IMPLICIT LEARNING OF

FIRST- AND SECOND-ORDER TRANSITION PROBABILITIES

by

Gilbert Remillard

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF ARTS

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Abstract

Using a serial reaction time task (Nissen & Bullemer, 1987), two experiments directly examined people's ability to implicitly learn first- (Experiment 1) and second-order (Experiment 2) transition probabilities. On each trial, the target appeared at one of four locations on the screen and participants pressed the corresponding key. In experiment 1, the probability that the target appeared at a particular location on trial (t) given its location on trial (t-1) was 0, 0.40, 0.50, or 0.60. In experiment 2, the probability that the target appeared at a particular location on trial (t) given its locations on trials (t-2) and (t-1) was 0, 0.40, 0.50, or 0.60. In both experiments, reaction time (error rate) was slower (greater) on low (0.40) than high (0.60) probability transitions. Performance on medium (0.50) transitions was in between. Differences in reaction time and error rate were greater in experiment 1 than experiment 2. The results suggest first- and second-order probabilities were learned, but that learning of second-order probabilities was impaired relative to learning of first-order probabilities. On explicit measures asking participants to indicate which transitions were more likely to occur (Experiment 1) or to estimate the transition probabilities (Experiment 2), performance was at chance. The results provide strong evidence that people can implicitly learn first- and second-order transition probabilities.

Implicit Learning of
First- and Second-Order Transition Probabilities

Implicit learning has been the focus of much research in recent years. A central reason for the growing interest in implicit learning is that it may represent a learning mechanism different from that underlying explicit learning (Shanks & St. John, 1994). In contrast to explicit learning, which proceeds with an awareness of what has been learned, implicit learning seems to proceed without conscious awareness (Berry, 1994; Reber, 1989; Seger, 1994; Shanks & St. John, 1994). This distinction suggests the existence of different learning mechanisms.

A number of research paradigms have been employed to study implicit learning. One that has become rather popular is sequence learning. Implicit sequence (or serial) learning is learning about a sequence of events in the absence of explicit, conscious knowledge of the sequence. Implicit serial learning has been studied using the serial reaction time (SRT) task (Lewicki, Czyzewska, & Hoffman, 1987; Nissen & Bullemer, 1987). On each trial of the SRT task, a target appears at any one of a number of locations on the computer screen and participants press, as quickly as possible, the key corresponding to the location of the target. The target then disappears and a few hundred milliseconds later reappears in a different location.

In most applications of the SRT task, the sequence of target locations repeats following a number of trials. Sequence learning is observed when the repeating sequence elicits faster reaction times than a sequence of random target locations. In other applications of the SRT task, target locations are contingent on previous locations. Sequence learning is observed when a change in the contingencies produces an increase in reaction time or when, given previous locations, more probable succeeding locations elicit faster reaction times than less probable succeeding locations. Awareness of the sequential structure has been assessed in a number of ways. These include verbal report (i.e., free recall), cued recall tasks in which participants predict the next target location, and recognition tasks in which participants judge whether subsequences were part of the sequence.

Numerous studies have provided evidence for implicit serial learning. Participants in these studies learn the sequence, as assessed by reaction time, and yet show no explicit knowledge of the sequence as assessed by verbal report, cued recall tasks, or recognition tasks (Cherry & Stadler, 1995; Cleeremans & McClelland, 1991, Experiment 1; Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Frensch & Miner, 1994; Hartman, Knopman, & Nissen, 1989; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Lewicki et al., 1987; Lewicki, Hill, & Bizot, 1988; McDowall, Lustig, & Parkin, 1995; Reed & Johnson, 1994; Stadler, 1989, 1993, 1995; Willingham, Greeley, & Bardone, 1993; Willingham, Nissen, & Bullemer, 1989). Moreover, sequence learning has been observed in individuals with memory impairments such as the elderly (Cherry & Stadler, 1995; Frensch & Miner, 1994; Harrington &

Haaland, 1992; Howard & Howard, 1989, 1992); those suffering from amnesia, Korsakoff's syndrome, or Alzheimer's disease (Cleeremans, 1993; Ferraro, Balota, & Connor, 1993; Knopman, 1991a; Knopman & Nissen, 1987; Nissen & Bullemer, 1987; Nissen, Willingham, & Hartman, 1989; Reber & Squire, 1994); and those exposed to amnesia-inducing drugs such as scopolamine and lorazepam (Knopman, 1991b, Experiment 1; Nissen, Knopman, & Schacter, 1987).

Although SRT studies show that something about a sequence has been learned, most fail to identify which of a number of possible constraints have actually been learned. This has been a major criticism of implicit serial learning studies because one cannot then be certain that the measures of explicit sequence knowledge assessed awareness of what was truly learned (Perruchet, Gallego, & Savy, 1990; Shanks, Green, & Kolodny, 1994; Shanks & St. John, 1994). If participants are learning A, then results from measures assessing conscious knowledge of B say nothing about participants' awareness of A. Measures must assess conscious knowledge of A. Thus it is *important* to isolate precisely the information learned. These are the goals of the current study -- to isolate the precise information learned and to assess explicit knowledge of the information.

Two kinds of information that could be learned are first- and second-order transition probabilities. A first-order transition probability is the probability of an event E occurring on trial t given the occurrence of the previous event A_1 on trial t-1 (symbolically, $P(E|A_1)$). A second-order transition probability is the probability of an event E occurring on trial t given the occurrence of the previous two events A_2 and A_1 on trials t-2 and t-1 respectively (symbolically, $P(E|A_2\text{-}A_1)$).

There is some evidence that, when exposed to a sequence of events, individuals may learn first- and second-order transition probabilities. Stadler (1992) observed that sequences high in statistical structure elicited faster reaction times than sequences low in statistical structure. Sequences high in statistical structure have fewer unique subsequences than sequences low in statistical structure, making events in the sequence more predictable on the basis of preceding events. Thus, participants may have learned first-, second-, or higher-order transition probabilities. However, Stadler did not assess the exact information learned. Statistical structure may also influence performance in non-SRT tasks such as in the mental calculation of sequences of arithmetic operations (Wenger & Carlson, 1996, Experiment 1).

There is also evidence that people can learn first- and second-order transitional probability information within a repeating sequence. For sequences of the form 1-2-3-2-4-3, reaction time on 2 following 1 and on 3 following 4 (which have first-order transition probabilities of 1.0) is faster than the reaction time on other transitions (which have first-order transition probabilities of 0.5) (Curran & Keele, 1993, Experiment 2; Frensch, Buchner,

& Lin, 1994). This comparison, however, confounds first-order transition probability with the number of response alternatives. For example, reaction time on 3 following 4 may be faster than on 3 following 2 not because P(3|4) = 1.0 is greater than P(3|2) = 0.50, but because there are fewer locations that can follow 4 than 2. Only location 3 can follow location 4, but locations 3 and 4 can follow location 2. Consequently, the number of response alternatives following 4 is less than that following 2. Increasing the number of response alternatives tends to increase reaction time (Hyman, 1953; Kornblum, 1975).

With respect to learning of second-order transition probabilities, Reed and Johnson (1994) presented participants with a sequence in which the location of the target on the current trial could not be predicted from its location on the previous trial, but was completely predictable from its location on the previous two trials. In other words, second-order transition probabilities were 1.0 (e.g., P(3|2-1) = 1.0) or zero (e.g., P(4|2-1) = 0). When the probabilities were switched (e.g., P(3|2-1) = 0 and P(4|2-1) = 1.0), reaction time increased sharply. Although participants seemed to have learned the second-order transition probabilities, they could have learned third- or higher-order transition probabilities as these covaried with second-order transition probabilities. Participants also could have learned the probability of an event E occurring on trial t given the occurrence of event A on trial t-2 because the switch in second-order transition probabilities also resulted in a change in these lag 2 probabilities. Finally there is the problem of frequency. When second-order transition probabilities were switched, new runs of three were introduced (e.g., 2-1-4). The increase in reaction time could have simply reflected a lack of practice with such runs (also see Jackson, Jackson, Harrison, Henderson, & Kennard, 1995).

The sequence used by Reed and Johnson (1994) had second-order transition probabilities of 0 vs 1.0. In a similar study, Schvaneveldt and Gomez (1996) used second-order transition probabilities of 0.20 vs 0.80. Reaction time was faster on the high probability transitions than on the low probability transitions suggesting that participants had learned the second-order transition probabilities. However, as in the Reed and Johnson (1994) study, second-order transition probabilities were confounded with higher-order transition probabilities and with lag 2 probabilities.

The most extensive study of people's ability to learn probabilistic information is that of Cleeremans and McClelland (1991; also see Cleeremans, 1993; Jimenez, Mendez, & Cleeremans, 1996). Participants performed a six-choice SRT task with a probabilistic sequence of target locations generated by a finite-state grammar. The participants were exposed to a massive 60,000 trials over the course of 20 sessions. Fifteen percent of the trials were nongrammatical; that is, the locations were chosen at random rather than from the grammar. With training, ungrammatical trials incurred increasingly longer response latencies relative to grammatical trials suggesting that participants were learning the underlying structure of the sequence. Moreover, first- and second-order transition probabilities were both negatively correlated with reaction time. This suggests learning of the first- and second-order transition probabilities. However, the complexity of the sequence produced by the grammar does not make it obvious to what extent participants were learning such probabilities. Other factors inherent in the sequence could have produced or contributed to the negative correlations.

To determine what these factors might be, we generated 60,000 trials in a manner identical to Cleeremans and McClelland and determined the various first- and second-order transition probabilities. First-order transition probabilities approached one of 0.05 (nongrammatical transitions), 0.20, 0.30, 0.40, or 0.60. Cleeremans and McClelland used the letters P, Q, S, T, V, and X to denote the six target locations. T-V was the only transition with a first-order transition probability near 0.60 (i.e., $P(V|T) = 0.64$). Transitions with first-order transition probabilities of 0.40 (e.g., Q-X) or 0.60 (e.g., T-V) were often involved in runs like Q-X-Q-X and T-V-T-V whereas transitions with first-order transition probabilities of 0.20 or 0.30 were not. Reaction times on the last element of runs like Q-X-Q-X and T-V-T-V tend to be fast due to what Cleeremans and McClelland have called short-term priming effects. Responding is affected by rapidly decaying activations from preceding trials. For example, responses to events (e.g., T) and sequential pairings of events (e.g., T-V) remain primed for a short period of time. Consequently, reaction times to the last element of runs like T-V-T and T-V-T-V are fast. Thus short-term priming effects may have contributed to the negative correlation between first-order transition probability and reaction time.

Another possible contributing factor is number of response alternatives. As an example, for the transitions P-Q, where P(Q|P) is near 0.20, and V-X, where P(X|V) is near 0.40, reaction time may be faster on the latter transition not because of its higher transition probability, but rather because there are three grammatical successors to V and four grammatical successors to P. Increasing the number of response alternatives tends to increase reaction time (Hyman, 1953; Kornblum, 1975). With respect to second-order transition probabilities, lag 2 information was a potential confound. For example, X was more likely than S to follow T-V. However, X was also more likely than S to occur on trial t given that T occurred on trial t-2. Finally, some of the first- and second-order transition probabilities were confounded. For example, X was more likely than S to follow T-V, but X was also more likely than S to follow V.

The Current Research

The preceding research provides some evidence that people can learn first- and second-order transition probabilities. However, the evidence is far from conclusive. Factors such as number of response alternatives, lag 2 probabilities, practice, short-term priming effects, and covariation of first-, second-, and higher-order transition probabilities are potential confounds in a number of the studies. Also, the use of fixed, repeating sequences, or complex probabilistic sequences as in Cleeremans and McClelland (1991) may introduce additional, unknown confounds. Even if people are in fact learning first- and second-order transition probabilities, the explicit/implicit status of the information is unknown. People's conscious awareness of first- and second-order transition probabilities has not been directly assessed. Finally, the transition probabilities used in most studies have been quite disparate (e.g., 0.5 vs 1.0, 0 vs 1.0, 0.20 vs 0.80, 0.05 vs 0.60). Would implicit learning be observed if transition probabilities were much closer (e.g., 0.40 vs 0.60)? The purpose of the two experiments in the current study was to address some of the above factors and examine people's ability to implicitly learn first- and second-order transition probabilities.

Experiment 1

Experiment 1 examined implicit learning of first-order transition probabilities (henceforth, first-order probabilities). Participants performed a four-choice SRT task over the course of three sessions. The sequences of target locations were pseudorandomly generated with first-order probabilities of 0.40, 0.50, and 0.60. For example, locations 2 and 3 might follow location 1 with probabilities 0.60 and 0.40 respectively, whereas locations 1 and 4 might follow location 2 with probabilities 0.50 and 0.50 respectively.

Slower reaction times on 3 than 2 following 1, and similar reaction times on 1 and 4 following 2, would indicate learning of the first-order probabilities.

A number of potentially confounding factors were addressed. Simple event frequencies, lag 2 probabilities, and lag 3 probabilities were all held constant. Given the occurrence of the target in any location, there were two locations at which it could appear next. Thus number of response alternatives was not confounded with first-order probability. Because high probability transitions occurred more frequently than low probability transitions, a difference in their reaction times could be due solely to differential practice. If this were the case, then, according to the power law of practice (Newell & Rosenbloom, 1981), reaction time performance on low and high probability transitions should asymptote at the same level with extended training. Consequently, if reaction time on low and high probability transitions neared asymptote in session 3, and if the difference in their reaction times persisted, then this would suggest that differential practice was not solely responsible for the reaction time difference.

First-order probabilities were not independent of second- or higher-order probabilities. For example, if 2 followed 1 with probability 0.60, then 2 also followed 3-1 and 4-3-1 with probability 0.60. As a result, slower reaction times on low than high probability transitions, and similar reaction times among medium probability transitions could reflect learning of first-, second-, or higher-order probabilities. To test for learning of first-order probabilities, the SRT task was modified in session three. For some blocks of trials in session three (i.e., the discrete blocks), the trials were presented in discrete sets of two rather than in a continuous fashion. After every second trial, a pause was introduced. Each discrete set of two trials was a transition (e.g., 1-3, 1-2, 2-1, 2-4, etc.) with each transition occurring equally often in a discrete block. Transitions were presented in a random order. The discrete blocks should make it difficult for participants to use second- or higher-order probability information. Consequently, slower reaction times on low than high probability transitions, and similar reaction times among medium probability transitions would be strong evidence for learning of the first-order probabilities.

