Memory & Cognition
1993, 21 (6), 819-827

Implicit serial learning: Questions inspired by Hebb (1961)

MICHAEL A. STADLER
University of Missouri–Columbia, Columbia, Missouri

Implicit serial learning occurs when indirect measures such as transfer reveal learning of a repeating sequence even when subjects are not informed of the repeating sequence, are not asked to learn it, and do not become of aware of it. This phenomenon is reminiscent of an experiment by Hebb (1961), who studied the repetition of sequences in a serial recall task. Two experiments investigated the relation between implicit serial learning and ideas about learning forwarded by Hebb and others who used his method. The experiments showed that implicit serial learning occurs even when the repeating sequence is intermixed with randomly generated sequences instead of being repeated continuously, that the organization of the sequence into regularly or irregularly grouped subsequences determines the extent of learning, and that the repetition effect observed does not depend on subjects' ability to recognize the repetition.

Some of the most fundamental discussions about learning have centered on what conditions are necessary and sufficient for it to occur. Hebb (1961) asked, does momentary attention to a sequence of stimuli leave a permanent record in the nervous system? Hebb's question was similar in spirit to many of the current questions about implicit learning and memory, those phenomena in which memory is measured not directly, as in recall tasks, but indirectly through a variety of transfer measures (see Reber, 1989; Richardson-Klavehn & Bjork, 1988, for reviews).

Hebb looked for an answer to his question with an experiment in which subjects briefly, but repeatedly, held the same sequence of digits in memory while doing a digit span task. The task required them, on each of a series of trials, to repeat back a randomly ordered list of nine digits read to them by the experimenter. Every third list of digits was the same, although the subjects were not informed of this. In Hebb's terms, listening to and repeating a list of digits creates an activity trace, a momentary representation of the list. The question was whether on the next trial that activity trace would be wiped out completely or whether a permanent, structural trace would be left behind. If the activity trace is wiped out, then repeating a list with other lists intervening between repetitions should have no effect on subjects' performance. If a structural trace is formed, then memory for the repeated list should improve over trials at a greater rate than memory for nonrepeated lists. Such a pattern of results would fit neatly with the general pattern of results in the implicit memory literature, and this is, in fact, what Hebb observed. He thus concluded that even very briefly retained information has a (relatively) permanent effect on memory.

A more recent development is reminiscent of Hebb's work. There have been numerous reports of implicit serial learning (e.g., Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Fendrich, Healy, & Bourne, 1991; Nissen & Bullemer, 1987; Stadler, 1992b; Willingham, Nissen, & Bullemer, 1989). In these studies, subjects performed a serial reaction time (RT) task in which on each trial an asterisk appeared above one of four locations arranged in a row across a computer screen. The subjects' task was simply to press a key corresponding to the asterisk's location. They did several blocks of trials of this task, during which a particular sequence of locations was repeated continuously. For example, if the four locations were designated A to D, the repeating sequence used by Nissen and Bullemer was DBCACBDCBA. This sequence cycled continuously, without a break at the end, so that the last A was followed by the first D. When subjects have been asked directly about the sequence after they have done the task, they have often not been able to deliberately express knowledge about the sequence (e.g., Willingham et al., 1989). However, indirect measures clearly show that learning takes place. As practice proceeds, RT decreases faster for subjects who respond to a repeating sequence than for subjects who respond to a completely random sequence. Moreover, if, after some practice with the repeating sequence, subjects are transferred to a completely random sequence, their RT increases dramatically.

Experiment 1 was presented in the author's PhD dissertation, which was submitted to the faculty of Purdue University. During that time, the author was supported by a David Ross Graduate Research Fellowship from Purdue. The author gratefully acknowledges John Capaldi, Richard Schweickert, Eliot Smith, and Howard Zelaznik, members of the doctoral committee, and Robert Proctor and Henry L. Roediger III, cochairs of the committee, for helpful comments, discussion, and suggestions. The author also acknowledges Leslie Alberstadt, Kelly Dugan, Joe Oubre, and Jackie Sharborough for assistance with data collection for Experiment 2. He is also grateful to Alice Healy, James Chumbley, and two anonymous reviewers for helpful comments on a previous version of the manuscript. Correspondence concerning this article should be addressed to the author at the Department of Psychology, 210 McAlester Hall, University of Missouri-Columbia, Columbia, MO 65211, or via e-mail to psymike@mizzou1.missouri.edu.

