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ABSTRACT

Five experiments involving a total of 44 college students addressed the effects of intercomponent consistency on skill acquisition in a class of cognitively demanding tasks requiring rapid integration of information and rapid application of rules. The role of consistency of external stimulus-to-rule linkage in facilitating learning and performing rule-based tasks was examined. After extensive consistent practice, subjects' performance was remarkably similar to performance observed in traditional perceptual learning tasks. This similarity suggests that mechanisms underlying perceptual learning (in visual search) and rule-based spatial learning are similar. Subjects who were trained such that consistent stimulus-to-rule association could be built up and strengthened with practice performed in a manner qualitatively and quantitatively different from subjects trained with inconsistent stimulus-to-rule relationships. This superiority of the consistent stimulus-to-rule trained subjects over the inconsistent stimulus-to-rule subjects was even more exaggerated in dual-task situations. The data have implications for the understanding and training of skilled problem-solving tasks. When training affords development of subcomponent automatization of the problem-solving activity, the chance of memory overload is reduced. The results suggest one trainable subcomponent, the perceptual/rule-based component. (Contains 47 references.) (Author/SLD)

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HUMAN RESOURCES

THE ROLE OF STIMULUS-TO-RULE CONSISTENCY IN LEARNING RAPID APPLICATION OF SPATIAL RULES

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Five experiments addressed the effects of intercomponent consistency on skill acquisition in a class of cognitively demanding tasks requiring rapid integration of information and rapid application of rules. The role of consistency of external stimulus-to-rule linkage in facilitating learning and performing rule-based tasks was examined. After extensive consistent practice, subjects' performance was remarkably similar to performance observed in traditional perceptual learning tasks. This similarity suggests that mechanisms underlying perceptual learning (in visual search) and rule-based spatial learning are similar. Subjects who were trained such that consistent stimulus-to-rule association could be built up and strengthened with practice performed in a manner qualitatively and quantitatively different from subjects trained with inconsistent stimulus-to-rule relationships. This superiority of the consistent stimulus-to-rule-trained subjects over the inconsistent stimulus-to-rule subjects was even more exaggerated in dual-task situations. The data have implications for the understanding and training of skilled problem-solving tasks. When training affords development of subcomponent automatization of the problem-solving activity, the chance of memory overload is reduced. The results suggest one such trainable subcomponent--the perceptual/rule-based components.

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The Role of Stimulus-to-Rule Consistency in Learning Rapid Application of Spatial Rules

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Five experiments addressed the effects of intercomponent consistency on skill acquisition in a class of cognitively demanding tasks requiring rapid integration of information and rapid application of rules. The role of consistency of external stimulus-to-rule linkage in facilitating learning and performing rule-based tasks was examined. After extensive consistent practice, subjects' performance was remarkably similar to performance observed in traditional perceptual learning tasks. This similarity suggests that mechanisms underlying perceptual learning (in visual search) and rule-based spatial learning are similar. Subjects who were trained such that consistent stimulus-to-rule association could be built up and strengthened with practice performed in a manner qualitatively and quantitatively different from subjects trained with inconsistent stimulus-to-rule relationships. This superiority of the consistent stimulus-to-rule-trained subjects over the inconsistent stimulus-to-rule subjects was even more exaggerated in dual-task situations. The data have implications for the understanding and training of skilled problem-solving tasks. When training affords development of subcomponent automatization of the problem-solving activity, the chance of memory overload is reduced. The results suggest one such trainable subcomponent—the perceptual/rule-based components.

INTRODUCTION

The study of "skills"—more precisely, skills acquisition—has a long history (for a review see Adams, 1987). From the earliest investigations researchers and practitioners have actively pursued an expanded understanding of skills in general and, in particular, how best to train for efficient skills acquisition (e.g., Book, 1925; Bryan and Harter, 1899; McGeoch, 1927; Pear, 1927; Solomon and Stein, 1896). Much has been learned since the early research of Bryan and Harter, Solomon and Stein, and their contemporaries. Clearly, the research efforts have increased our understanding of the acquisition of motor skills (Adams, 1987) and provided a more complete understanding of the dynamics of perceptual learning (e.g., Gibson, 1977; Schneider and Shiffrin, 1977). In recent years the skills research effort has moved toward an understanding of why skilled performers differ from novice or unskilled individuals (e.g., Adams, 1971; Fitts, 1964; Schmidt, 1975; Shiffrin and Schneider, 1977).

What is lacking—dramatically so from an applications perspective—is an understanding of the dynamics of the development of

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those skills that are heavily weighted with *cognitive* components. To develop more fully an understanding of cognitive skills development, an empirical attack is needed on two fronts. Ongoing investigations of cognitive skills development in a global sense must, of course, continue. But, at least as important, we must understand the similarities and differences in learning *high-performance* (Schneider, 1985) perceptual, motor, and cognitive skills. Armed with such a taxonomy, history need not repeat itself from a training and research perspective. The present research addresses these needs. In the current experiments we examined the learning and application of spatial rules. The task we employed—conceptually similar to a component of a chess game—provided the opportunity explicitly to examine skill development and asymptotic performance using laboratory techniques closely aligned with those used in traditional perceptual learning tasks; thus we could assess the "lawful" nature of the acquisition of more cognitively based skilled performance relative to more traditional perceptual learning.

It is a truism that practice is needed to become skilled at an activity. Practice can lead to extreme differences among trained and untrained performers. From the perspective of perceptual learning, researchers have dealt with the extreme differences in performance often observed between experts and novices by proposing that there are two qualitatively different forms of human information processing (e.g., Fitts, 1964; Logan, 1985; Posner and Snyder, 1975; Schneider and Shiffrin, 1977). In the present paper we refer to these two distinct forms of information processing as automatic and controlled. Using visual search as the primary paradigm, research examining automatic and controlled processing has catalogued numerous empirical differences between these two modes of processing (Fisk, Ackerman, and Schneider, 1987), demonstrated the qualitative differences in event-related brain potential between the two processes (Kramer, Schneider, Fisk, and Donchin, 1986), and suggested the generality of the automatic/controlled processing perspective to complex stimuli. (See Fisk, Schneider, and Logan, 1986, for a review of the major distinctions between automatic and controlled human information processing.)