Because high probability transitions were more frequent than low probability transitions, high probability transitions occurred more closely to one another and hence, may have benefitted to a greater extent from short-term priming effects. Short-term priming effects were handled in two ways. First, such effects should not be a factor in the discrete blocks. In the discrete blocks, transitions occurred with equal frequency and so short-term priming effects should equally affect low and high probability transitions. Second, short-term priming effects seem to weaken with training (Cleeremans & McClelland, 1991; Soetens, Boer, & Hueting, 1985). If short-term priming effects weaken with training and differences in reaction time between low and high probability transitions do not decrease, this would suggest that the differences in reaction time were not solely the result of short-term priming effects.

Short-term priming effects were assessed by comparing runs like 1-2-1-2 with runs like 4-2-1-2, and runs like 4-3-1-2 with runs like 1-3-1-2. Reaction time to the last element should be faster in the first than second run of each comparison. In the first comparison, the occurrence of 1-2-1 primes a subsequent 2; the result being a fast reaction time. In the second comparison, the occurrence of 1-3-1 primes a subsequent 3 which does not occur; the result being a slow reaction time. If differences in reaction time between fast and slow runs diminish with training, this would suggest a weakening of short-term priming effects.

At the end of session three, a multiple-choice questionnaire was administered to assess explicit knowledge of the first-order probabilities. There were four items with three choices per item. Each item corresponded to a location and required participants to indicate where the target was most likely to appear next given its current location. For example, one item stated that if the target appeared in location 1, then (a) it went to location 2 more often than to location 3, (b) it went to location 3 more often than to location 2, or (c) it went to locations 2 and 3 equally often.

Method

Participants

The participants were 16 university undergraduates (12 women, 4 men) ranging in age from 18 to 35 years (M = 22 years). One participant was replaced because she reported difficulty performing certain transitions, and because her reaction times on the reported transitions were exceptionally slow.

The SRT Task

The four-choice SRT task was run on a personal computer with a standard keyboard. Millisecond timing was implemented using Bovens and Brysbaert's (1990) Turbo Pascal routine. The display consisted of four short lines arranged in a row approximately 5 cm from the bottom of the screen. The lines were 0.3 cm in length and separated by intervals of 1.7 cm. The participants sat approximately 50 cm from the screen. The four response keys were the 'D', 'F', 'J', and 'K' keys. The response keys were compatibly mapped onto the four screen locations so that the 'D' key corresponded to the leftmost, or first, screen location, the 'F' key corresponded to the second location, and so on. Participants placed their left middle and index fingers on the 'D' and 'F' keys respectively, and their right index and middle fingers on the 'J' and 'K' keys respectively. Red stickers were applied to the response keys for ease in identification.

On each trial, the target, a lower-case 'o', appeared above one of the four lines and participants pressed the corresponding response key. If the correct key was pressed, the target immediately disappeared. If an incorrect key was pressed, this was an error and the target remained in its current location until the correct key was pressed. After the target disappeared, it reappeared 400 ms later at a different location. If any response keys were pressed after 400 ms, the reappearance of the target was further delayed until all keys were released. The computer recorded responses and reaction times (i.e., the time elapsed between target appearance and the first key press).

There was one session per day on three consecutive days. Session one began with a practice block of 50 random trials with the constraint that the target did not appear in the same location on successive trials. There were 12 blocks of trials in sessions one and two, and 14 blocks in session three. The blocks were 101 trials each with the exception of blocks 3, 6, 9, and 12 in session three. These were the discrete blocks. Each contained 40 discrete sets of two trials for a total of 80 trials. The discrete sets were separated by four x's lasting 1000 ms. The x's overwrote the four lines on the screen after every second trial. After 1000 ms, the x's were replaced by the four lines and 400 ms later the target appeared. At the beginning of session three was a 40-trial discrete block for practice.

Feedback concerning reaction time or error rate was provided at the end of each block. The numbers 1 to 12 or 1 to 14, corresponding to the number of blocks in a given session, appeared vertically along the side of the screen. An asterisk appeared beside numbers for discrete blocks. Beside the number of the just completed block, one of two types of information was displayed. If more than 10% of responses in the block were incorrect, the computer displayed the message 'too many errors' and the error rate (e.g., 15%). If the error rate was less than or equal to 10%, a horizontal line, its length representing the average reaction time for that block, was displayed. The average reaction time appeared at the end of the horizontal line. Thus participants could examine their reaction time performance across blocks by comparing the lengths of the lines. Participants initiated the next block of trials at their discretion by pressing a key in response to a prompt on the screen.

The Sequential Structure

For each participant, the sequence of target locations was randomly generated with the constraint that across every two blocks (i.e., 202 trials), first-order probabilities were as shown in Table 1 (see Appendix A for a description of how sequences were generated to meet these and other constraints). Numbering the four screen locations from left to right, 1, 2, 3, and 4 respectively, Table 1 describes the first-order probabilities and their labels. For example, if the target appeared in location 1 on trial (t-1), then on the subsequent trial (t), it appeared in either location 2, with probability 0.60, or in location 3, with probability 0.40. That is, $P(2|1) = 0.60$ and $P(3|1) = 0.40$.

First-order probabilities of 0.40 and 0.60 were labelled EL (for experimental low) and EH (for experimental high) respectively (see Table 1).

Table 1
First-Order Probabilities and Their Labels (Experiment 1)

		Trial (t)			
		1	2	3	4
	1	--	.60 (EH)	.40 (EL)	--
Trial	2	.50 (CH)	--	--	.50 (CL)
(t-1)	3	.50 (CL)	--	--	.50 (CH)
	4	--	.40 (EL)	.60 (EH)	--

In order to compare reaction times among medium probability transitions (e.g., reaction time on 1 versus 4 given 2), the four medium probability transitions were divided into two groups -- group CL (for control low) and group CH (for control high). Although there were a number of ways of forming two groups, I chose this particular formation because it most closely matched the EL and EH transitions. CL and CH transitions shared the same locations as EL and EH transitions respectively. For example, the CL transition 3-1 involved the same locations as the EL transition 1-3. The advantage of dividing the medium probability transitions in this manner is that it permitted one to determine whether a difference in reaction time between EL and EH transitions was due to learning of the first-order transition probabilities (e.g., 2 is more likely than 3 to follow 1), or to learning that a pair of locations tended to follow one another regardless of direction (e.g., locations 1 and 2 tend to follow one another). If the latter is learned, then the difference in reaction time between CL and CH transitions should be the same as that between EL and EH transitions. A smaller difference would suggest learning of the first-order transition probabilities. In sum, transitions could be categorized along two dimensions -- whether they belonged to the experimental (E) or control (C) group, and whether they were of low (L) or high (H) probability. A group (E, C) by probability (L, H) interaction with slower reaction times on EL than EH transitions, and a smaller difference between CL and CH transitions would suggest learning of the first-order probabilities.

Across every two blocks, the sequential structure was controlled in a number of ways. The target appeared in each location an equal number of times so that $P(1) = P(2) = P(3) = P(4) = 0.25$. Lag 2 probabilities were held constant at 0.50. For example, the probability of the target appearing in location 2 on trial (t) given its appearance in location 3 on trial (t-2) was 0.50. That is, $P(2|3\text{-}x) = 0.50$. Likewise, lag 3 probabilities were 0.50 (e.g., $P(2|4\text{-}x\text{-}x) = 0.50$). Other probabilities were also held constant at 0.50. For example, $P(2|1\text{-}3\text{-}x) = 0.50$. Finally, given any location, there were two possible locations that could follow (see Table 1). For example, locations 2 or 3 could follow location 1. As a result, first-order probability was not confounded with number of response alternatives.

In the sequential structure, second- and third-order probabilities were kept redundant with first-order probabilities. For example, redundant second- and third-order probabilities for $P(2|1) = 0.60$ (see Table 1) were $P(2|2\text{-}1) = P(2|1\text{-}3\text{-}1) = 0.60$. As a result, second- and third-order probabilities added no information over and above that provided by the first-order probabilities.

To ensure that each of the eight transitions (e.g., 1-2, 1-3, 2-1, etc.) served as an EL, EH, CL, and CH transition, four versions of Table 1 were created. One version was Table 1. A second version was created from Table 1 by interchanging EL and EH, and CL and CH transitions. The third version was created from Table 1 by interchanging EL and CL, and EH and CH transitions. The fourth version was formed from Table 1 by interchanging EL and CH, and EH and CL transitions.

Short-term priming effects. In order to assess short-term priming effects, the 32 possible runs of length four were classified according to three criteria (see Table 2) -- the run ends with an EL, EH, CL, or CH transition, the last three elements in a run form an alternation (A) or nonalternation (N), and the run is fast (F) or slow (S). As an example, consider the runs 1-3-1-3 and 4-3-1-3. Both runs end with the EL transition 1-3, and the last three elements in each run, 3-1-3, form an alternation. Reaction time should be faster to the last element of the first than second run because the 1-3 transition is repeated. Thus 1-3-1-3 was classified as a fast run and 4-3-1-3 as a slow run. For the EL runs 4-2-1-3 and 1-2-1-3, the last three elements, 2-1-3, form a nonalternation, and reaction time should be slower to the last element of the second than first run because the primed transition 1-2 does not follow the second 1.

Table 2
Categorization of the 32 Runs of Length Four as a Function of the Last Three Elements Comprising an Alternation (A) or Nonalternation (N) and the Run Being Fast (F) or Slow (S). Numbers in Parentheses Indicate the Approximate Number of Times a Run Occurred Across Every Ten Blocks of the SRT Task (Experiment 1)

	Transition Ending a Run (see Table 1)			
Run	EL	EH	CL	CH
FA	1-3-1-3 (20) 4-2-4-2 (20)	1-2-1-2 (45) 4-3-4-3 (45)	3-1-3-1 (25) 2-4-2-4 (25)	2-1-2-1 (37) 3-4-3-4 (37)
SA	4-3-1-3 (30) 1-2-4-2 (30)	4-2-1-2 (30) 1-3-4-3 (30)	2-1-3-1 (25) 3-4-2-4 (25)	3-1-2-1 (37) 2-4-3-4 (37)
FN	4-2-1-3 (20) 1-3-4-2 (20)	4-3-1-2 (45) 1-2-4-3 (45)	2-4-3-1 (37) 3-1-2-4 (37)	3-4-2-1 (25) 2-1-3-4 (25)
SN	1-2-1-3 (30) 4-3-4-2 (30)	1-3-1-2 (30) 4-2-4-3 (30)	3-4-3-1 (37) 2-1-2-4 (37)	2-4-2-1 (25) 3-1-3-4 (25)

Table 2 also lists the approximate number of times a specific run occurred across every ten blocks of the SRT task. Thus the FA run 1-3-1-3 ending with an EL transition occurred approximately 20 times across every ten blocks of the SRT task. Note that different proportions of EL and EH transitions were involved in different types of runs. For example, a smaller percentage of EL (40%) than EH (60%) transitions were involved in fast runs, whereas a greater percentage of EL (60%) than EH (40%) transitions were involved in slow runs. Therefore, calculating overall median reaction times on EL and EH transitions might result in a difference that is not due to learning of first-order probabilities. To avoid this problem, and also to assess short-term priming effects, the median reaction on the last element of a run was determined for each type of run in Table 2. Faster reaction times on fast than slow runs (i.e., an effect of speed) would suggest the presence of short-term priming effects. The convergence of reaction times on fast and slow runs across sessions (i.e., a session by speed interaction) would in turn suggest that short-term priming effects weakened with training.

Discrete blocks. In each of the four discrete blocks in session three, there were 80 trials presented in discrete sets of two trials with each set separated by four x's lasting one second. A discrete set contained one of the eight possible runs of two shown in Table 1. In a discrete block, the eight runs were presented five times and in a random order each time. Session three began with a 40-trial discrete block for practice. The eight runs of two trials were presented in a random order twice followed by four other runs randomly chosen from the eight runs.

The Awareness Questionnaire

The questionnaire to measure explicit knowledge of the first-order probabilities consisted of four items corresponding, respectively, to the first through fourth rows of Table 1. For each item, there were three options. The questionnaire is listed in Appendix B. As an example, item one corresponded to row one of Table 1 and asked participants to indicate whether the letter o, after appearing in position 1, went to position 2 more often than position 3, went to position 3 more often than position 2, or went to positions 2 and 3 equally often. The instructions located at the top of the questionnaire were read to participants and screen positions 1, 2, 3, and 4 were pointed out. After indicating their understanding of the instructions and items, participants completed the questionnaire on their own. The four lines that appeared on the screen during the SRT task remained on the screen for reference. The keyboard was removed so keys could not be pressed.

Procedure

The 16 participants were randomly assigned to the four versions of Table 1 resulting in four participants per version. The participants were tested individually. At the beginning of session one, the SRT task was described to participants and they were instructed to try and improve their reaction time with practice while keeping their error rate below 10%. At the start of session three, the discrete blocks were described to the participants. The structure underlying the sequence of locations was never mentioned. Immediately following the last block of session three, the questionnaire to assess explicit knowledge of the first-order probabilities was administered. Participants were not informed of the questionnaire until the end of session three.