As in Hebb's experiment, incidental exposure to a repeating sequence clearly produces learning.

The similarities between Hebb's experiment and implicit serial learning are obvious, but there are some clear differences as well. These similarities and differences raise some interesting questions about the basis of implicit serial learning. The experiments reported here examined some of these questions in an effort to further delineate the implicit serial learning phenomenon.

Perhaps the most salient difference between the two phenomena is that Hebb's repeating sequence was intermixed with other, nonrepeated, sequences. In implicit serial learning, the same sequence is repeated continuously without any other sequences intervening. This contrast raises the question of whether implicit serial learning would occur if random sequences were intermixed. One reason it might not depends on a distinction similar to Hebb's distinction between activity and structural traces. Does implicit serial learning occur only when the sequence is repeated continuously, so that it is always active in short-term memory? If so, this would be something like rehearsal; the subjects "know" the sequence only while it is continuously repeated during practice. Will implicit serial learning occur if the sequence is not kept continuously active in short-term memory?

This idea was tested by simply alternating repetitions of a repeating sequence with randomly generated sequences in a serial RT task. If implicit serial learning is due to something like a rehearsal process, then there should be no benefit under these conditions.

Some might claim that some studies have already answered this question. For example, Cohen et al. (1990) followed the typical procedure of training subjects with the repeating sequence for several blocks and then transferring them to a random sequence, but they also then transferred them back to the repeating sequence. Subjects clearly retained what they had learned during training; their RTs in the first block in which the repeating sequence was reintroduced were comparable to those in the last block of initial training. However, by the time these subjects were transferred to a random sequence, there was plenty of time for the formation of a structural trace (or its theoretical equivalent). That is, it may be that there was retention across the intervening block of random trials because the continuous rehearsal-like nature of training produced a structural trace. The question in the present experiments was whether a structural trace would build up even when the sequence was not repeated continuously during training.

Another issue addressed by these experiments was whether the organization of the sequence in implicit serial learning matters. In Hebb's experiment, each sequence was demarcated by the subject's attempt to recall it. In implicit serial learning, there is no demarcation of the beginning or end of the sequence. This lack of between-sequences organization may be especially problematic when random sequences are intermixed with the repeating sequence such that the repeating sequence may be indistinguishable from the random sequences.

Within-sequence organization may also be an important factor. Bower and Winzenz (1969) showed that the Hebb effect occurs only when the list of items is organized the same way from one repetition to the next. To use one of their examples, if a series of numbers was presented as 17-683-9452-7-56 the first time, where the dashes indicate the groupings, it might be presented the same way on subsequent trials or it might be presented as 176-839-45-275-6, 1-768-3945-2-756, and then 1768-39-45-2756. There was no repetition effect when the organization of the digits changed across trials. Thus, the effect of repetition occurred only when the organization of the sequence remained intact across repetitions. Inconsistent organization of the same sequence of digits produced no benefit, as if each new grouping was a new sequence.

Does organization influence implicit serial learning similarly? Another important difference between the two tasks must be considered. In the Hebb task, the subjects deliberately try to remember the sequence of digits. Under these conditions, the organization imposed is likely to be due, at least in part, to a conscious, strategic effort on the part of the subject to memorize the sequence. No such strategies should be employed by subjects in the implicit serial learning situation. Subjects are not even told that a discernible sequence will be presented, let alone asked to try to remember it.

Although subjects are not likely to deliberately organize and group the sequence in an implicit serial learning experiment, there might still be an effect of grouping. Kahneman and Henik (1981) showed, in a variety of situations, that Gestalt principles of organization seem to have an automatic influence on the perception of visual stimuli arranged in space. It might be that similar effects occur for stimuli arranged in time, so that inserting pauses into the sequence might automatically cause grouping by proximity.