As many of the early students of skill development suggested, statements such as "practice makes perfect" are only partially correct. Dramatic changes in performance occur when individuals are given extensive consistent practice. Consistent practice in visual search occurs when stimuli are consistently mapped (CM); that is, when an individual makes the same overt (or covert) response to stimuli (or class of stimuli) across training trials. If the individual receives varied mapping training (VM), a given stimulus requires responses that change across practice. Under VM training automatic processing will not develop and performance will not change dramatically with practice. Automatic processing develops with CM practice, not with VM practice. The CM/VM training distinction suggests a need to revise the old adage, which should more correctly be: "*CM* practice makes perfect." The distinction between VM and CM training is important because of the extreme quantitative and qualitative differences in performance observed when subjects are given VM as opposed to CM training. The *consistency* of the practice is critical in determining task performance (see Fisk et al., 1986, in press).

A major purpose of the present research was to address the effects of intercomponent consistency on skill acquisition in a class of cognitively demanding tasks requiring rapid integration of information as well as rapid application of rules. Specifically, we examined the role of consistency of external stimulus-to-rule linkage in facilitating the learning and performing of a rule-based classification task. Chess-like tasks were used in all of our experiments. The tasks required development of a complex multicomponent skill conceptually similar to a component in a chess game. Performance efficiency on the task was determined by how well the subject had learned to distinguish the "game pieces" from one another; understand how the pieces might legally move; and, most important, determine how or whether a targeted piece was threatened by an "enemy" piece.

The particular task that subjects were required to perform was chosen for three reasons. First, the task allowed manipulation of consistency of the external triggering stimulus-to-rule relationships (an intermediate component of the overall task). Second, the task was expected to have high external validity. Results from research examining skilled chess playing have shown generality across a range of tasks (Holding, 1985). In addition, an important aspect of chess training appears to be learning to find familiar patterns in order to determine strong moves (de Groot, 1965; Lasker, 1975). Saariluoma (1985) has pointed out that this phenomenon is general across various rule-based games such as "Go" (Reitman, 1976) and bridge (Charness, 1979). In addition, the use of external stimulus *patterns* to determine correct action appears relevant in skilled performance of many real-world tasks such as music (Sloboda, 1976), computer programming (Jeffries, Turner, Polson, and Atwood, 1981), electronic troubleshooting (Egan and Schwartz, 1979; Rasmussen and Jensen, 1974), interpreting X rays and medical diagnosis (Parasuraman, 1985), and in-flight refueling (Schneider, Vidulich, and Yeh, 1982). Thus the results obtained and conclusions generated from our research using the present task will have much promise of generalizing to other important real-world tasks.

The third reason for selecting the present task was that it capitalized on the easily identifiable "components" of related perceptual/rule-based tasks. For example, Saariluoma (1984, 1985) has shown that the information-processing components of the chess task—information intake (stimulus processing) and memory activation (use of rules)—are separable. Although the study of skill components, such as those required for playing chess, has a long history (e.g., Cleveland, 1907), a systematic "longitudinal" examination of the development of subcomponents of the skill has not been undertaken except for certain problem-solving tasks (e.g., Anzai and Simon, 1979). In the case of the problem-solving literature, when skill development has been examined, practice has been extremely limited and often only a single subject is used.

EXPERIMENT 1: SINGLE-TASK RULE LEARNING

Previous research using a real chess task has shown that skill in chess (measured by a rating system such as the Elo [1978] system) is closely related to speed of performing most chess-related tasks. It is not surprising that skilled chess players are substantially faster than novice players at recognizing chess pieces, counting minor pieces, finding threats, and determining whether a king is in check. Unfortunately, previous research has not examined the *development* of the perceptual/rule-based processes. Research that has examined rule-based learning has not looked at the mechanisms leading to successful problem solving in regard to the development of rule learning (Kotovsky, Hayes, and Simon, 1985) except with a limited number of subjects over a limited period (Anzai and Simon, 1979).

The first experiment examined purely quantitative performance improvements in a task requiring integration of both perceptual and rule learning. The task required subjects to determine the source of the "threat of capture" on a simulated game board. The stimulus-to-rule mappings were consistent. A consistent stimulus-to-rule mapping meant that a given external stimulus always, and uniquely, triggered a given movement rule (e.g., the letter *A* might always imply a "bishop"-like move). The present experiment provides the opportunity to evaluate the performance of subjects on this perceptual/rule-based task component compared with performance of experienced subjects on similar chess-like tasks.

Method

Subjects. Eighteen students from the University of South Carolina participated in this experiment in partial fulfillment of a course requirement. All subjects were inexperienced at chess (i.e., they could at most name the chess pieces but did not know how the pieces moved). All subjects reported English as their native language, were right-handed, and had vision corrected to 20/30 or better.

Procedure. On each trial the subjects' task was to decide as quickly as possible which character could legally move to "capture" a target character. To capture the target, a game piece (an uppercase letter) had to legally move from the space it occupied to the space occupied by the target. There was always one character that could capture the target on each trial. The subjects pushed a button on the computer keyboard corresponding to the capturing game piece to indicate their decision. The trial sequence began with presentation of the orientation display. The orientation display consisted of the game-piece letters and their associated response buttons, the subject's average accuracy and average reaction time for the current block of trials, and a message stating "Press the space bar to begin." Subjects were given cards showing how all of the characters could legally move; they could study these rule cards for up to 30 seconds between each trial. When the subject then pressed the space bar, the probe display, consisting of six uppercase letters plus a flashing *T*, was presented. The flashing *T* was the object to be "captured." The letters were presented on a game board that was 8.26 cm wide × 8.89 cm high. The game board was made up of 64 boxes, eight across and eight down; each box was 0.95 cm × 1.11 cm. One of the characters was positioned so that it could legally move from its box on the board to the space occupied by the flashing *T*. As feedback to facilitate rule learning, an illustration of the appropriate capturing character moving from its position to the position of the target followed the subject's response. Following a correct response by the subject, a pleasant two-second tune was played. An error tone sounded following an incorrect response. Subjects were encouraged to respond as accurately and as quickly as possible.

