improvement in Visualization skill should therefore be reflected in the Power measure.

This consideration becomes relevant for the study of Skill domains that do not involve choice behavior but that depend, like chess Skill does, on Visualization or auditory imaging. The procedure for measuring Power would not be directly applicable to such Skill domains, but it may be plausible to extrapolate to them certain research results obtained when the Power measure is applied with chess used as the research model.

Consider, for instance, musical composition skill, which depends on auditory imagery. Similarly, a key skill component of drawing from a model is the ability to Visualize the model when the eyes and hand are on the drawing. Neither of these skills involves discrete or definable choices. Are there exercises that can improve such skills?

This reviewer tested one such Visualization exercise back in the 1960s. It consisted of alternating several times between visualizing a particular sequence of chess moves and actually seeing that same sequence played out on the board. At that time, no methods were available for objectively measuring the effectiveness of this exercise. If the Power measure now showed that it is, indeed, effective for improving chess Visualization skill, we might infer, by extrapolation, that similar types of exercises may also work in these and a variety of other skill domains. Thus, the proposed procedure would provide an indirect way to address such questions for Skill domains that involve Visualization but not choice.

Many performance skills depend on covert behaviors and cognitive processes that are invisible to an outside observer

(Mechner 1992, pp. 18-21). The data consisting of the incorrect tries when the trainee is searching for the best move could provide a valuable window into such thought processes to a trainer, and would be more specific, valid, and informative than the standard oral reports obtained in response to the “Think out loud” type of request that chess trainers sometimes use (de Groot, 1965; Silman, 1991).

Conclusion

Hearst and Knott’s book will clearly stand for a long time as the definitive compendium on blindfold chess for chess players, students of games, and psychologists. Also, many of the topics covered in the book have implications for certain research issues in behavior analysis, psychology, neuroscience, performance learning, training, and education. The present review explores these and describes a possible research methodology for addressing them. In addition to its potential uses in educational testing and training, the proposed behavior analytic approach to skills research may help behavior analysts to continue reclaiming this vast and important domain of human behavior.

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