To explore this issue, three different grouping conditions were used in Experiment 1. In the first condition, the interval between trials was constant throughout the experiment, so that there were no cues to the beginning and end of the repeating sequence or the random sequences—they ran together. In the second condition, a pause was inserted after the last trial of the sequence in order to group the sequence consistently across repetitions, so that the beginning and end of the sequence was marked, as it would be in Hebb's task. In the last condition, the point at which the pause was inserted was random, so that the grouping was different across consecutive cycles, similar to the condition used by Bower and Winzenz (1969). As an example, consider the short sequence ABCD mixed with randomly generated sequences of four trials. In the no-grouping condition, each cycle of the repeating sequence was presented immediately after the preceding one, ABCDBDCDABCDCBACABCD. . . . In the consistent-grouping condition, a pause was presented after each cycle, ABCD BDCD ABCD CBAC ABCD. . . . In the random-grouping condition, a pause was presented after a randomly selected trial in each cycle, AB CDB DCDA BCDCBA CABC D. . . .

EXPERIMENT 1

Method

Subjects. The subjects were 36 introductory psychology students at Purdue University who participated as part of a course requirement. They were assigned to conditions randomly as they entered the laboratory.

Apparatus and Stimuli. The experiment was controlled by a microcomputer; the stimuli were presented via CGA video controllers and monitors. The monitors were positioned about 50 cm in front of the subjects. The subjects responded by pressing the C, V, B, and N keys on the keyboard, which was placed directly in front of the monitor. The target stimuli were asterisks which appeared above one of four underlined locations on the screen. The stimulus locations were separated center-to-center by approximately 1.3 cm; the asterisk was approximately 3 mm wide. All timing was in milliseconds, and the onset of each display was synchronized with the raster scan of the monitor.

Design. The subjects performed eight blocks of 100 trials. Each block consisted of five occurrences of the 10-trial repeating sequence, each of which was preceded by 10 trials generated randomly, creating 5 cycles each composed of a random sequence and the repeating one. All random sequences were random with the restriction that the target not appear in the same location on 2 successive trials. The repeating sequence was BDBCABCDBC, where the four target locations were designated A, B, C, and D, from left to right, respectively. All subjects responded to the same basic sequence of 800 trials, although three other versions of the repeating sequence were also used. Version 2 was CACDBCDACD, Version 3 was DBDACDABDA, and Version 4 was ACABDABCAB. Note that all of these sequences are isomorphic to the original sequence, so that they have identical statistical structure (see Stadler, 1992b). To illustrate, to construct Version 2, the A in Version 1 became B, the B became C, the C became D, and the D became A. The randomly generated sequences were similarly translated. An equal number of subjects in each group performed the task with each version.

The response to stimulus interval (RSI) was 400 msec except for trials after which a grouping cue occurred; on those trials, the RSI was 2,000 msec. In the consistent-grouping condition, the grouping cue was presented after the last trial in each subsequence of 10 trials. In the random-grouping condition, the grouping cue was presented after a randomly selected trial in each successive sequence of 10 trials. All of the subjects in the random-grouping condition were given the same sequence of RSIs.

Procedure. Each trial consisted of the presentation of the asterisk in one of the four locations, the subject's response, and then an RSI, the length of which depended upon the grouping manipulation. The leftmost response key corresponded to the leftmost stimulus location, and so on. The subjects used their left middle and index, and right index and middle fingers to press the four response keys, in that order.

The subjects were asked to respond by pressing the key corresponding to the asterisk's position as quickly as possible while maintaining about 95% accuracy. When the subjects made an error, the computer waited for the correct response (cf. Nissen & Bullemer, 1987), so they were also told that they should try to correct any errors as quickly as possible. After Blocks 1 to 7, the computer displayed the message "Time for a break" for 15 seconds, after which the message "Press any key to continue" appeared. The subjects initiated the subsequent block of trials at their own discretion. No mention was made to the subjects about the repeating pattern. They were merely told that the experiment was designed to study the effect of practice on RT. The computer recorded subjects' responses and RTs for later analyses.