Consistent stimulus-to-rule mapping was used throughout the experiment. This consistency was maintained by always mapping a given character onto a given movement rule. For example, the letter *Q* was always used to represent a "queen"-like movement rule for the entire experiment. The remaining five letters (see next section) were each consistently mapped onto unique movement rules.

The subjects completed 864 trials in one session that lasted about 1.5 hours. The trials were grouped into blocks of 24 trials per block. At the end of each block of trials the subject was given an opportunity to rest; on the average, subjects took about one break every 30 minutes.

Stimuli. There were six movement rules. The movement rules mimicked the following chess pieces: pawn, bishop, king, queen, knight, and rook. The characters used to represent the movement rules were the uppercase letters corresponding to the first letter of each movement rule (for example, *P* for pawn, *K* for king, etc.). A flashing uppercase *T* (displayed in reverse video) was used as the to-be-captured target letter. Subjects sat approximately 71 cm from the display; at that viewing distance the game board measured 6.65 deg visual angle in width and 7.16 deg in height.

Equipment. IBM PC/XT computers were programmed to present the appropriate stimuli, to collect responses, and to control timing of the display presentation. Standard IBM monochrome monitors were used to display the stimuli. Each computer was located in an individual room that was monitored by a laboratory staff member through a one-way mirror.

Results

Correct trial reaction-time performance (i.e., decision time) is plotted as a function of amount of practice in Figure 1. Error trials were excluded from the analysis. Each data point in the figure represents a maximum of 72 trials per subject (1440 trials per point across all subjects).

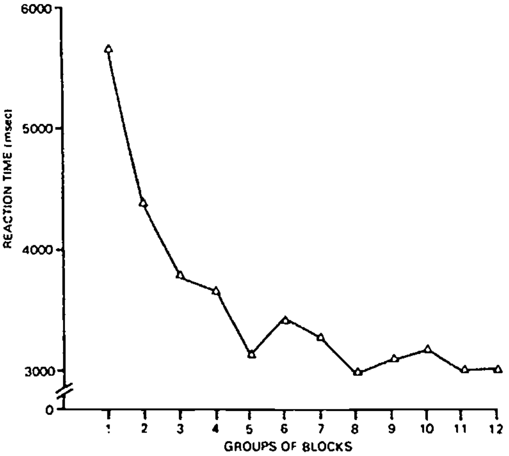

Figure 1. *Reaction time to indicate correctly the correct capturing "game-piece." The data are plotted as a function of practice (groups of blocks). Data from Experiment 1.*

Clearly, subjects learned to perform the task much more efficiently (faster and more accurately) as a result of practice, $F(11,198) = 17.29$, $p < 0.0001$. Initially subjects could identify the capturing stimulus in just under six seconds (5649 ms) with an average accuracy of 83%. In contrast, on the last group of blocks the subjects' average decision time dropped to just over three seconds (3117 ms) and errors were substantially reduced (average accuracy of 96%).

To put these Experiment 1 decision times into perspective, it is instructive to examine the performance of novice, moderate-to-good (USCF ratings of 1700 to 1999), and expert (USCF ratings of 2000 or above) chess players in a similar but real chessboard situation (see Elo, 1978, for a discussion of the USCF rating method). Saariluoma (1984) provides such data; his novice subjects were able to identify that a king was in check in about the same amount of time that it initially took our subjects. The subjects with a moderate level of chess skill were remarkably similar to our practiced subjects, with identification times averaging just under three seconds. The expert chess players were capable of identifying that a king was in check in about two seconds. Thus the present subjects' performance improvement was impressive; however, the locus of the improvement remains to be identified.

EXPERIMENT 2A: EXTENDED CONSISTENT STIMULUS-TO-RULE PRACTICE

The next experiment examined the effects of extensive consistent stimulus-to-rule training on the information-processing components of the perceptual/rule-based task. We investigated the changes that occurred with extended consistent stimulus-to-rule training on a "threat"-detection task similar to the task used in Experiment 1. In the present task, however, the subjects responded in order to indicate whether or not a prespecified character could capture the target character. Given that the task is consistent at the stimulus-to-rule level and at the rule-to-response level, we predict that both the overall reaction time and the comparison slope estimate will substantially decrease with practice *if* rule-based learning has the same improvement characteristics as perceptual learning (cf. Fisk and Schneider, 1983; Schneider, 1985).

Method

Subjects. Six students from the University of South Carolina were subjects in the experiment. Each subject was paid $4 per one-hour session for the first 10 sessions; thereafter each subject received $5 per session for the remainder of the experiment. All subjects were inexperienced at chess, had vision corrected to 20/30 or better, and were right-handed. English was the native language for four of the six subjects; however, all subjects were fluent in English.

Procedure. The subjects' task was to decide as quickly as possible whether or not one of a *prespecified* subset of characters could legally move to "capture" a target character. On each trial there could be from one to three prespecified characters (i.e., memory-set size of 1, 2, or 3). The subjects pushed one button on the computer keyboard if a memory-set character could capture the target and pushed a different button if no capture was possible. A trial sequence would begin with presentation of the orientation display. The orientation display consisted of the memory set (i.e., the characters to be examined as possible "captors"), the subject's average accuracy and average reaction time for the current block of trials, and a message stating "Press D for demo." The subjects could memorize the characters in the memory set and push the *D* key to see how the characters legally moved. When the subject pressed the demo button, the legal move of each character of the *current* memory set was individually demonstrated. The legal moves could be seen an unlimited number of times. When the subject knew how the character(s) in his or her memory set moved, he or she could press the space bar and the probe display would be presented. The probe display was constructed similar to its counterpart in Experiment 1 and consisted of six letters in addition to the flasing *T*. All memory-set items were included in the display on the probe (simulated chessboard) display. A *positive trial* meant that one and only one of the memory-set characters was positioned so that it could legally move from its box on the board to the space occupied by the flashing *T*. A *negative trial* meant that no capture was possible on this trial. After the subject's response on positive trials, the capturing character moved from its position to the position of the target. Following a correct response a pleasant two-second tone (selected randomly from a set of short tones) was played. An error tone immediately following an incorrect response.