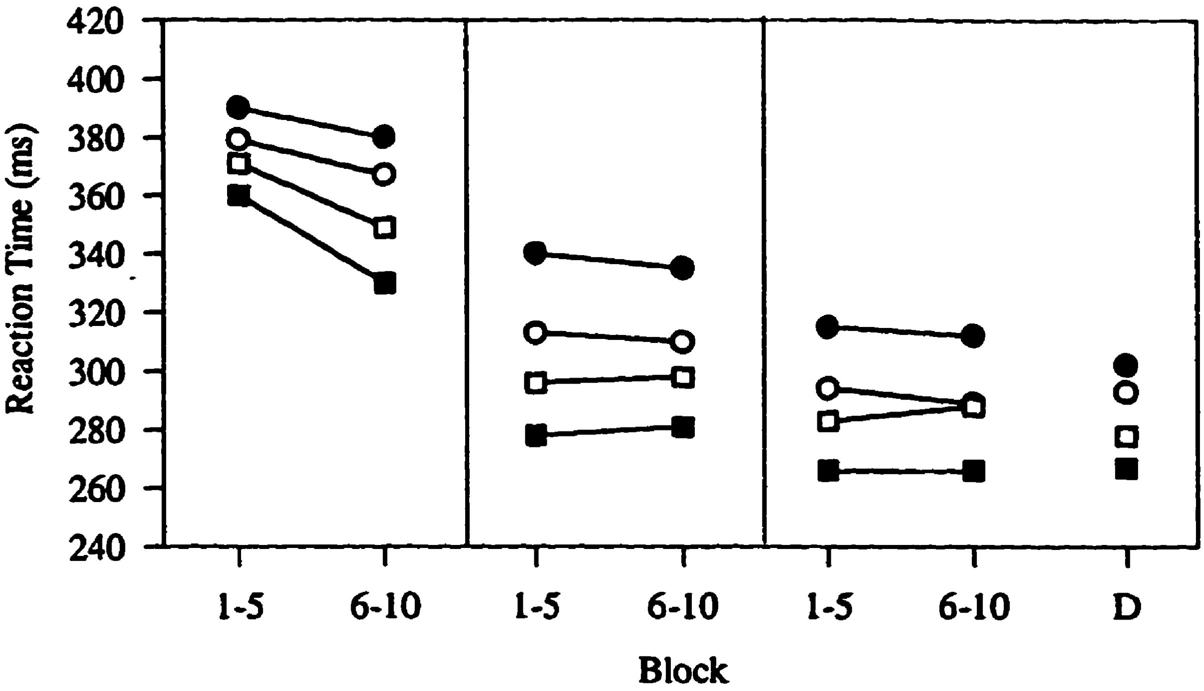
Results and Discussion

Of main interest was reaction time performance early versus late in training. Consequently, analyses focused on sessions 1 and 3. Reaction time analyses were based on the reaction times of correct responses. Error rates were also examined. If participants were learning the first-order probabilities, they might be expected to make errors on a greater percentage of EL than EH transitions and on a similar percentage of CL and CH transitions. The level of significance for all analyses was $p < .05$.

The median reaction time on the last element of a run was determined for each type of run in Table 2. Median reaction times were determined over blocks of five (i.e., blocks 1-5 and 6-10) in order to obtain a sufficient number of observations, especially for FA and FN runs ending with an EL transition. The percentage of runs that incurred an incorrect response on the last element was also determined for each type of run. Figure 1 shows reaction time and error rate, averaged across runs, as a function of session, transition, and block. The results from the discrete blocks are also shown in Figure 1. Figure 2 shows reaction time and error rate, averaged across blocks 1-5 and 6-10, as a function of session, transition, and run.

Reaction time and error rate analyses were conducted in four stages. First, session 3 performance was examined to determine whether participants learned the first-order probabilities. Second, practice and short-term priming effects were examined to determine whether these diminished with training. Third, the data from the discrete blocks were analyzed. Finally, the time course of learning was examined by comparing performance in session 1 to that in session 3, and by looking more closely at performance within session 1.

Session 3



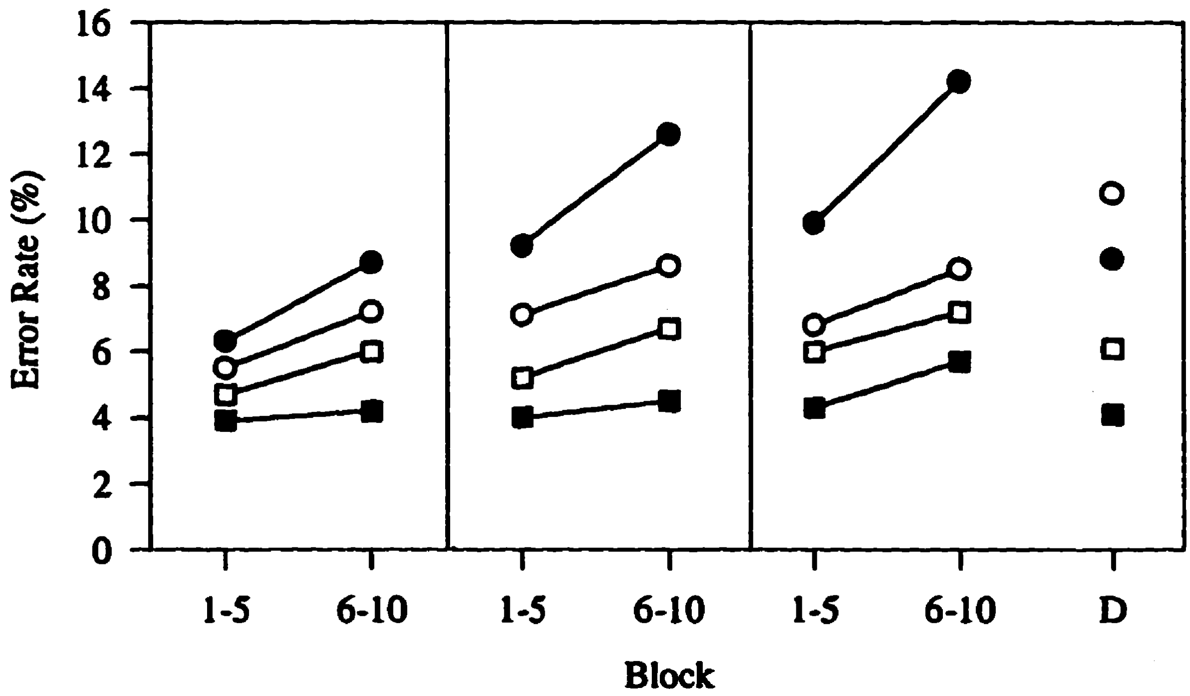


Figure 1. Reaction time (top panel) and error rate (bottom panel) as a function of session (separated by vertical lines), block (discrete blocks = D), and transition (EL = closed circles, EH = closed squares, CL = open circles, CH = open squares) in experiment 1.

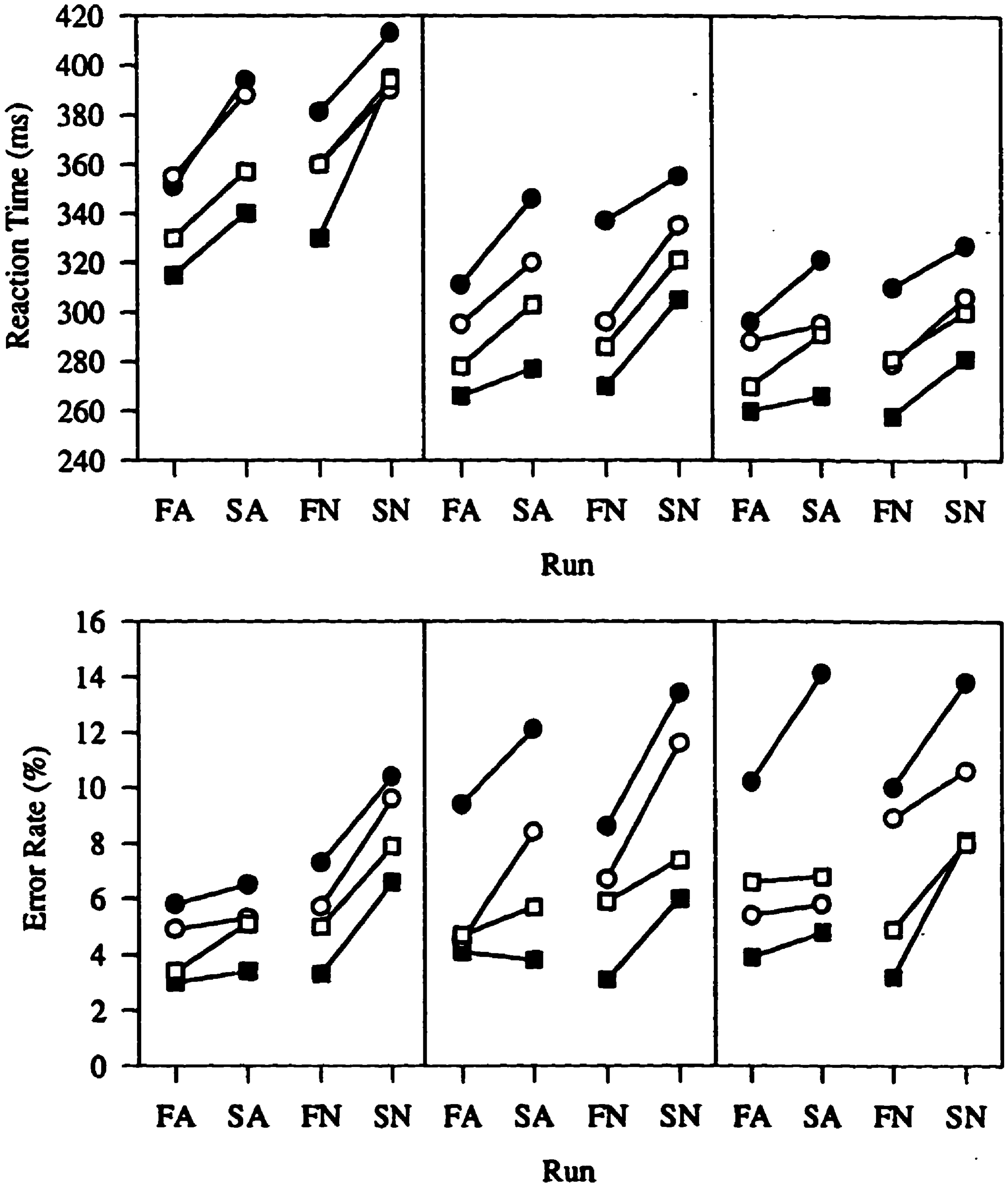


Figure 2. Reaction time (top panel) and error rate (bottom panel) as a function of session (separated by vertical lines), run, and transition (EL = closed circles, EH = closed squares, CL = open circles, CH = open squares) in experiment 1.

Analyses of variance with group (E, C), probability (L, H), block (1-5, 6-10), speed (F, S), and ending (A, N) as within-subjects factors were performed on the reaction time and error rate data from session 3. Only results involving group by probability will be discussed.

Reaction time. The analysis revealed a group x probability interaction, $F(1, 15) = 22.91$, $MSE = 2348.58$, $p < .001$. Reaction time was slower on EL ($M = 314$ ms) than EH ($M = 266$ ms) transitions, $F(1, 15) = 60.11$, $MSE = 2387.19$, $p < .001$, and there was no difference between CL ($M = 292$ ms) and CH ($M = 285$ ms) transitions, $F(1, 15) < 1$. The group x probability interaction was qualified by a marginal speed x group x probability interaction, $F(1, 15) = 3.44$, $MSE = 208.01$, $p = .084$, and a significant ending x speed x group x probability interaction, $F(1, 15) = 7.02$, $MSE = 2387.19$, $p = .018$. In spite of the qualifications, the preceding pattern of differences was observed in all runs. For each run, reaction time was slower on EL than EH transitions, four $F(1, 15)$s > 25.87, four ps $< .001$, and there was no difference between CL and CH transitions, four $F(1, 15)$s < 2.97, four ps $> .10$. Thus session 3 reaction times suggest learning of the first-order probabilities. Participants were slower on EL than EH transitions, and there was no difference between CL and CH transitions.

Error rate. The analysis revealed a group x probability interaction, $F(1, 15) = 28.95$, $MSE = 39.51$, $p < .001$. Error rate was greater on EL ($M = 12.0\%$) than EH ($M = 5.0\%$) transitions, $F(1, 15) = 20.37$, $MSE =$

155.38, $p < .001$, and there was no difference between CL ($M = 7.6\%$) and CH ($M = 6.6\%$) transitions, $F(1, 15) < 1$. Although the group x probability interaction was qualified by an ending x group x probability interaction, $F(1, 15) = 5.98$, $MSE = 47.35$, $p = .027$, and a marginal block x speed x ending x group x probability interaction, $F(1, 15) = 3.53$, $MSE = 13.27$, $p = .080$, the preceding pattern of differences was observed in most runs. For each run, the error rate was greater on EL than EH transitions, four $F(1, 15)$s > 8.86, four ps < .010. There was no difference between CL and CH transitions for FA, SA, and SN runs, three $F(1, 15)$s < 1.56, three ps > .231. However, for FN runs, error rate was greater on CL than CH transitions, $F(1, 15) = 5.15$, $p = .038$. In general, error rates in session 3 paralleled the reaction times. The only exception was the error rate difference between CL than CH transitions in the context of FN runs.

Practice and Short-Term Priming Effects

Reaction time. The session 3 difference in reaction time between EL and EH transitions was unlikely due to differences in practice. Reaction time performance on EL and EH transitions approached asymptote, and the difference in their reaction times persisted. Evidence for near asymptotic performance comes from the fact that for both EL and EH transitions, reaction time in session 3, averaged across runs, did not change from block 1-5 to block 6-10, both $F(1, 15)$s < 1. Moreover, for both EL and EH transitions, the difference in reaction time between sessions 2 and 3 was much less than that between sessions 1 and 2. Despite performance on EL and EH transitions nearing asymptote, the difference in reaction time between EL and EH transitions persisted. Indeed, the reaction time difference between EL and EH transitions, averaged across blocks and runs, did not change from session 1 to session 3, $F(1, 15) < 1$. The difference in reaction time between CL and CH transitions also did not change from session 1 to session 3, $F(1, 15) = 1.32$, $MSE = 1065.21$, $p = .269$.

Short-term priming effects were clearly present in the current experiment. Reaction time was faster on fast than slow runs. Averaging across ending and sessions 1 and 3, the effect of speed was significant for EL, EH, CL, and CH transitions, four $F(1, 15)$s > 31.12, four ps $< .001$. However, short-term priming effects cannot account for the session 3 difference in reaction time between EL and EH transitions. The difference in reaction time between EL and EH transitions changed little from session 1 to session 3 but short-term priming effects weakened. The session x speed interaction was significant for EL, $F(1, 15) = 13.38$, $p = .002$, and EH transitions, $F(1, 15) = 36.84$, $p < .001$, and marginally significant for CL, $F(1, 15) = 3.42$, $p = .084$, and CH transitions, $F(1,15) = 3.92$, $p = .066$. Additionally, reaction time was slower on EL than EH transitions in the discrete blocks where short-term priming effects were not a factor (see Discrete Blocks section).