Results

Reaction-time analyses were conducted for only those trials on which the subject responded correctly the first time. Inspection of the data revealed that RTs for the first 10 trials (the random sequence in the first cycle) were dramatically longer than the RTs for the rest of the random sequences, due no doubt to the fact that subjects were unfamiliar with the task at that point. In subsequent blocks, only the first 2 trials were similarly affected. These trials were thus not included in the analyses (excluding the long RTs on these trials makes finding a repetition effect *less* likely because these trials were from random sequences). Otherwise, trials with RTs less than 100 msec or greater than 1,500 msec were dropped; these amounted to only 0.42% of the trials.

Accuracy was generally quite high, and did not differ significantly between the no-grouping, consistent-grouping, or random-grouping conditions (94.1%, 95.0%, and 93.3%, respectively). Nothing in the accuracy data contradicted the interpretations of the RT data or suggested that a speed–accuracy tradeoff had occurred, so only the RT data will be discussed in detail.

To simplify the analyses, mean RT for random and repeating sequence trials was calculated for each block. This yielded a grouping (none, consistent, or random) × sequence type (random or repeating) × block (1 to 8) design, with repeated measures on the last two factors.

The RT data are presented in Figure 1. In this figure, the data are presented as mean RT for the repeating sequence in Cycle 1 and for the random and repeating sequences in each of the remaining 39 cycles. Each successive group of 5 cycles constituted a block of trials. After the first few cycles, RT was faster for the repeating sequence than for the random sequences in all conditions, but this repetition effect was smaller in the no-grouping condition than in the consistent-grouping condition, and smaller still in the random-grouping condition. The size of the repetition effect increased with practice in all conditions, but increased more for the no-grouping and consistent grouping conditions.

These observations were confirmed by a grouping (no, consistent, random) × sequence type (repeating vs. random) × block (1 to 8) ANOVA with repeated measures on sequence type and block and by some planned comparisons. The repetition effect was reliable, as evidenced by a main effect of sequence type [$F(1,33) = 115.99$, $MS_e = 1{,}704.79$, $p < .0001$]. Planned comparisons showed that the effect was significant in each of the three grouping conditions [$Fs(1,11) \geq 27.26$, $ps < .0003$]. Furthermore, there was a repetition effect for 12, 12, and 11 of the 12 subjects in the no-, consistent-, and random-grouping conditions, respectively. All of these were significant by a sign test ($ps < .004$). Thus, implicit serial learning clearly occurred in all three conditions, despite the intermixed random sequences, and even when there was no grouping or when grouping was random.

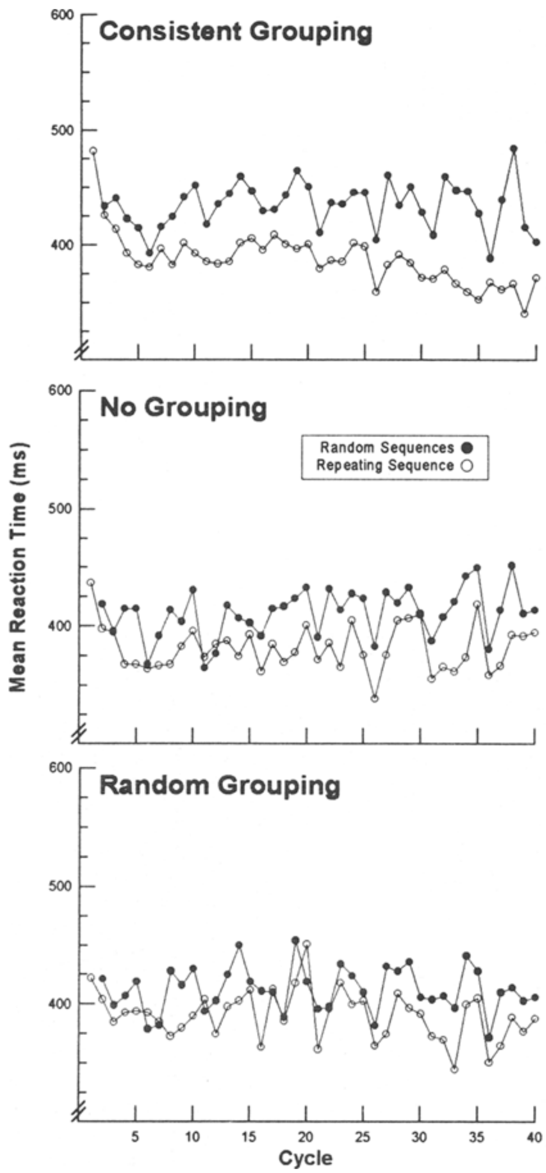

Figure 1. Mean RT for the repeating and random sequences across cycles by grouping condition in Experiment 1.