Subjects were encouraged to respond as accurately and as quickly as possible. For the first two sessions the experimenter stressed accuracy more than speed. Following the second session the subjects were encouraged to use the speed and accuracy information on the orientation display to maximize their speed without letting accuracy suffer.

Design. The independent variables, manipulated within subjects, were memory-set size and possibility (or not) of capture (positive or negative trials). There were 24 trials making up a block of trials—four positive trials per memory-set size and four negative trials per memory-set size. Order of trial presentation was randomly permuted within each block.

Subjects required between 15 and 20 sessions to complete the required 6048 trials. Each session consisted of 30 minutes of subject participation followed by a five-minute rest break; after the break subjects participated for another 20 minutes. At most two sessions were completed per day.

Stimuli and equipment. The characters used in the experiment were the uppercase letters *A* through *F*. Assignment of letters to unique movement rules was counterbalanced by a partial Latin square. A flashing uppercase *T* (displayed in reverse video) was used as the to-be-captured target letter for all subjects. As before, there were six movement rules, which mimicked actual chess movement rules. The "game board" (probe display) and other equipment were the same as those used in Experiment 1.

Results

The reaction-time data were collapsed for analysis into 25 groups of blocks (240 trials per subject per group of blocks). The first 48 trials were considered task orientation trials and were eliminated from the analysis. The data will be discussed from two broad perspectives. First, we will examine changes in the effect of comparison load as a function of practice. Second, decision times as a function of memory-set size and trial type (positive or negative) will be addressed.

Comparison load. In traditional laboratory visual search tasks a major difference between search for consistently mapped (CM) versus variably mapped (VM) stimuli is the observation that response time is an increasing function of the number of comparisons to be made if subjects are performing a VM search, whereas search time is relatively independent of the number of comparisons in CM search (Briggs and Johnsen, 1973; Schneider and Shiffrin, 1977). The number of comparisons to be made—referred to as comparison load—is the product of the number of items in the memory-set and the test display size. The effect of comparison load on reaction time in VM search (and the lack of such an effect in CM search) has been shown to be similar for digit, letter, word, and semantic category search (see Fisk and Schneider, 1983; Schneider and Shiffrin, 1977). In this experiment the comparison load for memory-set sizes 1, 2, and 3 would be 6, 12, and 18, respectively, because the display size was six (six potential comparisons to the flashing *T*).

The estimate of the comparison slope for positive and negative trials as a function of practice is presented in Figure 2. Examination of the figure shows an improvement function similar to word and semantic category search (Fisk and Schneider, 1983). The comparison slope decreased by 85% and 75% from the first group of blocks to the last group of blocks for positive and negative trials, respectively. The comparison slope significantly decreased as a function of practice for both positive trials, $F(24,120) = 4.96$, $p < 0.0001$, and negative trials, $F(24,120) = 8.68$, $p < 0.0001$.

Decision time. Figure 3 shows the actual re-

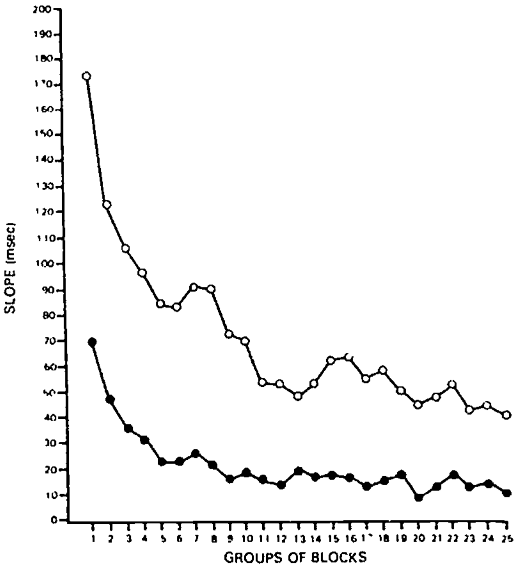

Figure 2. *Average comparison slope estimates (in ms) for positive trials (solid circles) and negative trials (open circles). The data are shown as a function of practice (groups of blocks). Data from Experiment 2A.*

action-time data plotted as a function of memory-set size both early (first group of blocks) and late (last group of blocks) in practice. The figure shows the dramatic overall reduction in reaction time as a result of the consistent stimulus-to-rule practice. Also apparent from the figure is the flattening of the comparison slope; that is, the interaction between memory-set size and practice, $F(2,10) = 23.53$, $p < 0.0002$. After practice subjects could determine when a movement rule was applicable independent of the memory-set size; however, if no movement rule was applicable (negative trials), then reaction times were affected by comparison load. This latter observation is supported by an inspection of Figure 3 and by a significant interaction between trial type (positive/negative) and memory-set size, $F(2,10) = 11.07$, $p < 0.003$. The increase in reaction time as a function of memory-set size for the negative trials probably reflects a rechecking process adopted by the subjects. This effect of increased latency for negative trials relative to the positive trials is also seen across skill levels when chess players are asked to scan a chessboard for the presence or absence of a king in check (Saariluoma, 1984). Importantly, Saariluoma did *not* find an interaction among experience levels and positive/negative trials. In the present experiment there was a marginally significant interaction between practice (early trials versus late trials) and trial type, $F(1,5) = 6.45$, $p = 0.0519$. The Saariluoma results and the present data suggest that our subjects would have difficulty eliminating (cf. Schneider and Fisk, 1983) this rechecking process even with continued training.

Given the complexity of the task, error rates were lower than might have been expected. After practice the positive-trial error rates were 0.08, 0.11, and 0.11 for memory-set sizes 1, 2, and 3, respectively. Negative-trial error rates were 0.03, 0.05, and 0.02 for memory-set sizes 1, 2, and 3, respectively. An ANOVA on the error rates revealed that none of the main effects or interactions were significant.