Error rate. Error rate was smaller on fast than slow runs. Averaging across ending and sessions 1 and 3, the effect of speed was significant for EL, EH, CL, and CH transitions, four $F(1, 15)s > 5.43$, four $ps < .035$. Unlike the reaction time data, however, the session x speed interaction was not significant for any of the transitions, four $F(1, 15)s < 1.51$, four $ps >$ .239. Whereas differences in reaction time between fast and slow runs decreased with training, differences in error rate did not. If short-term priming effects are mainly responsible for the difference in reaction time between fast and slow runs, and if priming effects diminish with training, then the lack of any session x speed interaction for the error rate data suggests that something other than, or in addition to, short-term priming effects underlies the difference in error rate between fast and slow runs.

The Discrete Blocks

The four discrete blocks were designed to test for learning of first-order probabilities by making it difficult for participants to use second- or higher-order probabilities. In addition, short-term priming effects should not be a factor as transitions occurred with equal frequencies. Analyses of variance with group (E, C) and probability (L, H) as within-subjects factors were performed on the reaction time and error rate data (see Figure 1). Only results involving group by probability will be discussed.

Reaction time. The analysis revealed a group x probability interaction, $F(1, 15) = 4.92$, $MSE = 337.60$, $p = .042$. Reaction time was slower on EL ($M = 302$ ms) than EH ($M = 267$ ms) transitions, $F(1, 15) = 40.37$, MSE = 246.23, $p < .001$, and there was a marginal difference between CL (M = 293 ms) and CH (M = 278 ms) transitions, $F(1, 15) = 3.82$, MSE = 463.59, $p = .070$. The experimental difference coupled with the absence of a control difference strongly suggest learning of the first-order probabilities.

In sum, practice and short-term priming effects, and learning of second- or higher-order probabilities cannot fully account for the session 3 difference in reaction time between EL and EH transitions. Therefore participants must have learned the first-order probabilities.

Error rate. The analysis failed to yield a group x probability interaction, $F(1, 15) < 1$. However, error rate was greater on EL (M = 8.8%) than EH (M = 4.1%) transitions, $F(1, 15) = 7.98$, MSE = 22.03, $p = .013$, and there was a marginal difference between CL (M = 10.8%) and CH (M = 6.1%) transitions, $F(1, 15) = 3.43$, MSE = 51.20, $p = .084$. Thus results from the error rate data tended to parallel those from the reaction time data.

Time Course of Learning

Learning appeared to emerge early in training (see Figure 1). Differences in reaction time between EL and EH transitions, and between CL and CH transitions did not change from session 1 to session 3. To further examine the time course of learning, analyses of variance with session (1, 3), group (E, C), probability (L, H), block (1-5, 6-10), speed (F, S), and ending (A, N) as within-subjects factors were performed on the reaction time and error rate data. Only results involving session by group by probability will be discussed. Within session 1, the block by group by probability interaction was of main interest.

Reaction time. The analysis revealed a marginal session x group x probability interaction, $F(1, 15) = 3.87$, $MSE = 816.50$, $p = .068$. Although differences between EL and EH transitions, and between CL and CH transitions did not change from session 1 to session 3, the difference of the difference scores increased marginally across sessions. Thus there was some learning across sessions. The three-way interaction was qualified by a speed x session x group x probability interaction, $F(1, 15) = 12.69$, $MSE = 106.98$, $p = .003$. The session x group x probability interaction was significant for slow runs, $F(1, 15) = 8.62$, $MSE = 502.09$, $p = .010$, but not for fast runs, $F(1, 15) < 1$.

Within session 1, there seemed to be little learning across blocks (see Figure 1). Indeed, there was no block x group x probability interaction, $F(1, 15) < 1$. However, the difference in reaction time between EL and EH transitions increased from block 1-5 to block 6-10, $F(1, 15) = 6.77$, $MSE = 894.09$, $p = .020$, and the difference between CL and CH transitions did not, $F(1, 15) = 1.83$, $MSE = 1071.38$, $p = .196$. Thus there was some learning across blocks within session 1.

Within block 1-5 of session 1, the group x probability interaction was significant, $F(1, 15) = 7.36$, $MSE = 1126.49$, $p = .016$. Reaction time was slower on EL ($M = 390$ ms) than EH ($M = 359$ ms) transitions, $F(1,$

15) = 13.85, MSE = 2105.57, p = .002, and there was no difference between CL (M = 379 ms) and CH (M = 371 ms) transitions, $F(1, 15) < 1$.

The results suggest that, although there was some learning across sessions and across blocks within session 1, a good portion of the learning emerged within the first five blocks of session 1. It must be cautioned, however, that differential practice, uncontrolled short-term priming effects, and learning of second- or higher-order probabilities were potential confounds in session 1.

Error rate. The analysis revealed a session x group x probability interaction, $F(1, 15) = 6.59$, $MSE = 30.90$, $p = .021$. The difference in error rate between EL and EH transitions increased from session 1 to session 3, $F(1, 15) = 5.78$, $MSE = 72.42$, $p = .030$. The difference between CL and CH transitions did not change from session 1 to session 3, $F(1, 15) < 1$. The three-way interaction was qualified by a marginal ending x session x group x probability interaction, $F(1, 15) = 3.96$, $MSE = 43.46$, $p = .065$, and a significant block x ending x session x group x probability interaction, $F(1, 15) = 8.87$, $MSE = 16.69$, $p = .009$. The session x group x probability interaction was significant for runs ending with an alternation, $F(1, 15) = 6.67$, $MSE = 56.26$, $p = .021$, but not for runs ending with a nonalternation, $F(1, 15) < 1$.

Within session 1, there was no block x group x probability interaction, $F(1, 15) = 2.45$, $MSE = 9.96$, $p = .139$. However, the difference in error rate between EL and EH transitions increased from block 1-5 to block 6-10, $F(1, 15) = 6.47$, $MSE = 11.88$, $p = .022$, and the difference between CL and CH transitions did not, $F(1, 15) < 1$.

Within block 1-5 of session 1, the group x probability interaction was not significant, $F(1, 15) < 1$. There was no difference in error rate between EL ($M = 6.3\%$) and EH ($M = 4.0\%$) transitions, $F(1, 15) = 1.98$, $MSE = 86.95$, $p = .180$, nor between CL ($M = 5.5\%$) and CH ($M = 4.7\%$) transitions, $F(1, 15) < 1$.

With respect to the time course of learning, results from the reaction time data and from the error rate data differed in two ways. First, the error rate difference between EL and EH transitions increased across sessions, whereas the reaction time difference remained unchanged. Second, there was no difference in error rate between EL and EH transitions in block 1-5 of session 1, but there was a difference in reaction time. One explanation for these results is that participants were cautious early in training thereby minimizing the difference in error rate between EL and EH transitions.

Awareness of the First-Order Probabilities

To determine participant awareness of the first-order probabilities, responses on the questionnaire were analyzed. On the questionnaire, two items pertained to EL/EH transitions and two to CL/CH transitions. For example, if participants received the sequential structure as described in Table 1, then items 1 and 4 on the questionnaire pertained to EL/EH transitions, and items 2 and 3 pertained to CL/CH transitions (see Appendix B).

For each participant, it was determined how many times (out of 2) an EL transition, an EH transition, and the equal option EL=EH were chosen. For example, if option (a) of item 1 and option (c) of item 4 were chosen, then an EH transition was chosen once, an EL transition chosen zero times, and the equal option EL=EH chosen once. Similarly, it was determined how many times (out of 2) a CL transition, a CH transition, and the equal option CL=CH were chosen. If there was an awareness of the first-order probabilities, then EL transitions should be chosen less often than EH transitions, and CL and CH transitions should be chosen equally often. The mean number of times (out of 2) EL, EH, CL, and CH transitions were chosen were 0.69, 0.88, 0.69, and 1.0 respectively. An analysis of variance with group (E, C) and probability (L, H) as within-subjects factors failed to yield a group x probability interaction, $F(1, 15) < 1$. There was no difference between EL and EH transitions, nor between CL and CH transitions, both $F(1, 15)$s < 1. Thus participants were as likely to choose EL transitions as EH transitions indicating they had little explicit knowledge of the first-order probabilities.

Choice and reaction time. Since there was no awareness of the first-order probabilities, choices made on the questionnaire should not correlate with reaction time. For example, if 1-2 was chosen over 1-3 (i.e., an EH over EL transition), and 4-2 was chosen over 4-3 (i.e., an EL over EH transition), the difference in reaction time between EL and EH transitions should not differ across the two pairs. If reaction time is correlated with choice, reaction time on EL transitions should be greater than that on EH transitions in the first pair, and vice versa in the second pair.

For each participant, EL and EH transitions were divided into two groups. If an EL transition was chosen over an EH transition on the questionnaire (e.g., 1-3 over 1-2), the pair 1-3 and 1-2 was assigned to choice-group EL. If an EH transition was chosen over an EL transition (e.g., 4-3 over 4-2), the pair 4-3 and 4-2 was assigned to choice-group EH. If one transition was chosen over another twice (e.g., an EH transition over an EL transition twice), one pair was randomly assigned to each choice-group. This ensured 16 participants per choice-group. Thus EL transitions tended to be chosen over EH transitions in choice-group EL, and vice versa in choice-group EH. Similarly, CL and CH transitions were divided into two groups -- choice-group CL, where CL transitions tended to be chosen over CH transitions, and choice-group CH where the converse was true. If reaction time is correlated with choices made on the questionnaire, reaction time should be faster on EL than EH transitions in choice-group EL, and on EH than EL transitions in choice-group EH. In other words, there should be a choice-group x transition interaction. Similarly for CL and CH transitions.

The mean number of times (out of 1) EL and EH transitions were chosen on the questionnaire were, respectively, 0.50 and 0.13 for choice-group EL; and 0.19 and 0.75 for choice-group EH. An analysis of variance with choice-group (EL, EH) and transition (EL, EH) as within-subjects factors revealed a choice-group x transition interaction, $F(1, 15) = 19.29$, $MSE = 0.18$, $p = .001$. In choice-group EL, EL transitions were chosen marginally more often than EH transitions, $F(1, 15) = 4.35$, $MSE = .26$, $p = .054$. In choice-group EH, EH transitions were chosen more often than EL transitions, $F(1, 15) = 7.64$, $MSE = .33$, $p = .014$. These results are not surprising given the way the choice-groups were formed. The results were also similar to those for choice-groups CL and CH, and transitions CL and CH.

Due to the reduced number of observations in each choice-group, median reaction times for each of the four runs, FA, SA, FN, and SN, were calculated over all ten blocks of session 3. Averaging across the runs, reaction times on EL and EH transitions were 320 ms and 265 ms for choice-group EL; and 311 ms and 269 ms for choice-group EH. An analysis of variance with choice-group (EL, EH), transition (EL, EH), speed (F, S), and ending (A, N) as within-subjects factors was performed on the reaction time data. The critical choice-group x transition interaction was not significant, $F(1, 15) = 1.81$, $MSE = 415.77$, $p = .199$, and was not involved in any higher-order interactions. Reaction time was slower on EL than EH transitions in choice-group EL, $F(1, 15) = 41.72$, $MSE = 2361.46$, $p < .001$, and in choice-group EH, $F(1, 15) = 33.65$, $MSE = 1661.30$, $p <$

.001. A similar pattern of results was observed for reaction times in the discrete blocks. For CL and CH transitions, there were no choice-group (CL, CH) x transition (CL, CH) interactions, and there were no differences in reaction time between CL and CH transitions, all *p*s > .213. The nonsignificant choice-group x transition interactions in the nondiscrete and discrete blocks suggest reaction time was not correlated with choices made on the questionnaire.

In comparing choice-groups EL and EH, and also CL and CH, it must be kept in mind that counterbalancing of the transitions across conditions was less than perfect. For example, the transition 1-3 was an EH transition three times in choice-group EL, and only once in choice-group EH. Nonetheless, the choice-groups were similar in a number of important ways. For example, the number of within-hand transitions proceeding out-in (e.g., 1-2 and 4-3), and the number proceeding in-out (e.g., 2-1 and 3-4) that served as EL and EH transitions were the same in choice-groups EL and EH. Similarly for between-hand transitions.

In sum, results from the awareness questionnaire indicate participants had little explicit knowledge of the first-order probabilities. EL transitions were as likely to be chosen as EH transitions. Moreover, reaction time was not correlated with choices made on the questionnaire.

First-Order Probabilities of Zero

Table 1 shows that a number of transitions never occurred. For example, 4 never followed 1, and 1 never followed itself. In other words, $P(4|1) = P(1|1) = 0$. To determine if such information was learned, the types of errors that were made early versus late in training were examined. If the percentage of all errors that are non-occurring transitions declines with practice, this would suggest participants learned which transitions never occurred. For example, if the target went to location 2 following location 1, and the response key corresponding to location 4 rather than to location 2 was pressed, then this would be an error that was a non-occurring transition, namely 1-4. Such errors should decline with training if participants are learning which transitions never occur.

For each participant, the percentage of errors that were non-occurring transitions was calculated over the first 10 blocks of sessions 1 and 3. Of all the errors committed on EL, EH, CL, and CH transitions, the percentages that were non-occurring transitions were 47%, 57%, 48%, and 48% in session 1; and 16%, 26%, 13%, and 14% in session 3 respectively. An analysis of variance with session (1, 3), group (E, C), and probability (L, H) as within-subjects factors revealed only an effect of session, $F(1, 15) = 142.61$, $MSE = 247.49$, $p < .001$. The effect of session was significant for EL, EH, CL, and CH transitions, four $F(1, 15)$s > 18.07, four ps $< .002$. With practice, there was a reduced likelihood of making errors that were non-occurring transitions. This is evidence for learning of first-order probabilities of zero.