As noted, it appears in Figure 1 that the repetition effect is biggest in the consistent grouping condition and smallest in the random grouping condition. The sequence type × grouping interaction was significant [$F(2,33) = 5.50$, $MS_e = 1{,}704.78$, $p < .0087$]. Interaction contrasts that compared the sequence type effect for each possible pair of grouping conditions showed that the repetition effect was reliably different between the consistent- and random-grouping conditions [$F(1,33) = 10.72$, $MS_e = 27{,}276.62$, $p < .0025$] and the consistent- and no-grouping conditions [$F(1,33) = 4.41$, $MS_e = 27{,}276.62$, $p < .0435$], but not the no-grouping and random-grouping conditions [$F(1,33) = 1.38$, $MS_e = 27{,}276.62$, $p > .10$].

Reaction time decreased over blocks, of course. The main effect of block was significant [$F(7,231) = 2.17$, $MS_e = 1{,}162.69$, $p < .0375$]. The sequence type × block interaction was significant [$F(7,231) = 9.62$, $MS_e = 351.37$, $p < .0001$], as was the grouping × sequence type × block interaction [$F(14,231) = 1.81$, $MS_e = 351.37$, $p < .0387$]. Interaction contrasts for each grouping condition that compared the linear decrease in RT over blocks between the repeating and random sequences were significant for the consistent- and no-grouping conditions, but not the random-grouping condition [$Fs(1,33) = 25.79$, 4.98, and 3.23, $MS_e = 247{,}635.37$, $ps < .0001$, .0325, and .0814, respectively]. A final interaction contrast tested the hypothesis that RT decreased (linearly) over blocks, that the linear change was bigger for the repeating than for the random sequences, and that this difference was bigger for consistent grouping than random grouping. This contrast was also significant [$F(1,33) = 5.38$, $MS_e = 247{,}635.37$, $p < .0267$].

It was observed that learning occurred early in practice. In fact, the repetition effect is evident in Figure 1 even at Block 1 (Cycles 1-5). Mean RT per 10-trial sequence was examined for Sequences 2 to 9, or Trials 21 to 90, from Block 1. Sequences 2, 4, 6, and 8 were the repeating sequence; Sequences 3, 5, 7, and 9 were random sequences.[1] These data were submitted to a sequence type (random vs. repeating) × grouping (none, consistent, and random) × pair (Sequences 2 and 3, 4 and 5, 6 and 7, and 8 and 9, made up pairs 1 to 4, respectively) ANOVA, with repeated measures on sequence type and pair.

Mean RTs (averaged over grouping conditions) for the repeating and random sequences were 449 and 427, 411 and 414, 400 and 418, and 387 and 419, for Cycles 1 to 4. Mean RT for the repeating sequence was slower than for the random sequence in the first pair, but RT decreased much faster over pairs for the repeating sequence than for random sequences. By Pair 4, mean RT for the repeating sequence was much faster than for the random sequence. This pattern was roughly the same for each grouping condition; there were no main effects or interactions involving the grouping factor. Although the main effect of sequence type was not significant [$F(1,33) = 2.43$, $MS_e = 1{,}677.28$, $p > .10$], sequence type and pair interacted significantly [$F(3,99) = 6.77$, $MS_e = 1{,}413.28$, $p < .0003$]. An interaction contrast that compared the linear trends for the repeating and random sequences over pairs was significant [$F(1,33) = 18.55$, $MS_e = 60{,}372.04$, $p < .0002$], indicating a faster decrease in RT for the repeating sequence than for random sequences. Thus, sequence learning occurred early in practice. Interestingly, Hebb (1961) also noted an advantage for the repeated list early in his experiment (on the second presentation).