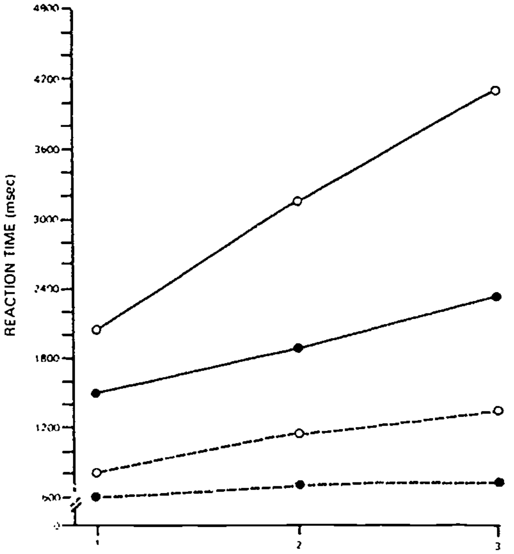

Figure 3. *Reaction time plotted as a function of memory-set size early in practice (solid lines) and late in practice (dashed lines). Solid circles represent average correct-trial reaction time when a capture was possible (positive trials), and the open circles show reaction time when no capture was possible (negative trials). Note that memory-set sizes 1, 2, and 3 correspond to a comparison load of 6, 12, and 18. Data from Experiment 2A.*

Overall, these results are similar to those reported for many complex CM perceptual learning tasks (e.g., Fisk and Schneider, 1983). One important aspect of extended CM training not explicitly examined by the current experiment is the reduction in the resource requirements associated with CM training (Logan, 1979; Schneider and Fisk, 1982). The following experiment examines the resource sensitivity of the now well-learned task.

EXPERIMENT 2B: ASSESSMENT OF RESOURCE COST

The next experiment examined the resource cost associated with assessment/selection of appropriate movement rules. Previous research has shown that after practice, CM visual search is resource-*insensitive*. However. with VM practice performance remains resource-*sensitive* (e.g., Ackerman, 1987; Fisk and Schneider, 1983; Schneider and Fisk, 1982, 1984). The purpose of Experiment 2B was to test whether consistent stimulus-to-rule practice would reduce the subjects' sensitivity to increased mental workload.

A dual task was used to assess the resource sensitivity of the chess game task. The subjects were required to perform a reverse-order digit-span task concurrently with the chess game task; they also performed single-task versions of the digit and chess game tasks. Subjects were instructed to maximize their digit-task performance during dual-task trials even if their capture performance in the chess game task was degraded (see Schneider and Fisk, 1982, for elaboration on the importance of this methodological consideration).

Method

Procedure. The same subjects who were trained in Experiment 2A participated in this dual-task assessment experiment. In this experiment the subjects performed three different tasks that were manipulated between blocks of trials: (1) a single-task digit span; (2) a single-task chess game; and (3) a combined digit-span and chess game task.

In the digit-span conditions the subjects were required to hold seven digits in memory and enter them into the computer in the *reverse order* of their presentation at the end of the trial. For example, if the digits were presented in the order 7369485, the correct input would be 5849637. Subjects were scored based on the number of digits entered in the correct reverse order up to the first incorrect entry. For example, using the foregoing digit sequence, an entry of 5819637 would receive a score of two correct because the first error occurred after the second digit. For single-task digit span the subjects would be shown the seven digits (each presented one at a time for one second each), be given a five-second retention period (blank screen), and then be shown the signal to enter the digits into the computer. The dual task consisted of showing subjects the digits, having them perform the chess game task, and then having them enter the digits into the computer. In both single and dual tasks subjects were given unlimited time to enter the digits and could "erase" a digit during entry.

Except for the single-task chess game task, the subjects' primary task was to remember the digits in reverse order. During dual-task trials only digit-recall accuracy feedback was given to the subjects in order to emphasize the importance of the digit task.

Design. The manipulation of interest was the effect of memory load on chess game performance as a function of memory-set size. Subjects completed 90 blocks of trials (30 blocks per task) in 8 to 12 one-hour sessions.

Results

Single- and dual-task reaction times are presented in Table 1. Error rates were equivalent to those in Experiment 2A and did not differ between single- and dual-task trials. Subjects were able to maintain performance in the digit-span task (6.7 average digit span for single task, 6.65 for dual task) while performing the movement decision task as well as they could perform the two tasks individually. There was a slight increase in overall reaction time in dual task; however, added memory load (the digit task) had the same effect at all levels of memory-set size and for positive and negative trials; this is shown by the lack of an interaction between single/dual-task trials and memory-set size, $F(2,10) = 1.14, p > 0.3$, and by the nonsignificant interaction between single/dual trials and trial type (positive/negative), $F(1,5) = 1.59, p > 0.26$. The comparison slope estimates also

TABLE 1

Reaction Time for Single- and Dual-Task Trials (Experiment 2B)

	Positive			*Negative*		
Subject	*M1*	*M2*	*M3*	*M1*	*M2*	*M3*
			Single-Task Trials			
1	690	880	1209	964	1214	2348
2	1266	1329	1479	1222	2401	2646
3	388	547	487	551	696	735
4	499	630	529	541	719	803
5	738	999	872	791	1133	1418
6	807	903	788	899	1240	1343
Average	731	881	894	828	1118	1548
			Dual-Task Trials			
1	643	1182	1026	1277	1727	3233
2	1473	1803	1830	1682	2186	2961
3	486	454	409	454	524	691
4	687	819	750	862	994	1145
5	793	1008	915	968	1278	1466
6	797	1015	906	946	1209	1248
Average	813	1046	973	1030	1319	1305

suggest the resource insensitivity of the rule-based task. Single-task comparison slope estimates were 13.5 ms and 61 ms for positive and negative trials, respectively; the dual-task comparison slopes were not different: 13.1 and 63 ms for positive and negative trials, respectively. These data support the view that performance in the chess task with the consistent stimulus-to-rule mapping is dominated by automatic component processes (see Logan, 1979, for a review of the concurrent memory-load criteria of automaticity.) The following experiments (3A and 3B) assess performance on rule-based tasks predicted to be dominated by controlled processing components.

EXPERIMENT 3A: INCONSISTENT STIMULUS-TO-RULE MAPPING

Experiment 3A specifically addresses the effect of inconsistency at the stimulus-to-rule level on performance. The present experiment was the same as Experiment 2A except that the mapping among the external stimuli and the movement rules was inconsistent across trials. Previous research has shown that visual search performance does not improve substantially with varied mapping training (e.g., Fisk and Schneider, 1983; Schneider and Shiffrin, 1977). We would predict similar results for the inconsistent rule-based task if stimulus-to-rule consistency is critical for task improvement.