Participants in the current experiment clearly learned the underlying structure of the sequence of target locations. More specifically, they learned the first-order probabilities of 0, 0.40, 0.50, and 0.60. To unambiguously show this, it was necessary to discount the possibility that learning had been limited to the second- or higher-order probabilities of 0.40, 0.50, and 0.60. This was the purpose of the discrete blocks. However, it could be argued that the results from the discrete blocks did not completely rule out the possibility that learning had been limited to second- or higher-order probabilities. Although the discrete blocks made it difficult to use second- or higher-order probability information, they did not make it impossible. Perhaps a better approach would have been to compare the performance of participants in the current experiment to that of a group that had received sequences in which second- and higher-order probabilities were 0.40, 0.50, and 0.60, but in which first-order probabilities were 0.50. If participants in the current experiment only learned second- or higher-order probabilities, then the reaction time difference between low and high probability transitions in the comparison group should be the same as that observed in experiment 1. The purpose of experiment 2 was to provide a comparison group, and also to examine people's ability to implicitly learn second-order probabilities.

Experiment 2

Experiment 2 was similar to experiment 1 in that second-order probabilities were 0.40, 0.50, and 0.60. However, first-order probabilities of 0.40 and 0.60 in experiment 1 were now 0.50 in experiment 2. If learning in experiment 1 was limited to second- or higher-order probabilities, then reaction time differences between transitions should be similar in the two experiments. Experiment 2 also examined implicit learning of second-order probabilities. Slower reaction times on low than high probability transitions, and similar reaction times among medium probability transitions would indicate learning of the second-order probabilities. Unlike experiment 1, the questionnaire to assess awareness of the second-order probabilities required an indication of the probabilities with which events followed pairs of events. For example, one item required participants to indicate the percentage of the time that 1 and 4 followed the run 1-2.

Method

Participants

The participants were 20 university undergraduates (11 women, 9 men) ranging in age from 17 to 28 years (M = 19 years).

The SRT Task

The SRT task was similar to that in experiment 1 except for the following. There was one session per day on four consecutive days. Session one began with a practice block of 50 random trials with the constraint that the target did not appear in the same location on successive trials. There were 10 blocks of trials in sessions one, two, and three, and eight blocks in session four. The blocks were 122 trials each with the exception of blocks 5 and 8 in session three, and blocks 3 and 6 in session four. These were the discrete blocks. Each contained 48 discrete sets of three trials for a total of 144 trials. The discrete sets were separated by four x's lasting 1000 ms. The x's overwrote the four lines on the screen after every third trial. After 1000 ms, the x's were replaced by the four lines and 400 ms later the target appeared. At the beginning of session three was a 48-trial discrete block for practice.

The Sequential Structure

For each participant, the sequence of target locations was randomly generated with the constraint that across every two blocks (i.e., 244 trials), second-order probabilities were as shown in Table 3 (see Appendix A for details). Numbering the four screen locations from left to right, 1, 2, 3, and 4 respectively, Table 3 describes the second-order probabilities and their labels. For example, if the target appeared in locations 1 and 2 on trials (t-2) and (t-1) respectively, then on trial (t), it appeared in location 1 with probability 0.60, or in location 4 with probability 0.40. That is, $P(1|1\text{-}2) = 0.60$ and $P(4|1\text{-}2) = 0.40$.

Second-order probabilities of 0.40 and 0.60 were labelled EL (for experimental low) and EH (for experimental high) respectively (see Table 3). In order to compare reaction times among the medium probability transitions (e.g., reaction time on 2 versus 3 given 2-1), the eight medium probability

Table 3
Second-Order Probabilities and Their Labels (Experiment 2)

Trials (t-2) (t-1)	Trial (t) 1	2	3	4
1-2	.60 (EH)	--	--	.40 (EL)
1-3	.40 (EL)	--	--	.60 (EH)
2-1	--	.50 (CH)	.50 (CL)	--
2-4	--	.50 (CH)	.50 (CL)	--
3-1	--	.50 (CH)	.50 (CL)	--
3-4	--	.50 (CH)	.50 (CL)	--
4-2	.40 (EL)	--	--	.60 (EH)
4-3	.60 (EH)	--	--	.40 (EL)

transitions were divided into two groups -- group CL (for control low) and group CH (for control high). Because second-order transitions involved runs of three, it was difficult to fully match EL and CL, and EH and CH transitions in terms of locations. However, alternations were matched. The alternations 3-1-3 and 3-4-3 were labelled CL transitions because they involved the same locations as the alternations 1-3-1 and 4-3-4 which were EL transitions. Similarly, the alternations 2-1-2 and 2-4-2 were labelled CH transitions because they involved the same locations as the alternations 1-2-1 and 4-2-4 which were EH transitions. The runs 3-1-2 and 3-4-2, which did not match any of the EL or EH transitions, were labelled CH transitions because their alternatives 3-1-3 and 3-4-3 had been labelled CL transitions. Similarly, the runs 2-1-3 and 2-4-3 were labelled CL transitions. Transitions could now be categorized along two dimensions -- whether they belonged to the experimental (E) or control (C) group, and whether they were of low (L) or high (H) probability. A group (E, C) by probability (L, H) interaction with slower reaction times on EL than EH transitions and no difference between CL and CH transitions would suggest learning of the second-order probabilities.

Across every two blocks, the sequential structure was controlled in a number of ways. The target appeared in each location an equal number of times. First-order probabilities of 0.40 and 0.60 in experiment 1 were now 0.50. Lag 2 and lag 3 probabilities were 0.50. Other probabilities were also held constant at 0.50. For example, P(4|2-1-x) = 0.50 and P(4|3-x-2) = 0.50. Finally, given any run of two, there were two possible locations that could follow (see Table 3). For example, locations 1 or 4 could follow the run 1-2. As a result, second-order probability was not confounded with number of response alternatives.

In the sequential structure, third-order probabilities were kept redundant with second-order probabilities. For example, redundant third-order probabilities for P(1|1-2) = 0.60 (see Table 3) were P(1|2-1-2) = P(1|3-1-2) = 0.60. As a result, third-order probabilities added no information over and above that provided by the second-order probabilities.

To ensure that each of the 16 transitions (e.g., 1-2-1, 1-2-4, 1-3-1, etc.) served as an EL, EH, CL, and CH transition, four versions of Table 3 were created. One version was Table 3. A second version was created from Table 3 by interchanging EL and EH, and CL and CH transitions. The third version had EL and EH transitions in column one of Table 3 become CH transitions, and EL and EH transitions in column four become CL transitions. Proceeding from top to bottom, the four CH transitions in column two of Table 3 became EH, EL, EL, EH transitions respectively, and the four CL transitions in column three became EL, EH, EH, and EL transitions respectively. The fourth version was formed from the third version by interchanging EL and EH, and CL and CH transitions.

Short-term priming effects. As in experiment 1, the 32 possible runs of length four were categorized according to the run ending with an EL, EH, CL, or CH transition, the last three elements comprising an alternation (A) or nonalternation (N), and the run being fast (F) or slow (S). Table 4 categorizes the 32 runs. Faster reaction times on fast than slow runs (i.e., an effect of speed) would suggest the presence of short-term priming effects. The convergence of reaction times on fast and slow runs across sessions (i.e., a session by speed interaction) would in turn suggest that short-term priming effects weakened with training.

Discrete blocks. In each of the four discrete blocks, there were 144 trials presented in discrete sets of three trials with each set separated by four x's lasting one second. A discrete set contained one of the 16 possible runs of three shown in Table 3. In a discrete block, the 16 runs were presented three times and in a random order each time. Session three began with a 48-trial discrete block for practice. The 16 runs of three trials were presented once in a random order.

Table 4
Categorization of the 32 Runs of Length Four as a Function of the Last Three Elements Comprising an Alternation (A) or Nonalternation (N) and the Run Being Fast (F) or Slow (S). Numbers in Parentheses Indicate the Approximate Number of Times Runs Occurred Across Every Eight Blocks of the SRT Task (Experiment 2)

	Transition Ending a Run (see Table 3)			
Run	EL	EH	CL	CH
FA	3-1-3-1 (24) 3-4-3-4 (24)	2-1-2-1 (36) 2-4-2-4 (36)	1-3-1-3 (24) 4-3-4-3 (24)	1-2-1-2 (36) 4-2-4-2 (36)
SA	2-1-3-1 (24) 2-4-3-4 (24)	3-1-2-1 (36) 3-4-2-4 (36)	4-3-1-3 (36) 1-3-4-3 (36)	4-2-1-2 (24) 1-2-4-2 (24)
FN	3-4-2-1 (24) 3-1-2-4 (24)	2-4-3-1 (36) 2-1-3-4 (36)	4-2-1-3 (24) 1-2-4-3 (24)	4-3-1-2 (36) 1-3-4-2 (36)
SN	2-4-2-1 (24) 2-1-2-4 (24)	3-4-3-1 (36) 3-1-3-4 (36)	1-2-1-3 (36) 4-2-4-3 (36)	1-3-1-2 (24) 4-3-4-2 (24)

The Awareness Questionnaire

The questionnaire to measure explicit knowledge of the second-order probabilities consisted of eight items. Each item corresponded to one of the eight rows of Table 3. The item corresponding to row one of Table 3 was a diagram of the target moving from position 1 to position 2 and then to positions 1 and 4 (see Appendix C). The question that followed asked participants to estimate the percentage of the time the target went to positions 1 and 4 following its occurrence in positions 1 and then 2. Participants were instructed to choose their two estimates from the list of eight numbers such that they added to 100. For example, if one estimate was 40, the other had to be 60. Participants were told the items pertained to the blocks of trials that were performed over the last four days with the exception of the discrete blocks. Each of the eight items appeared on a separate page. The order of the items was random for each participant. The four lines that appeared on the screen during the SRT task remained on the screen for reference. The keyboard was removed so keys could not be pressed.

Procedure

The procedure followed that of experiment 1, except the questionnaire to assess explicit knowledge of second-order probabilities was administered immediately after the last block of session four.

Results and Discussion

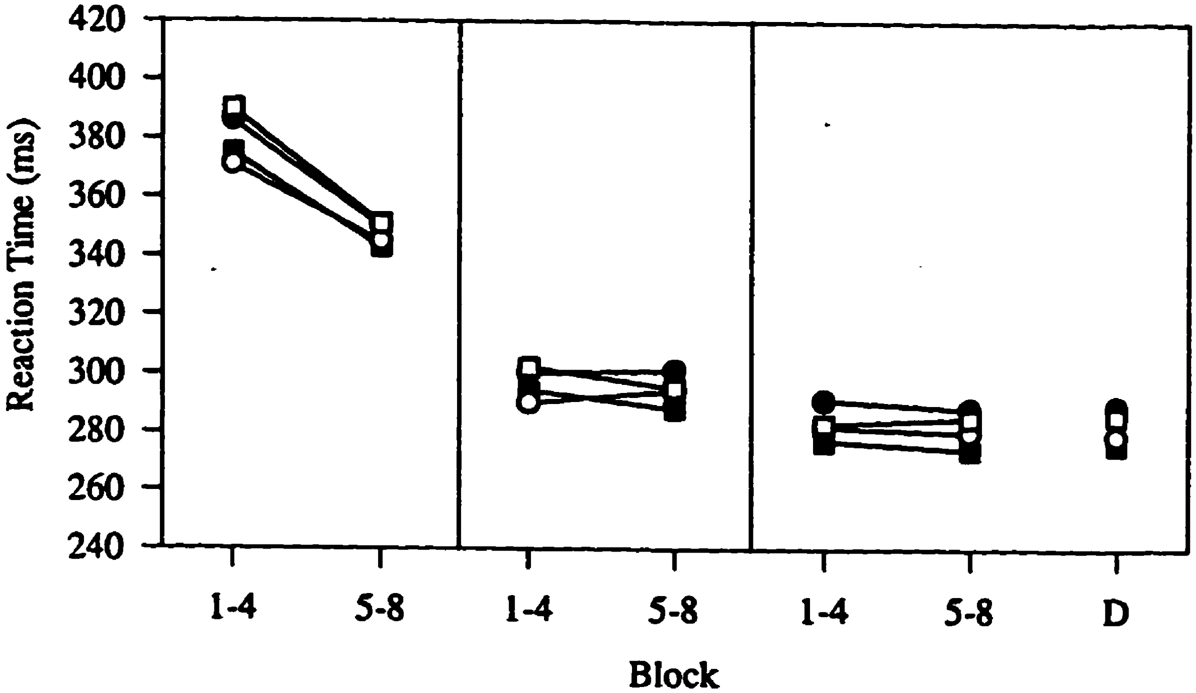
Of main interest was reaction time performance early versus late in training. Consequently, analyses focused on sessions 1 and 3. Analyses were carried out on session 3 and not session 4 because, by the end of session 3, the level of practice was similar to that in experiment 1. The number of trials and the frequency of occurrence of runs of three associated with each second-order probability were similar to that in experiment 1. Since we wished to compare learning in experiments 1 and 2, it was deemed important to keep the level of practice across experiments similar. Reaction time analyses were based on the reaction times of correct responses. Error rates were also examined. If participants were learning the second-order probabilities, they might be expected to make errors on a greater percentage of EL than EH transitions and on a similar percentage of CL and CH transitions. The level of significance for all analyses was $p < .05$.

The median reaction time on the last element of a run was determined for each type of run in Table 4. Median reaction times were determined over blocks of four (i.e., blocks 1-4 and 5-8). The percentage of runs that incurred an incorrect response on the last element was also determined for each type of run. Figure 3 shows reaction time and error rate, averaged across runs, as a function of session, transition, and block. The results from the discrete blocks are also shown in Figure 3. Figure 4 shows reaction time and error rate, averaged across blocks 1-4 and 5-8, as a function of session, transition, and run.

Reaction time and error rate analyses were conducted in four stages. First, session 3 performance was examined to determine whether participants learned the second-order probabilities. Second, practice and short-term priming effects were examined to determine whether these diminished with training. Third, the data from the discrete blocks were analyzed. Finally, the time course of learning was examined by comparing performance in session 1 to that in session 3, and by looking more closely at performance within session 1.