EXPERIMENT 2

Experiment 1 showed that implicit serial learning will occur even when the repeating pattern is not "rehearsed." The effect of repeating the pattern was, in fact, quite robust, and was apparent even in the first block of trials. Also, the organization of the sequence had a clear impact on the size of the repetition effect. Repeating the same sequence of trials over and over had a much larger effect on performance if the sequence was consistently marked as a unit. If, instead, the sequence was randomly broken into different pieces each time it occurred, learning was reduced, but it was not eliminated.

Experiment 2 had several purposes. One was simply to replicate the effects observed in Experiment 1. For reasons to be discussed, there were several changes between Experiments 1 and 2. If the general pattern of results observed in Experiment 1 survived those changes, then the effects could be regarded as reliable.

Experiment 2 used a less-well-structured sequence as a repeating sequence. Stadler (1992b) showed that the statistical structure of a repeating sequence influences the degree of implicit serial learning such that more-well-structured sequences are more easily learned. The sequence used in Experiment 1 had a moderate degree of statistical structure, less than did the sequence used by Nissen and Bullemer (1987) and many others after them, but more than would be found in the typical random sequence. That sequence was chosen in order to give a reasonable chance to finding a repetition effect. However, this leaves open the possibility that the repetition effect was due to the difference in structure between the repeating and random sequences instead of being due to learning. In Experiment 2, a 12-trial sequence that had a level of statistical structure comparable to that of the typical random sequence of 12 trials was used.

The way in which the different degrees of grouping was accomplished was also changed in Experiment 2. Instead of just one grouping cue per sequence of 12 trials, there were three. This was done partly because a longer sequence was used in this experiment and partly to make the grouping manipulation more comparable to that of Bower and Winzenz (1969), who used several grouping cues per sequence.

Finally, subjects' awareness of the repeating sequence was assessed in Experiment 2. Interestingly, Hebb touched on this issue as well. Hebb asked his subjects if they had noticed that one of the sequences was repeated; 25 of the 40 did notice the repetition. Unfortunately, Hebb did not further explore what is now a central question about implicit serial learning: Does learning depend upon awareness of the repeating sequence?

Without going into great detail, some have answered this question "no" (Lewicki, Hill, & Bizot, 1988; Nissen & Bullemer, 1987; Stadler, 1989; Willingham et al., 1989), but others have said "yes" (e.g., Fendrich et al., 1991; Perruchet & Amorim, 1992). This debate is remindful of others, such as those on subliminal perception (e.g., Cheesman & Merikle, 1986; Greenwald, 1992; Holender, 1986) and artificial grammar learning (e.g., Dulany, Carlson, & Dewey, 1984, 1985; Reber, Allen, & Regan, 1985). It no doubt will not be settled here. However, Experiment 2 used an objective recognition measure of subjects' explicit memory for the repeating sequence and then compared the RT results for more and less aware subjects. If the repetition effect depends upon subjects' explicit knowledge of the sequence, then there should be a difference between the performance of those subjects who can recognize the repeating sequence and those who cannot.

Method

The method was the same as that of Experiment 1, with the following exceptions.

Subjects. The subjects were 96 undergraduates at Louisiana State University, who participated in return for extra credit in psychology courses. Upon entering the laboratory, they were assigned to groups randomly.

Apparatus and Stimuli. All features of presentation were the same as in Experiment 1, except that the stimuli were displayed on VGA monitors.

Design. Each of the eight blocks of trials again consisted of five cycles, each of which was made up of a random sequence of 12 trials and the 12-trial repeating sequence, yielding a total of 120 trials per block. The repeating sequence was ABADBCDACBDC. This sequence has the lowest level of statistical structure possible in a sequence of 12 trials. In Experiment 1, one triplet and some pairs of successive trials were repeated within the sequence. In Experiment 2, no pairs (and thus no triplets) of successive trials were repeated. The sequence was not translated into several versions in this experiment.

The RSI in this experiment was 500 msec, except when a pause was inserted; then it was 2,500 msec. Pauses were inserted after every fourth trial in the consistent-grouping condition; three pauses were randomly inserted within every successive 12-trial sequence in the random-grouping condition.