Method

Subjects. Six students from the University of South Carolina were recruited for participation in this experiment. Each subject was paid $4 per session (about one hour) for the first 10 sessions in which they participated and $5 per session for the remaining sessions of the experiment. All subjects were inexperienced at chess. Two of the subjects withdrew from the experiment after completing approximately half of the required trials and were not replaced.

Design. The design of this experiment was the same as in Experiment 2A except that the relationship among the letters and the movement rules was inconsistent. This inconsistent stimulus-to-rule mapping forced subjects to remap a given stimulus letter onto a different movement rule on each trial. The same six letters and movement rules that were used in Experiments 2A and 2B were used in the present experiment.

Subjects completed the 6048 trials in an average of 30 sessions. As in the previous experiments, each session consisted of subject participation for 30 minutes followed by a five-minute rest break; after the rest break the subjects participated for another 20 minutes. Subjects completed at most two sessions per day.

Results

The reaction-time data were collapsed into 25 groups of blocks (240 trials per subject per group of blocks). The first 48 trials were considered task orientation trials and eliminated from the analysis. The comparison slopes, presented as a function of practice for both positive and negative trials, are shown in Figure 4. As was the case in Experiment 2A, the average estimate of subjects' comparison slope improved as a function of practice. However, the improvement was considerably less than seen in Experiment 2A. Only the negative-trials slope estimate improved (statistically) with practice, $F(24,72) = 3.68, p < 0.001$. Positive-trial slope estimates did not reliably decrease with practice, $F(24,72) = 1.34, p = 0.174$. Overall the improvement attributed to practice was only 45%. On the average subjects given the consistent stimulus-to-rule training (in Experiment 2A) were five times faster at determining the presence or absence of a "threatening" situation (i.e., a piece positioned ready to capture the target).

The actual reaction-time data, presented as a function of memory-set size both early and late in practice, are presented in Figure 5. Examination of the figure leads to the conclusion that although the subjects did improve, the inconsistent stimulus-to-rule training did not lead to a qualitatively different form of information processing. Reaction times remained linearly related to the number of moves in the memory set. The comparison slope estimates for performance late in practice suggested that both the positive- and the negative-trial comparison process was serial and self-terminating. (That is, the ratio of negative to positive slopes was 2.35, which is indicative of a serial, self-terminating comparison process.) Error rates were acceptable (Reed, 1976); however, the present subjects' performance was more prone to error compared with the subjects in Experiment 2A. Early in practice error rates were 0.06, 0.08, and 0.12 for positive-trial memory-set sizes 1, 2, and 3, respectively. Negative-trial error rates were 0.06, 0.05, and 0.09 for memory-set sizes 1, 2, and 3, respectively. Late in practice the positive-trial error rates slightly decreased to 0.04, 0.05, and 0.10 for memory-set sizes 1, 2, and 3, respectively. Negative-trial error rates increased as a function of memory-set size, measuring 0.03, 0.07, and 0.11 for memory-set sizes 1, 2, and 3, respectively.

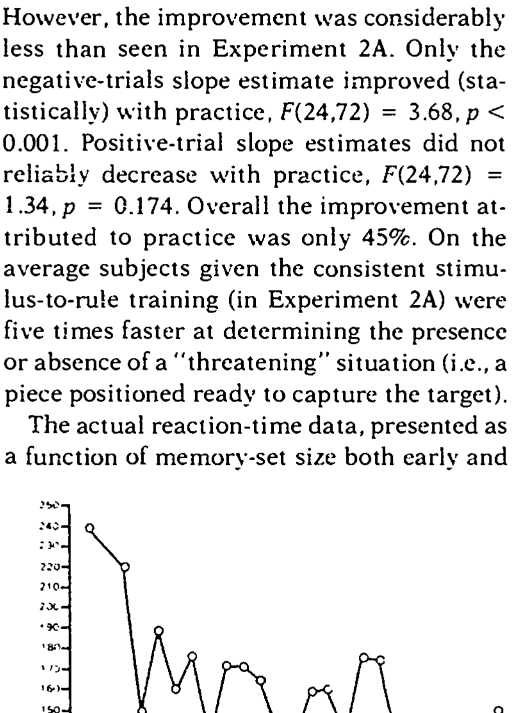

Figure 4. *Average comparison slope estimates (in ms) for positive trials (solid circles) and negative trials (open circles). The data are shown as a function of practice (groups of blocks). Data from Experiment 3A.*

When Figure 5 is compared with Figure 3, the reaction-time data show how much slower, overall, the subjects given inconsistent stimulus-to-rule training performed when compared with the consistent stimulus-to-rule training group. After the first group of training blocks the subjects receiving inconsistent stimulus-to-rule training were 557 ms slower (averaged across memory-set sizes and positive and negative trials) than the subjects receiving consistent stimulus-to-rule training. This difference almost doubled after practice. At that time the subjects who received inconsistent stimulus-to-rule training were 1051 ms slower than the

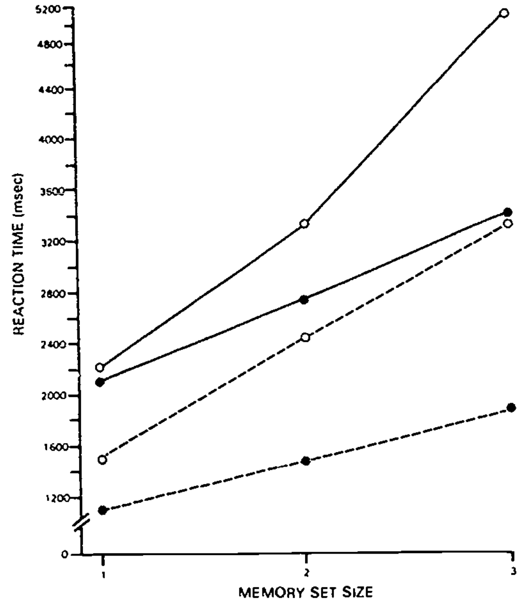

Figure 5. *Reaction time plotted as a function of memory-set size early in practice (solid lines) and late in practice (dashed lines). Solid circles represent average correct-trial reaction time when a capture was possible (positive trials), and the open circles show reaction time when no capture was possible (negative trials). Data from Experiment 3A.*

subjects who received consistent stimulus-to-rule training.