<u>Session 3</u>

Analyses of variance with group (E, C), probability (L, H), block (1-4,



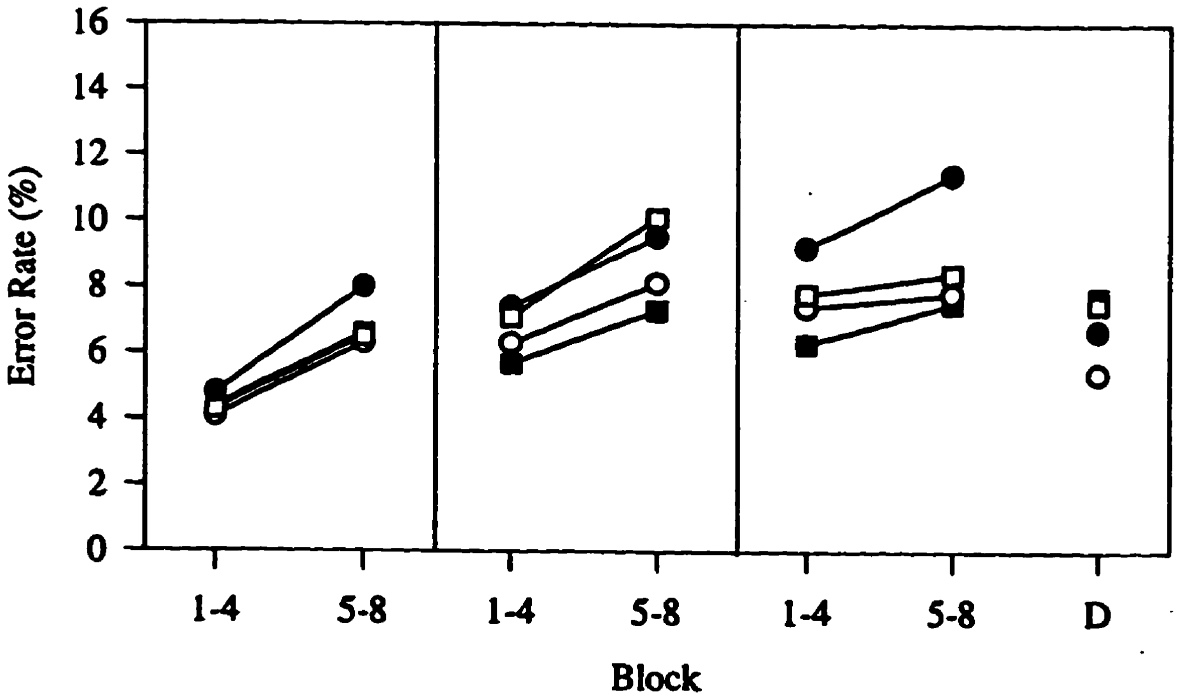


Figure 3. Reaction time (top panel) and error rate (bottom panel) as a function of session (separated by vertical lines), block (discrete blocks = D), and transition (EL = closed circles, EH = closed squares, CL = open circles, CH = open squares) in experiment 2.

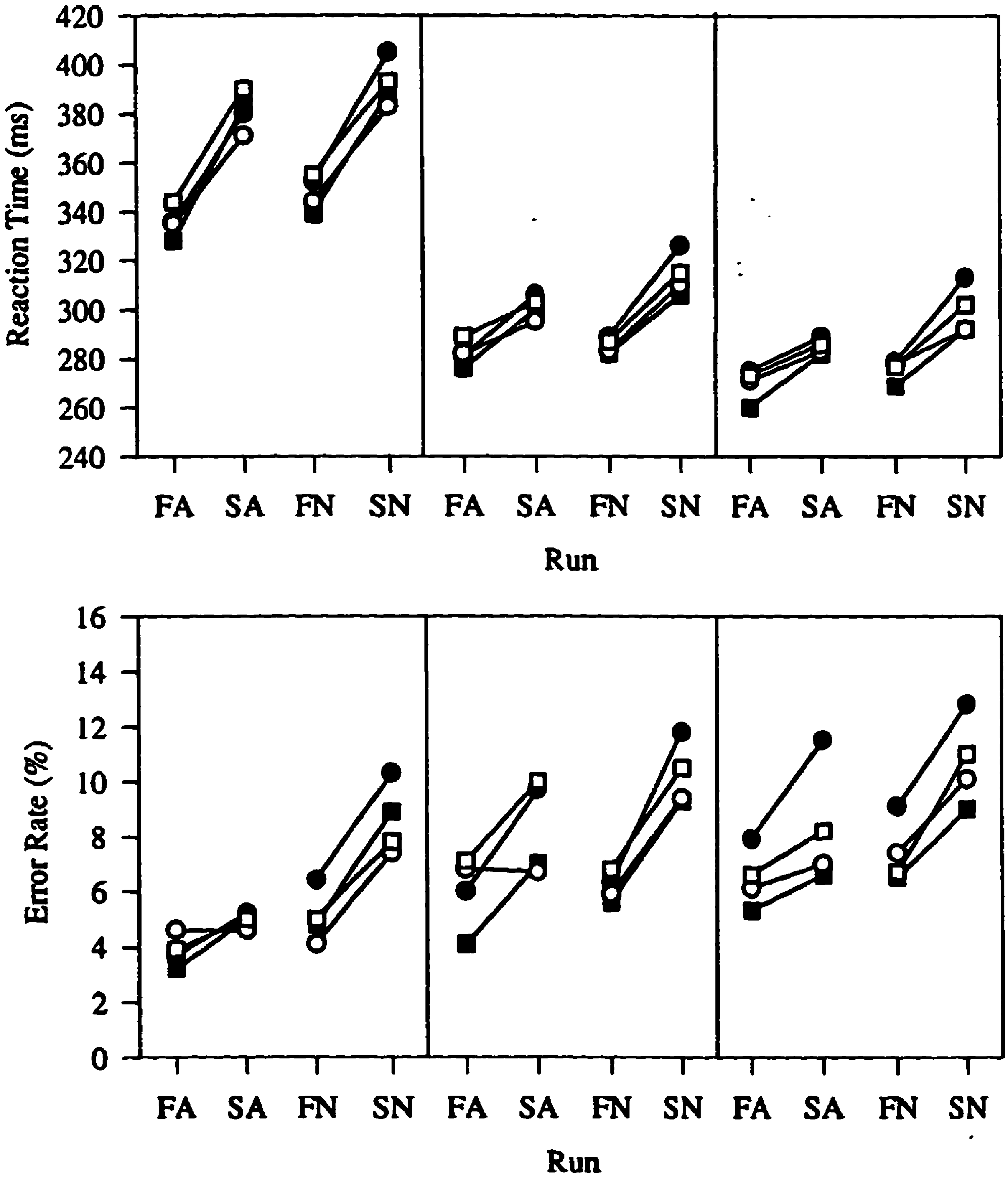


Figure 4. Reaction time (top panel) and error rate (bottom panel) as a function of session (separated by vertical lines), run, and transition (EL = closed circles, EH = closed squares, CL = open circles, CH = open squares) in experiment 2.

5-8), speed (F, S), and ending (A, N) as within-subjects factors were performed on the reaction time and error rate data from session 3. Only results involving group by probability will be discussed.

Reaction time. The analysis revealed a group x probability interaction, $F(1, 19) = 5.84$, $MSE = 1916.49$, $p = .026$. Reaction time was slower on EL ($M = 289$ ms) than EH ($M = 276$ ms) transitions, $F(1, 19) = 21.69$, $MSE = 666.76$, $p < .001$, and there was no difference between CL ($M = 281$ ms) and CH ($M = 284$ ms) transitions, $F(1, 19) < 1$. Although the group x probability interaction was qualified by an ending x speed x group x probability interaction, $F(1, 19) = 7.21$, $MSE = 295.67$, $p = .015$, the preceding pattern of differences was observed in most runs. Reaction was slower on EL than EH transitions for runs FA, FN, and SN, three $F(1, 19)$s > 11.00, three ps $< .005$, but not for run SA, $F(1, 19) = 2.01$, $p = .172$. For each run, there was no difference in reaction time between CL and CH transitions, four $F(1, 19)$s < 1.74, four ps $> .203$. Thus session 3 reaction times suggest learning of the second-order probabilities. Participants were slower on EL than EH transitions, and there was no difference between CL and CH transitions.

Error rate. The analysis revealed a group x probability interaction, $F(1, 19) = 13.69$, $MSE = 44.31$, $p = .002$. Error rate was greater on EL ($M = 10.3\%$) than EH ($M = 6.9\%$) transitions, $F(1, 19) = 39.50$, $MSE = 23.76$, $p < .001$, and there was no difference between CL ($M = 7.7\%$) and CH (M

= 8.1%) transitions, $F(1, 19) < 1$. Although the group x probability interaction was qualified by a marginal block x speed x group x probability interaction, $F(1, 19) = 3.05$, $MSE = 27.58$, $p = .097$, the preceding pattern of differences was observed in most runs. Error rate was greater on EL than EH transitions for runs FA, SA, and SN, three $F(1, 19)$s > 6.15, three ps $< .024$, but not for run FN, $F(1, 19) = 2.30$, $p = .145$. For each run, there was no difference in error rate between CL and CH transitions, four $F(1, 19)$s < 1. In general, error rates in session 3 paralleled reaction times.

Practice and Short-Term Priming Effects.

Reaction time. The session 3 difference in reaction time between EL and EH transitions was unlikely due to differences in practice. Reaction time performance on EL and EH transitions approached asymptote, and the difference in their reaction times persisted. Evidence for near asymptotic performance comes from the fact that for both EL and EH transitions, reaction time in session 3, averaged across runs, did not change from block 1-4 to block 5-8, both $F(1, 19)$s < 1.05, both ps $> .320$. Moreover, for both EL and EH transitions, the difference in reaction time between sessions 2 and 3 was much less than that between sessions 1 and 2. Despite performance on EL and EH transitions nearing asymptote, the difference in reaction time between EL and EH transitions persisted. Indeed, the reaction time difference between EL and EH transitions, averaged across blocks and runs, did not change from session 1 to session 3, $\underline{F}(1, 19) = 1.55$, $\underline{MSE}$ = 546.90, $\underline{p} = .228$. The difference in reaction time between CL and CH transitions decreased marginally from session 1 to session 3, $\underline{F}(1, 19) = 3.93$, $\underline{MSE}$ = 926.04, $\underline{p} = .062$.

Short-term priming effects were clearly present in the current experiment. Reaction time was faster on fast than slow runs. Averaging across ending and sessions 1 and 3, the effect of speed was significant for EL, EH, CL, and CH transitions, four $\underline{F}(1, 19)$s > 58.00, four $\underline{p}$s $< .001$. However, short-term priming effects cannot account for the session 3 difference in reaction time between EL and EH transitions. The difference in reaction time between EL and EH transitions changed little from session 1 to session 3 but short-term priming effects weakened. The session x speed interaction was significant for each transition, four $\underline{F}(1, 19)$s > 13.01, four $\underline{p}$s $< .003$.

The preceding analyses examined short-term priming effects associated with runs of two (e.g., 1-2, 1-3, etc). The EL, EH, CL, and CH transitions in the current experiment, however, involved runs of three (e.g., 1-2-1, 4-2-1, etc). Short-term priming effects associated with runs of three were examined by comparing runs like 1-2-4-3-1-2-4 (a fast run) with runs like 4-2-4-3-1-2-4 (a slow run). Both runs have the same last six elements. If there are short-term priming effects associated with runs of three, reaction time should be faster to the last element of the first than second run because in the first run, 1-2-4 is repeated. Short-term priming effects were also examined by comparing runs like 1-2-4-3-1-2-1 (a slow run) with runs like 4-2-4-3-1-2-1 (a fast run). In the first run, the initial 1-2-4 should prime a subsequent 1-2-4, but what occurs is 1-2-1. The result is a slow reaction time. There is no such priming in the second run.

Reaction times on slow and fast runs were 368 ms and 362 ms in session 1; and 284 ms and 281 ms in session 3 respectively. The overall difference of 5 ms was significant, $F(1, 19) = 5.30$, $p = .033$. The effect of speed suggests there were short-term priming effects associated with runs of three. The difference between slow and fast runs decreased from 6 ms in session 1, to 3 ms in session 3. The decrease was not significant but surprisingly, the difference of 3 ms in session 3 was reliable, $F(1, 19) = 5.02$, $p = .037$. Similar analyses carried out on experiment 1 reaction times revealed an effect of speed, $p = .002$, and a session x speed interaction, $p = .006$. The difference between slow and fast runs decreased from 12 ms in session 1, to 2 ms in session 3.

In experiments 1 and 2, there were short-term priming effects associated with runs of three. These effects decreased with training, but not reliably so in experiment 2. The short-term priming effects were rather weak in experiment 2 (e.g., 3 ms in session 3) and so were probably not responsible for the reaction time difference between EL and EH transitions. Indeed, reaction time was still slower on EL than EH transitions in session 3 when considering just the longer runs described above, $F(1, 19) = 14.87$, $p = .001$. Moreover, there was a difference in reaction time between EL and EH transitions in the discrete blocks (see Discrete Blocks section) where short-term priming effects were not a factor.

Error rate. Error rate was smaller on fast than slow runs. Averaging across ending and sessions 1 and 3, the effect of speed was significant for EL, EH, CL, and CH transitions, four $F(1, 19)$s > 8.33, four ps $< .010$. Unlike the reaction time data, however, the session x speed interaction was not significant for any of the transitions, four $F(1, 19)$s < 1.21, four ps $>$ .284. This is identical to what was found in experiment 1 and suggests that something other than, or in addition to, short-term priming effects may underlie the difference in error rate between fast and slow runs.

The Discrete Blocks

The four discrete blocks were designed to test for learning of second-order probabilities by making it difficult for participants to use third- or higher-order probabilities. In addition, short-term priming effects should not be a factor as transitions occurred with equal frequencies. Analyses of variance with group (E, C) and probability (L, H) as within-subjects factors were performed on the reaction time and error rate data (see Figure 3). Only results involving group by probability will be discussed.

Reaction time. The analysis revealed a marginal group x probability interaction, $F(1, 19) = 3.90$, $MSE = 495.14$, $p = .063$. Reaction time was slower on EL (*M* = 289 ms) than EH (*M* = 276 ms) transitions, $F(1, 19) = 5.15$, *MSE* = 350.97, $p = .035$, and there was no difference between CL (*M* = 279 ms) and CH (*M* = 286 ms) transitions, $F(1, 19) = 1.01$, *MSE* = 382.45, $p = .329$. The results strongly suggest learning of the second-order probabilities.

In sum, practice and short-term priming effects, and learning of third- or higher-order probabilities cannot fully account for the session 3 difference in reaction time between EL and EH transitions. Therefore participants must have learned the second-order probabilities.