Procedure. The procedure for performance of the serial RT task was the same as in Experiment 1. After that was complete, the subjects were asked to do a brief recognition test. They were informed that a sequence of locations had been repeated many times during the first phase of the experiment. They were then asked to respond to a series of four trial sequences just as they had in the first phase of the experiment, except that when each of these was complete they were to make a judgment about whether it had been part of the repeating sequence in the first part of the experiment. They made their judgments by circling a number on a scale that ranged from 1 to 6, 1 indicating that the preceding sequence was *Definitely not repeated*, 6 indicating that the preceding sequence was *Definitely repeated*. For scoring purposes, Responses 1 to 3 were considered negative responses and Responses 4 to 6 were considered positive responses. After making each judgment, the subject initiated the next four trial sequences by pressing a key.

The subjects responded to 12 randomly ordered sequences during the recognition phase. Six of these were from the repeating sequence; the sequences ABAD, BCDA, and CBDC were each presented twice. These sequences were selected because they preserved the grouping that occurred in the consistent grouping condition. The other 6 sequences were selected so that each location would be used the same number of times as in the sequences from the repeating sequence; they were ABDA, ADAB, BCAD, BADC, CBCD, and CDCB.

Results

The data from 1 subject in the no-grouping condition were lost to an error in writing the data to disk; the RT data for that subject were replaced with the mean RTs of the other subjects in that group. As in Experiment 1, the trials from the random sequence in the first cycle were dropped, as were the first two trials of the random sequence in the first cycle of the remaining blocks. Also, RTs less than 100 msec or greater than 1,500 msec were discarded; these amounted to 0.54% of the trials.

Mean accuracy was 95.2, 92.8, and 94.7 for the consistent-grouping, no-grouping, and random-grouping conditions, respectively. Comparable analyses were carried out on both the accuracy and RT data; nothing in the accuracy analyses contradicted the RT analyses or suggested a speed–accuracy tradeoff, so only the RT data will be presented.

The RT data are presented in Figure 2. As in Experiment 1, the data are presented by cycle, beginning with the repeating sequence in Cycle 1. The data were somewhat more orderly than in Experiment 1, and the repetition effect appears to be somewhat smaller. This was expected, of course, given the change in the structure of the sequence. Still, the overall pattern remained the same. A repetition effect was discernible in all three conditions, but was most apparent in the consistent-grouping condition and least in the random-grouping condition. The repetition effect started off small in all three conditions, but grew as practice continued.

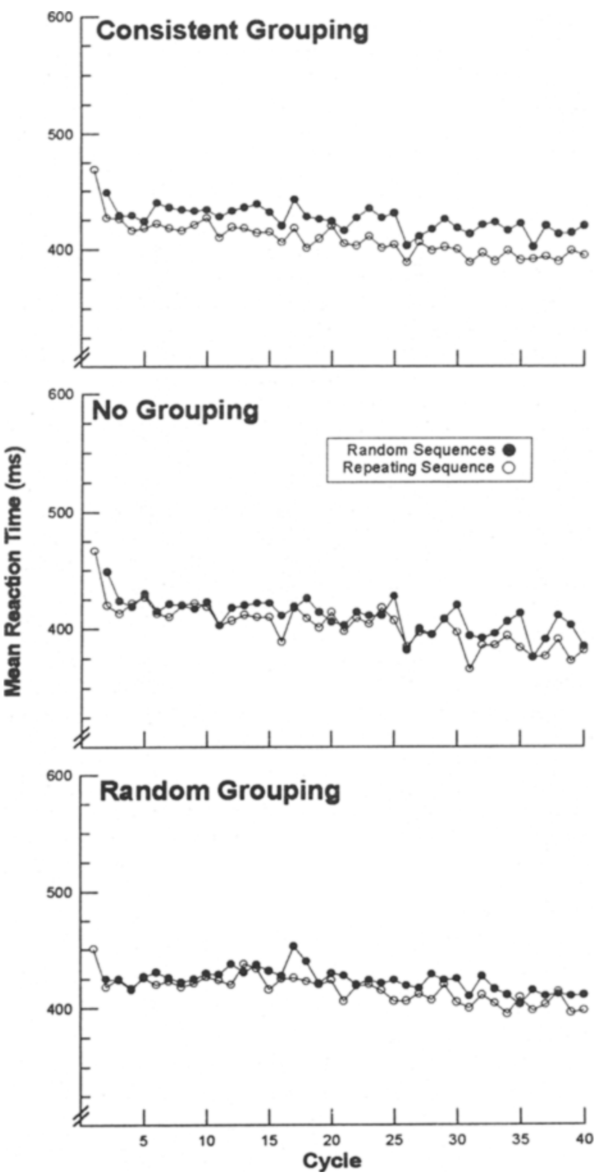

Figure 2. Mean RT for the repeating and random sequences across cycles by grouping condition in Experiment 2.