Data from the present experiment, when compared with their appropriate counterparts from Experiment 2A, support the conclusion that performance characteristics are a function of the type of rule-based training. Consistent stimulus-to-rule training results in performance that is both quantitatively and qualitatively different from novice-level performance. Inconsistent stimulus-to-rule practice does not lead to qualitatively different performance.

In addition, the subjective evidence also suggests that the inconsistent rule-based task was much more demanding than the consistent rule-based task: the two subjects who dropped out of the experiment commented that the task was too demanding for them. The subjects who completed the experiment spoke freely of its difficulty, suggesting that the task demanded most of their cognitive resources. The next experiment was conducted to examine the resource sensitivity of the inconsistent stimulus-to-rule processing.

EXPERIMENT 3B: DUAL-TASK ASSESSMENT

This experiment was the same as Experiment 2B except that the stimulus-to-rule mapping was inconsistent. Only two of the four subjects were willing to participate in the present experiment. Of the two who refused to continue participating, one withdrew from the experiment after two dual-task sessions and the other withdrew immediately following Experiment 3A.

Results

The individual data from the two subjects who finished the experiment are presented in Table 2. Both subjects' single-task digit spans were equivalent to their dual-task digit spans. The data presented in Table 2 provide additional evidence that the inconsistent stimulus-to-rule training did not lead to automatic component processing. For both of the subjects the effect of added memory load (the digit-span task) was interactive with

TABLE 2

Reaction Time for Single- and Dual-Task Trials (Experiment 3B)

	Positive			*Negative*		
Subject	*M1*	*M2*	*M3*	*M1*	*M2*	*M3*
			Single-Task Trials			
1	913	1284	1700	2074	3102	3042
3	1174	1684	2321	1315	2601	3326
Average	1043	1484	2010	1694	2851	3184
			Dual-Task Trials			
1	1065	1657	1891	2373	3061	3636
3	1381	1703	3309	1926	3549	5638
Average	1223	1680	2600	2149	3305	4637

memory-set size; as memory-set size increased, the effect of the added memory load also increased. The effect of added memory load was more pronounced for the negative trials than for the positive trials. Digit span did not differ between single- and dual-task trials, being 6.6 (6.4 and 6.9 for each subject) for single-task trials and 6.7 (6.5 and 6.9 for each subject) for dual-task trials.

Both subjects were less accurate on dual-task trials. For single-task trials error rates were 0.00, 0.05, and 0.13 for positive-trial memory-set sizes 1, 2, and 3, respectively. Negative-trial error rates were 0.00, 0.07, and 0.07 for memory-set sizes 1, 2, and 3, respectively. For dual-task trials the positive-trial error rates were 0.00, 0.13, and 0.16 and the negative-trial error rates were 0.00, 0.10, and 0.22 for memory-set sizes 1, 2, and 3, respectively.

CONCLUSIONS

The experiments were conducted to address the effects of intercomponent consistency on skill acquisition in a class of tasks requiring the learning and rapid application of rules. The importance of "perceptual" processes (e.g., chunking, perceiving relationships, etc.) in problem solving has long been understood (see, e.g., Chase and Simon, 1973; Newell and Simon, 1972; Simon and Barenfeld, 1969). However, empirical data have been lacking that demonstrate similarities in the development of perceptual and rule-dependent processes. The present subjects' performance was remarkably similar to performance observed with perceptual learning tasks in traditional visual search (Fisk and Schneider, 1983; Schneider and Shiffrin, 1977). This similarity suggests that mechanisms underlying perceptual learning (in visual search) and rule-based spatial learning are similar. In the present experiments the performance of subjects who were trained such that consistent stimulus-to-rule associations could be built up and strengthened with practice was far superior to that of subjects trained with inconsistent stimulus-to-rule relationships. This superiority was even more exaggerated in dual-task situations. Indeed, performance appears limited by components of tasks requiring controlled processing.

The present data also suggest that similar *detection* mechanisms underlie the visual search and memory activation for verbal stimuli such as semantic categories and the spatial movement rules. Previous results (e.g., Ackerman, 1986; Fisk and Schneider, 1983) show that practice in VM semantic category search leads to minimal performance improvement and minimal reduction in the comparison load effect, and that it results in an information-scanning process that remains extremely resource-sensitive. In striking contrast, CM semantic category search practice greatly improved speed of performance, substantially reduced the comparison load effect, and resulted in an information-scanning process that was resource-insensitive. This similarity between previous semantic category search data and the present data is important because it points to the validity of suggesting the relevance of consistent mapping in the training for *patterns of information* in complex tasks. The recognition of patterns of information is most certainly called for in order to perform many decision-making tasks successfully.

The present data have implications for the understanding and training of skilled problem-solving tasks. When playing a game of skill such as chess or when making rapid decisions in real-world situations, performance is dependent upon a sequence of information integration and the emergent choices. The information demands of such tasks can easily overload the active, effortful decision-making process. Indeed, many situations or tasks requiring problem solving place sharp limits on the cognitive processing capacity of the problem solver. In novel or changing problem environments added memory requirements (such as inconsistent or unfamiliar rules) can easily overload the problem solver's limited processing capacity (see Kotovsky et al., 1985, for a review). When training allows the development of automatization of subcomponents of the problem-solving activity, the chance of memory overload is reduced. The present data point to one such trainable subcomponent clearly present in most real-world problem-solving situations—the perceptual and rule-based components.

Although more questions remain to be answered, the present line of research should increase our ability to develop effective and efficient training programs for many real-world tasks that demand rapid information integration and decision making. The possibilities are exciting.

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REFERENCES

Ackerman, P. L. (1986). Individual differences in information processing: An investigation of intellectual abilities and task performance during practice. *Intelligence, 10,* 109–139.

Ackerman, P. L. (1987). Individual differences in skill learning: An integration of psychometric and information-processing perspectives. *Psychological Bulletin, 102,* 3–27.

Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior, 3,* 111–149.

Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychological Bulletin, 101,* 41–47.

Anzai, Y., and Simon, H. A. (1979). The theory of learning by doing. *Psychological Review, 86,* 124–140.

Book, W. F. (1925). *The psychology of skill.* New York: Gregg.

Briggs, G. E., and Johnsen, A. M. (1973). On the nature of central processes in choice reactions. *Memory and Cognition, 1,* 91–100.

Bryan, W. L., and Harter, N. (1899). Studies on the telegraphic language: The acquisition of a hierarchy of habits. *Psychological Review, 6,* 345–375.

Charness, N. (1979). Components of skill in bridge. *Canadian Journal of Psychology, 33,* 1–16.

Chase, W. G., and Simon, H. A. (1973). Perception in chess. *Cognitive Psychology, 5,* 29–46.

Cleveland, A. A. (1907). The psychology of chess and learning to play it. *American Journal of Psychology, 18,* 269–308.

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

Egan, D., and Schwartz, B. (1979). Chunking in recall of symbolic drawings. *Memory and Cognition, 7,* 149–158.

Elo, A. (1978). *The rating of chessplayers, past and present.* New York: Arco.

Fisk, A. D., Ackerman, P. L., and Schneider, W. (1987). Automatic and controlled processing theory and its application to human factors problems. In P. A. Hancock (Ed.), *Human factors psychology* (pp. 159–197) Amsterdam: North-Holland.

Fisk, A. D., and Schneider, W. (1983). Category and word search: Generalizing search principles to complex processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9,* 177–195.

Fisk, A. D., Schneider, W., and Logan, G. D. (1986). *An examination of the characteristics of automatic and controlled human information processing.* Unpublished manuscript, Georgia Institute of Technology, School of Psychology, Atlanta.

Fitts, P. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of human learning* (pp. 243–285). New York: Academic Press.

Gibson, E. J. (1977). How perception really develops: A view from outside the network. In D. LaBerge and S. J. Samuels (Eds.), *Basic processes in reading: Perception and comprehension* (pp. 155–173). Hillsdale, NJ: Erlbaum.

Holding, D. H. (1985). *The psychology of chess skill.* Hillsdale, NJ: Erlbaum.

Jeffries, R., Turner, A., Polson, P., and Atwood, M. (1981). Processes involved in designing software. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 111–141). Hillsdale, NJ: Erlbaum.

Kotovsky, K., Hayes, J. R., and Simon, H. A. (1985). Why are some problems hard? Evidence from Tower of Hanoi. *Cognitive Psychology, 17,* 248–294.

Kramer, A., Schneider, W., Fisk, A. D., and Donchin, E. (1986). The effects of practice and task structure on components of the event-related brain potential. *Psychophysiology, 23,* 33–47.

Lasker, E. M. (1975). *Lasker's manual of chess.* New York: Dover.

Logan, G. D. (1979). On the use of a concurrent memory load to measure attention and automaticity. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 189–207.

Logan, G. D. (1985). Skill and automaticity: Relations, implications, and future directions. *Canadian Journal of Psychology, 39,* 367–386.

McGeoch, J. A. (1927). The acquisition of skill. *Psychological Bulletin, 24,* 437–466.

Newell, A., and Simon, H. A. (1972). *Human problem solving.* Englewood Cliffs, NJ: Prentice-Hall.

Parasuraman, R. (1985). Detection and identification of abnormalities in chest X-rays: Effects of reader skill, disease prevalence, and reporting standards. In R. E.

Eberts and C. G. Eberts (Eds.), *Trends in ergonomics/human factors II* (pp. 59–66). Amsterdam: Elsevier Science Publishers.

Pear, T. H., (1927). Skill. *Journal of Personnel Research, 5*, 478–489.

Posner, M. I., and Snyder, C. R. R. (19‾5). Attention and cognitive control. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola symposium* (pp. 55–85). Hillsdale, NJ: Erlbaum.

Rasmussen, J., and Jensen, A. (1974). Mental procedures in real-life tasks: A case study of electronic troubleshooting. *Ergonomics, 17*, 293–307.

Reed, A. V. (1976). List length and the time course of recognition in immediate memory. *Memory and Cognition, 4*, 16–30.

Reitman, J. (1976). Skilled perception in GO: Deducing memory structures from inter-response times. *Cognitive Psychology, 8*, 336–356.

Saariluoma, P. (1984). *Coding problem spaces in chess: A psychological study*. Commentationes scientiarum socialium 23. Helsinki, Finland: The Finnish Society of Sciences and Letters.

Saariluoma, P. (1985). Chess players' intake of task-relevant cues. *Memory and Cognition, 13*, 385–391.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82*, 225–260.

Schneider, W. (1985). Training high-performance skills: Fallacies and guidelines. *Human Factors, 27*, 285–300.

Schneider, W., and Fisk, A. D. (1982). Concurrent automatic and controlled visual search: Can processing occur without resource cost? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8*, 261–278.

Schneider, W., and Fisk, A. D. (1983). Attention theory and mechanisms for skilled performance. In R. A. Magill (Ed.), *Memory and control of action* (pp. 119–143). New York: North-Holland.

Schneider, W., and Fisk, A. D. (1984). Automatic category search and its transfer. *Journal of Experimental Psychology: Learning, Memory and Cognition, 10*, 1–15.

Schneider, W., and Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, attention. *Psychological Review, 84*, 1–66.

Schneider, W., Vidulich, M., and Yeh, Y. Y. (1982). Training spatial skills for air-traffic control. In *Proceedings of the Human Factors Society 26th Annual Meeting* (pp. 10–14). Santa Monica, CA: Human Factors Society.

Shiffrin, R. M., and Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Review, 84*, 127–190.

Simon, H. A., and Barenfeld, M. (1969). Information-processing analysis of perceptual processes in problem solving. *Psychological Review, 76*, 475–483.

Sloboda, J. A. (1976). Visual perception of musical notation: Registering pitch symbols in memory. *Quarterly Journal of Psychology, 28*, 1–16.

Solomon, L., and Stein, G. (1896). Normal motor automatism. *Psychological Review, 3*, 492–512.