Error rate. The analysis failed to yield a group x probability interaction, $F(1, 19) < 1$. There was no difference in error rate between EL (*M* = 6.7%) and EH (*M* = 7.7%) transitions, $F(1, 19) = 1.38$, *MSE* = 7.93, $p = .255$, nor between CL (*M* = 5.4%) and CH (*M* = 7.5%) transitions, $F(1, 19) = 2.87$, *MSE* = 15.24, $p = .107$. Thus the results from the error rate data did not parallel those from the reaction time data.

Time Course of Learning

Learning appeared to emerge early in training (see Figure 3). The difference in reaction time between EL and EH transitions did not change from session 1 to session 3. However, the difference between CL and CH transitions decreased marginally. This is most likely the result of the large difference in reaction time between CL and CH transitions in block 1-4 of session 1. To further examine the time course of learning, analyses of variance with session (1, 3), group (E, C), probability (L, H), block (1-4, 5-8), speed (F, S), and ending (A, N) as within-subjects factors were performed on the reaction time and error rate data. Only results involving session by group by probability will be discussed. Within session 1, the block x group x probability interaction was of main interest.

Reaction time. The session x group x probability interaction was not significant, $F(1, 19) < 1$. However, there was a block x session x group x probability interaction, $F(1, 19) = 5.33$, $MSE = 361.97$, $p = .032$. The interaction undoubtedly reflects the decreasing difference in reaction time between CL and CH transitions across blocks in session 1.

Within session 1, the block x group x probability interaction was significant, $F(1, 19) = 7.03$, $MSE = 397.34$, $p = .016$. The difference in reaction time between EL and EH transitions did not change from block 1-4 to block 5-8, $F(1, 19) < 1$, and the difference between CL and CH transitions decreased, $F(1, 19) = 5.68$, $MSE = 621.43$, $p = .028$.

Within block 1-4 of session 1, the group x probability interaction was significant, $F(1, 19) = 9.69$, $MSE = 1859.10$, $p = .006$. Reaction time was slower on EL ($M = 386$ ms) than EH ($M = 375$ ms) transitions, $F(1, 19) = 6.29$, $MSE = 707.68$, $p = .021$, and on CH ($M = 390$ ms) than CL ($M = 370$ ms) transitions, $F(1, 19) = 6.61$, $MSE = 2292.04$, $p = .019$.

The results suggest that, for EL and EH transitions, most of the learning emerged within the first four blocks of session 1. It must be cautioned, however, that differential practice, uncontrolled short-term priming effects, and learning of third- or higher-order probabilities were potential confounds in session 1. For CL and CH transitions, I have no explanation for the initial difference in block 1-4 of session 1.

Error rate. The analysis revealed a session x group x probability interaction, $F(1, 19) = 5.58$, $MSE = 26.13$, $p = .029$. The difference in error rate between EL and EH transitions increased from session 1 to session 3, $F(1, 19) = 10.11$, $MSE = 24.83$, $p = .005$. The difference between CL and CH transitions did not change from session 1 to session 3, $F(1, 19) < 1$.

Within session 1, there was no block x group x probability interaction, $F(1, 19) < 1$. The difference in error rate between EL and EH transitions did not change from block 1-4 to block 5-8, $F(1, 19) = 1.69$, $MSE = 10.88$, $p = .210$, nor did the difference between CL and CH transitions, $F(1, 19) < 1$.

Within block 1-4 of session 1, the group x probability interaction was not significant, $F(1, 19) < 1$. There was no difference in error rate between EL ($M = 4.8\%$) and EH ($M = 4.4\%$) transitions, $F(1, 19) < 1$, nor between CL ($M = 4.1\%$) and CH ($M = 4.3\%$) transitions, $F(1, 19) < 1$.

With respect to the time course of learning, results from the reaction time data and from the error rate data differed in two ways. First, the error rate difference between EL and EH transitions increased across sessions, whereas the reaction time difference remained unchanged. Second, there was no difference in error rate between EL and EH transitions, and between CL and CH transitions in block 1-4 of session 1, but there was a difference in reaction time. It was noted in experiment 1 that one explanation for these results is that participants were cautious early in training thereby minimizing the difference in error rate between transitions.

Awareness of Second-Order Probabilities

To determine participant awareness of the second-order probabilities, responses on the questionnaire were analyzed. On the questionnaire, four items pertained to EL/EH transitions, and four to CL/CH transitions. For example, if participants received the sequential structure as described in Table 3, then the item in Appendix C pertained to an EL/EH transition. The left blank concerned an EH transition and the right blank concerned an EL transition. For each participant, the average probability estimates for EL, EH, CL, and CH transitions were determined. If there was an awareness of the second-order probabilities, then EL transitions should receive smaller probability estimates than EH transitions, and CL and CH transitions should receive similar estimates. The mean probability estimates for EL, EH, CL, and CH transitions were 49.4%, 50.6%, 50.2%, and 49.8% respectively. An analysis of variance with group (E, C) and probability (L, H) as within-subjects factors failed to yield a group x probability interaction, $F(1, 19) < 1$. There were no differences between EL and EH, and CL and CH transitions, both $\underline{F}(1, 19)$s < 1. The results indicate that participants had little explicit knowledge of the second-order probabilities. Probability estimates for each transition were at 50%.

For each participant, it was also determined how many times (out of 4) an EH transition was chosen (i.e., given a higher probability estimate), an EL transition was chosen, and EL and EH transitions were given equal probability estimates. A similar analysis was conducted with CL and CH transitions. If there was an awareness of the second-order probabilities, then EL transitions should be chosen less often than EH transitions, and CL and CH transitions should be chosen equally often. The mean number of times (out of 4) that EL, EH, CL, and CH transitions were chosen were 1.50, 1.85, 1.75, and 1.60 respectively. An analysis of variance with group (E, C) and probability (L, H) as within-subjects factors failed to yield a group x probability interaction, $\underline{F}(1, 19) < 1$. There were no differences between EL and EH, and CL and CH transitions, both $\underline{F}(1, 19)$s < 1.16, both $\underline{p}$s $> .296$. Thus participants were as likely to choose EL transitions as EH transitions indicating they had little explicit knowledge of the second-order probabilities.

There was a slight, nonsignificant tendency for participants to choose EH transitions over EL transitions. To identify the source of this bias, the four items pertaining to EL/EH transitions were further examined. It seems there was a tendency to choose EH alternations involving locations 1 and 2, or 3 and 4 (e.g., 1-2-1 in Table 3) over the corresponding EL transition (e.g., 1-2-4). Of the 20 participants, 13 chose the EH alternation involving locations 1 and 2, or 3 and 4 (e.g., 1-2-1) and 3 chose the alternative (e.g., 1-2-4) for a difference of 10 participants. The remaining four participants gave the two transitions equal probability estimates. It would appear that frequently occurring alternations involving locations 1 and 2, or 3 and 4 were particularly salient.

Awareness and reaction time. Participants seemed to be aware that EH alternations involving locations 1 and 2, or 3 and 4 (e.g., 1-2-1 in Table 3) were more likely to occur than the corresponding EL transitions (e.g., 1-2-4). To test the possibility that this awareness contributed to reaction time differences between EL and EH transitions, the eight transitions in rows 1, 3, 6, and 8 of Table 3 were removed from the analyses. Thus EL, EH, CL, and CH alternations involving locations 1 and 2, or 3 and 4 (i.e., 1-2-1, 2-1-2, 3-4-3, and 4-3-4) as well as their alternatives (i.e., 1-2-4, 2-1-3, 3-4-2, and 4-3-1) were no longer considered. If an awareness of the greater likelihood of occurrence of EH alternations involving locations 1 and 2, or 3 and 4 was responsible for reaction time differences between EL and EH transitions, then such differences should not be observed in the reduced set of transitions. Note that across the four versions of Table 3, each of the eight transitions in the reduced set served as an EL, EH, CL, and CH transition.

Due to the reduced number of observations, median reaction times for each of the four runs, FA, SA, FN, and SN, were calculated over all eight blocks of session 3. Averaging across runs, reaction time was slower on EL (M = 294 ms) than EH (M = 272 ms) transitions, $F(1, 19) = 9.19$, $p = .007$, and there was no difference between CL (M = 279 ms) and CH (M = 284 ms) transitions, $F(1, 19) < 1$. Thus awareness of the greater likelihood of occurrence of EH alternations involving locations 1 and 2, or 3 and 4 was not responsible for the general reaction time difference between EL and EH transitions. Interestingly, when only the eight transitions from rows 1, 3, 6, and 8 of Table 3 were analyzed (i.e., transitions from rows 2, 4, 5, and 7 were removed), there was no difference in reaction time between EL (M = 292 ms) and EH (M = 286 ms) transitions, $F(1, 19) < 1$, nor between CL (M = 282 ms) and CH (M = 287 ms) transitions, $F(1, 19) < 1$. In light of the lack of difference in reaction time between EL and EH transitions, it is interesting to note that probability estimates were smaller for EL (M = 47.8%) than EH (M = 52.3%) transitions, $F(1, 19) = 5.94$, $p = .025$. This suggests that awareness may actually hinder reaction time performance.

In sum, results from the questionnaire indicate participants had little explicit knowledge of second-order probabilities. Probability estimates and the number of times (out of 4) that transitions were chosen did not vary across EL, EH, CL, and CH transitions. Participants appeared to be aware that EH alternations involving locations 1 and 2, or locations 3 and 4 (e.g., 1-2-1 in Table 3) were more likely to occur than their corresponding EL transitions (e.g., 1-2-4). When these transitions were removed from the analyses, reaction time was still slower on EL than EH transitions.

Non-Occurring Transitions

In the current experiment, transitions such as 1-1 and 1-4 never occurred. The non-occurring transitions were identical to those in experiment 1 (see Table 1). In experiment 1, the likelihood of making errors that were non-occurring transitions decreased with training. This implied learning of first-order probabilities of zero. To replicate the results of experiment 1, the probability of making errors that were non-occurring transitions was examined as a function of training. For each participant, the percentage of errors that were non-occurring transitions was calculated over the first eight blocks of session 1, and the eight blocks of session 3. Of all the errors committed on EL, EH, CL, and CH transitions, the percentages that were non-occurring transitions were 60%, 53%, 55%, and 61% in session 1; and 16%, 13%, 10%, and 12% in session 3 respectively. An analysis of variance with session (1, 3), group (E, C), and probability (L, H) as within-subjects factors revealed only an effect of session, $F(1, 19) = 242.30$, $MSE = 329.43$, $p < .001$. The effect of session was significant for EL, EH, CL, and CH transitions, four $F(1, 19)$s > 43.30, four ps < .001. As in experiment 1, there was a reduced likelihood, with training, of making errors that were non-occurring transitions. This could reflect learning of first- or second-order probabilities of zero.

Comparing Experiments 1 and 2

Figures 1 and 3 show that session 3 differences in reaction time and error rate between EL and EH transitions were smaller in experiment 2 than in experiment 1. Analyses of variance with experiment (1, 2) as a between-subjects factor, and group (E, C), probability (L, H), block (first half, second half), speed (F, S), and ending (A, N) as within-subjects factors were performed on the reaction time and error rate data of session 3. Only effects involving experiment by group by probability will be discussed.

Reaction time. There was an experiment x group x probability interaction, $F(1, 34) = 4.97$, $MSE = 2107.12$, $p = .032$, which was qualified by an ending x speed x experiment x group x probability interaction, $F(1, 34) = 14.56$, $MSE = 454.29$, $p = .001$. For each run, the difference in reaction time between EL and EH transitions was smaller in experiment 2 than in experiment 1, four $F(1, 34)$s > 7.19, four ps $< .012$. The difference between CL and CH transitions did not vary from experiment 1 to experiment 2 for runs SA, FN, and SN, three $F(1, 34)$s < 2.48, three ps $> .124$. For run FA, the difference between CL and CH transitions was marginally greater in experiment 1 than experiment 2, $F(1, 34) = 3.54$, $p = .068$.

Error rate. The experiment x group x probability interaction was not significant, $F(1, 34) = 1.83$, $MSE = 42.19$, $p = .185$. However, the difference in error rate between EL and EH transitions was smaller in experiment 2 than in experiment 1, $F(1, 34) = 5.65$, $MSE = 81.82$, $p = .023$, and the difference between CL and CH transitions did not vary across experiments, $F(1, 34) < 1$.

The results clearly indicate impaired learning in experiment 2 relative to experiment 1. This suggests learning in experiment 1 was not limited to second- or higher-order probabilities. Otherwise, learning would have been similar in the two experiments. Consequently, there must have been first-order probability learning in experiment 1.

General Discussion

First- and Second-Order Probabilities Can be Learned Implicitly

Participants in the current study clearly learned first- (experiment 1) and second-order (experiment 2) probabilities. In the nondiscrete blocks of session 3, the difference in reaction time between EL and EH transitions was greater than the difference between CL and CH transitions. More specifically, reaction time was slower on EL than EH transitions, and there was no difference between CL and CH transitions. The difference between EL and EH transitions could not be attributed solely to practice effects nor to short-term priming effects. Practice and short-term priming effects weakened with training, whereas the difference in reaction time between EL and EH transitions did not. The difference between EL and EH transitions could also not be attributed solely to learning of second- or higher-order probabilities in experiment 1, nor to learning of third- or higher-order probabilities in experiment 2. In the discrete blocks, where use of higher-order probability information was limited, the pattern of results was similar to that in the nondiscrete blocks. The only exception was the marginal difference between CL and CH transitions in experiment 1. Moreover, learning in experiment 2, where second-order probabilities were identical to those in experiment 1 but first-order probabilities were held constant, was impaired relative to learning in experiment 1. This suggests that learning in experiment 1 was not restricted to second- or higher-order probabilities. Schvaneveldt and Gomez (1996, Experiments 1 and 2) also found impaired learning of second-order probabilities relative to first-order probabilities. However, their second-order sequences were comprised of a greater number of transitions than were first-order sequences. For example, the transition 1-4 occurred in second-order but not first-order sequences. Thus statistical structure was a confound (see Stadler, 1992). This was not a problem in the current study.

Although participants in the current study learned first- and second-order probabilities, there was no apparent awareness of what was learned. When asked to indicate whether EL transitions were less likely, more likely, or as likely to occur as EH transitions, the first option was chosen as often as the second option. Moreover, choice was uncorrelated with reaction time in experiment 1. For some transitions in experiment 2, there may have been an awareness of the second-order probabilities. Removing the transitions increased the reaction time difference between EL and EH transitions. When just those transitions were considered, there was no difference between EL and EH transitions. This suggests, if anything, a negative relationship between awareness and learning which contrasts with the positive relationship for fixed, repeating sequences (e.g., Curran & Keele, 1993; Stadler, 1995; Willingham et al., 1989; but see Mayr, 1996, Experiment 2).

The explicit measures that were used in the current study assessed precisely the information that was learned in the SRT task (i.e., transition probabilities), were objective (i.e. forced-choice), and reinstated some of the cues present during the SRT task (e.g., the four horizontal lines). Nonetheless, it could still be argued that they were not sensitive enough. As a result, participants may not have been truly unaware of the transition probabilities. A more sensitive approach would have required participants to respond to one (experiment 1) or two (experiment 2) target locations and then predict in which of two locations the target was most likely to appear next. The problem with such an approach, however, is that it may not only tap into explicit knowledge, but also implicit knowledge (for a discussion of this point, see Cohen & Curran, 1993; Neal & Hesketh, 1997; Perruchet & Gallego, 1993; Stadler, 1997). Results from the discrete blocks showed that responding to one or two events facilitated responding to the likely next event. It is possible that such facilitation could have formed the basis for explicit predictions. Consequently, I believe that the measures of explicit knowledge that were used were the most appropriate.

Learning in other paradigms. Implicit learning of first-order probabilities is not limited to the SRT task. Evidence has been gathered using other paradigms. These include the control of spatial orientation by external cues (Lambert & Sumich, 1996), a flanker task (Ottaway, Johnson, & Reed, 1996; Experiment 1), a fine-motor catching task (Green & Flowers, 1991), learning of color-word associations in a stroop task (Musen & Squire, 1993), and learning of object-location associations (Musen, 1996, Experiment 3). In these studies, first-order probabilities were 0 versus 1.0, 0.20 versus 0.80, or 0.25 versus 0.75. In the current study, the gap was narrowed to 0.40 versus 0.60 for both first- and second-order probabilities.

Performing a flanker task, participants in the Ottaway et al. (1996; Experiment 2) study were unable to learn second-order probabilities of 0 versus 1.0. This contrasts with the learning of second-order probabilities of 0.40 versus 0.60 in the current study. The tasks used in the two studies differed in a number of ways. One way in which they differed is that events in the flanker task were presented simultaneously, whereas events in the current study were presented successively. Flankers varied along three dimensions -- shape (circle, square), line type (solid, hatched), and line orientation (vertical, horizontal) -- and the conjunction of two dimensions (e.g., shape and line type) was predictive of one of two possible responses. For example, if the flankers were circles with solid lines or squares with hatched lines then this predicted one response. If the flankers were circles with hatched lines or squares with solid lines then this predicted the other response. Thus the two relevant dimensions were presented simultaneously. Participants were unable to learn flanker-response associations.

In the current study, the location of the target on trials (t-2) and (t-1), which were presented successively, was predictive of its location on trial (t). To learn second-order probabilities, it would seem necessary to first conjoin the two dimensions, or trials (t-2) and (t-1) and then form an association between the conjunction and the to be predicted event. Simultaneous presentations may decrease the likelihood of successfully forming conjunctive associations. Indeed, in covariation detection experiments (e.g., Lewicki, 1986), implicit learning of the covariation between two features presented simultaneously in a stimulus complex may be difficult to achieve (Hendrickx, De Houwer, Baeyens, Eelen, & Van Avermaet, 1997; but see Musen & Squire, 1993). Along similar lines, learning in classical conditioning paradigms is impaired if the conditioned and unconditioned stimuli are presented simultaneously rather than successively (Domjan, 1993, p. 67).

Is Implicit Learning Quick or Gradual?

The majority of the difference in reaction time between EL and EH transitions emerged within the first 500 trials of session 1 (see Figures 1 and 3, top panel). This suggests that learning of first- and second-order probabilities occurred quickly. However, the early difference between EL and

EH transitions could reflect differential practice effects (e.g., Stadler, 1992, 1993) or short-term priming effects (e.g., Cleeremans & McClelland, 1991).

There is some evidence that learning was not limited to session 1. First, short-term priming effects weakened across sessions. It is possible that learning of the sequential structure was responsible for the decline in short-term priming effects (Cleeremans & McClelland, 1991). As first- and second-order probabilities were learned, the knowledge increasingly overrode short-term priming effects. Second, the percentage of errors that involved making non-occurring transitions decreased across sessions. This suggests that with training, participants learned which transitions never occurred. Third, differences in error rate between EL and EH transitions increased across sessions. This could reflect cautious behavior in session 1, but it could also reflect learning of the transition probabilities. Finally, the difference in reaction time between the difference scores EL minus EH and CL minus CH increased marginally across sessions in experiment 1. This suggests that there was some learning of the transition probabilities across sessions. Thus early differences in reaction time between EL and EH transitions may have been due mostly to practice and short-term priming. As the effects diminished with training, they were offset by learning of the sequential structure. Consequently, there was little change in the reaction time difference between EL and EH transitions.

Other studies using probabilitistic sequences (e.g., Cleeremans &

McClelland, 1991; Jimenez et al., 1996; Schvaneveldt & Gomez, 1996; Shanks et al., 1994, Experiment 2) and complex repeating sequences (e.g., Stadler, 1993; Willingham et al., 1993) have also observed differences in reaction time early in training. Unlike the current study however, differences in reaction time between probable and improbable transitions, or repeating and random sequences increased with training. The use of fairly disparate transition probabilities (e.g., 0.10 vs 0.90, 0.20 vs 0.80, 0.05 vs 0.40 and 0.60, etc.), or awareness of the sequential structure may have more than offset the weakening of practice and short-term priming effects.

In sum, differences in performance between more and less probable events may be the result of practice and short-term priming effects early in training, and learning of the probabilities later in training (see Cleeremans & McClelland, 1991; Stadler, 1992, 1993). This suggests that implicit sequence learning is a gradual process.

On Mechanisms

Although there are a number of models of sequence learning (Cleeremans, 1993, 1994; Frensch & Miner, 1994; Jimenez et al., 1996; Keele & Jennings, 1992), the precise mechanisms are not well understood. The goal of the current study was not to investigate possible mechanisms. However, any mechanism of implicit serial learning must account for three features of the data. First, reaction time decreased as a linear function of transition probability. In the nondiscrete blocks of session 3, reaction times on EL, C (the average of CL and CH transitions which did not differ significantly), and EH transitions were, respectively, 314 ms, 289 ms, and 266 ms in experiment 1; and 289 ms, 283 ms, and 276 ms in experiment 2. Reaction times on C transitions fell halfway between that of EL and EH transitions. In both experiments, reaction times were slower on EL than C transitions, two ps $< .011$, and on C than EH transitions, two ps $< .017$. Thus, as transition probability increased from 0.40 to 0.50 to 0.60, reaction time decreased linearly. Bertelson (1961, Experiment 2) observed a similar pattern of results in a two-choice SRT task with first-order probabilities of 0.25, 0.50, and 0.75. A second feature of the data was the greater difference in reaction time between first-order probabilities of 0.40 and 0.60 than between second-order probabilities of 0.40 and 0.60. In experiment 1, the session 3 difference between EL and EH transitions was 48 ms. In experiment 2, the difference was 13 ms. Finally, there were short-term priming effects associated with runs of two and three, and these effects diminished with training. It is unclear whether the weakening of short-term priming effects was due to learning of the sequential structure or to other factors.

Any mechanism of implicit serial learning must account for the above features of the data. A mechanism would also have to address a number of issues. For example, are excitatory or inhibitory processes involved? Are spatial orienting mechanisms, response mechanisms, or other mechanisms involved? What are the effects of attention, awareness, and intention to learn on learning? etc. Clearly, much work needs to be done before a moderate understanding of implicit serial learning is achieved.

Conclusion

Before mechanisms of implicit serial learning can be postulated, it is crucial that we understand precisely what it is that is being learned in the SRT task. Evidence has suggested that what is learned are first- and second-order probabilities (e.g., Cleeremans, 1993; Jimenez et al., 1996; Perruchet et al., 1990; Stadler, 1992). However, the evidence has been far from conclusive. The goal of the current study was to provide stronger evidence that people could in fact learn first- and second-order probabilities in an implicit fashion. The results from two experiments showed that they could. Further research should attempt to isolate the mechanisms responsible for the reaction time differences between transitions with transition probabilities of 0.40, 0.50, and 0.60.

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Appendix A

Generating the Sequences of Target Locations

Sequences corresponding to Tables 1 and 3 were generated using the left and right matrices in Table 5, respectively. A matrix consisted of 16 rows. Each row was labelled with one of the 16 possible three-element runs that occurred in a sequence. The elements in a row determined what could follow the three-element run indicated by the row label. For example, row 1-2-4 in the left matrix consisted of six 2's and nine 3's (for a total of 15 elements) which meant that in the sequence, 2 would follow 1-2-4 six times, and 3 would follow 1-2-4 nine times. Note that for some rows in the left matrix, numbers appear in pairs such as 7/8 and 8/7. When sequences were generated, the numbers alternated between the first and second members of each pair. If the first number in each pair was used to generate one sequence, then the second number was used to generate the next sequence, and vice versa.

To generate a sequence (i.e., two blocks of trials), the following algorithm was employed.

1) Permute the elements in each of the 16 rows

2) Choose a starting row at random (e.g., 4-2-4)

3) Choose the first element in the row that has not previously been chosen

4) Use the last two elements of the current row label together with

Table 5
Generation Matrices Corresponding to Tables 1 and 3

Row Label	Table 1: 1	Table 1: 2	Table 1: 3	Table 1: 4	Table 3: 1	Table 3: 2	Table 3: 3	Table 3: 4
1-2-1	-	9	6	-	-	9	9	-
1-2-4	-	6	9	-	-	6	6	-
1-3-1	-	6	4	-	-	6	6	-
1-3-4	-	4	6	-	-	9	9	-
2-1-2	7/8	-	-	8/7	9	-	-	6
2-1-3	5	-	-	5	6	-	-	9
2-4-2	5	-	-	5	6	-	-	9
2-4-3	7/8	-	-	8/7	9	-	-	6
3-1-2	8/7	-	-	7/8	9	-	-	6
3-1-3	5	-	-	5	6	-	-	9
3-4-2	5	-	-	5	6	-	-	9
3-4-3	8/7	-	-	7/8	9	-	-	6
4-2-1	-	6	4	-	-	6	6	-
4-2-4	-	4	6	-	-	9	9	-
4-3-1	-	9	6	-	-	9	9	-
4-3-4	-	6	9	-	-	6	6	-

the chosen element to determine the next row from which to choose. For example, if the current row is 4-2-4, and 3 was chosen from that row, then the next row to choose from is row 2-4-3.

5) Repeat steps 3 and 4 until all elements in the matrix have been chosen. This would be 200 elements for the left matrix, and 240 elements for the right matrix. The last three elements chosen always correspond to the row label of the starting row. For example, if the starting row was 4-2-4, then elements 198, 199, and 200 (or 238, 239, and 240 for the right matrix) would be 4, 2, and 4 respectively.

6) Take the first element in the sequence and tack it onto the end of the sequence resulting in a 201-element sequence. For the right matrix, take

the first two elements in the sequence and tack them onto the end of the sequence resulting in a 242-element sequence.

7) Let elements 1 to 101 inclusive form one sequence (i.e., one block of trials), and let elements 101 to 201 inclusive form a second sequence (i.e., the next block of trials). Thus the last element of the first sequence is the same as the first element of the second sequence. In the case of the right matrix, let elements 1 to 122 inclusive form one sequence, and let elements 121 to 242 inclusive form a second sequence. Thus the last two elements of the first sequence are the same as the first two elements of the second sequence.

Given an initial starting row (e.g., 4-2-4), there was no guarantee that the algorithm would choose every element in the matrix. If the algorithm terminated prematurely, it was because an element had to be chosen from the starting row 4-2-4, and there was no element to choose. All elements had been previously chosen. If this happened, then the next row in the matrix (i.e., row 4-3-1) was chosen as the starting row and the algorithm restarted at step 3. This continued until a successful cycling of the entire matrix was achieved. If none of the 16 rows were appropriate starting rows, then the algorithm was restarted at step 1.

Appendix B

The Awareness Questionnaire of Experiment 1

The following four questions pertain to the 12 sets you did yesterday and the day before and to the 10 unstarred sets you did today. Each question has three options. Choose the option that you feel is correct.

When the letter o appeared in position 1, it then went to position 2 or 3.

(a) It went to position 2 more often than to position 3.
(b) It went to position 3 more often than to position 2.
(c) It went to positions 2 and 3 equally often.

When the letter o appeared in position 2, it then went to position 1 or 4.

(a) It went to position 1 more often than to position 4.
(b) It went to position 4 more often than to position 1.
(c) It went to positions 1 and 4 equally often.

When the letter o appeared in position 3, it then went to position 1 or 4.

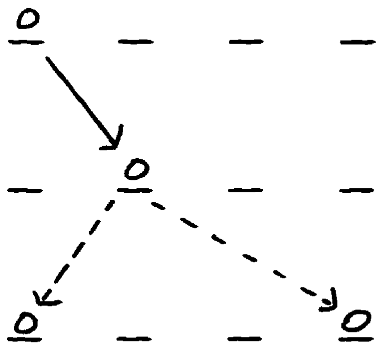
(a) It went to position 1 more often than to position 4.
(b) It went to position 4 more often than to position 1.
(c) It went to positions 1 and 4 equally often.

When the letter o appeared in position 4, it then went to position 2 or 3.

(a) It went to position 2 more often than to position 3.
(b) It went to position 3 more often than to position 2.
(c) It went to positions 2 and 3 equally often.

Appendix C

An Item from the Awareness Questionnaire of Experiment 2



Suppose the o moved from position 1 to position 2. Now from position 2, the o went to position 1 _____% of the time and to position 4 _____% of the time.

35 40 45 50 50 55 60 65