These observations were confirmed by the analyses. A grouping × block × sequence type ANOVA, with repeated measures on the last two factors, revealed a reliable effect of sequence type [$F(1,93) = 142.86$, $MS_e = 400.89$, $p < .0001$]. Moreover, this effect was significant in each of the grouping conditions, as shown by comparisons that examined the repetition effect separately for each group [all $Fs(1,31) \geq 24.81$, all $ps < .0001$]. Of the 32 subjects in each group, 30, 27, and 25 were faster for repeating than for random sequences (all $ps < .002$ by sign tests).

The size of the repetition effect varied across grouping conditions. The interaction between sequence type and grouping condition was significant [$F(2,93) = 12.93$, $MS_e = 400.89$, $p < .0001$]. Interaction contrasts compared the size of the repetition effect across grouping conditions. The repetition effects in the consistent-grouping and no-grouping conditions were reliably different [$F(1,93) = 19.50$, $MS_e = 6{,}414.26$, $p < .0001$], as were those in the consistent-grouping and random-grouping conditions [$F(1,93) = 19.30$, $MS_e = 6{,}414.26$, $p < .0001$]. The no-grouping and random-grouping conditions did not differ [$F(1,93) < 1$].

Reaction time, of course, decreased over blocks [$F(7,651) = 20.73$, $MS_e = 661{,}341.74$, $p < .0001$]. Block interacted with sequence type [$F(7,651) = 9.30$, $MS_e = 181.70$, $p < .0001$], but the grouping × sequence type × block interaction was not significant [$F(14,651) = 1.03$, $MS_e = 181.70$, $p > .25$]. A contrast of linear trends that compared the change in RT over blocks for the repeating and random sequences was significant [$F(1,93) = 39.60$, $MS_e = 72{,}673.64$, $p < .0001$], supporting the observation that the repetition effect grew bigger with practice. This change in the size of the repetition effect with practice did not vary, however, across grouping conditions.

Separate analyses of the Block 1 data were also carried out. The general pattern was the same as in Experiment 1. The data were again submitted to a grouping × sequence type × pair ANOVA, with repeated measures on the last two factors. Mean RTs (averaged over grouping conditions) for repeating and random sequences were 464 and 442, 424 and 428, 423 and 424, and 419 and 430 msec for Pairs 1 to 4, respectively. The rate with which RT decreased was clearly faster for the repeating sequences than for the random sequences. The main effect of sequence type was not significant [$F(1,93) < 1$], but the cycle × sequence type interaction was [$F(3,279) = 10.63$, $MS_e = 920.03$, $p < .0001$]. An interaction contrast was again used to compare the linear trends across pairs for the random and repeating sequences. This was also significant [$F(1,93) = 20.31$, $MS_e = 43{,}770.02$, $p < .0001$], supporting the observation that in Block 1 RT decreased faster for the repeating sequences than for the random sequences. Again, this indicates that learning was occurring even as early as Block 1.

The final issue is awareness and what part it plays in the effects observed in subjects' performance of the serial RT task. The first step in answering this question was to determine, separately for each grouping condition, whether there was any evidence that the subjects, or some subset of them, were in fact aware of the sequence. To do this, the percent of the subjects that made each possible number of correct responses on the recognition test was compared with the percent that would be expected by chance. That is, subjects could make between 0 and 12 correct responses on the recognition test. By guessing, most would be expected to get about 6 correct, but some would do better and others would do worse. The question was whether the distribution of subjects by number of correct responses was different from what would be expected by chance. Table 1 presents the percent of the subjects that made a given number of correct responses and the percent that would be expected by chance. Only the distribution of subjects in the consistent-grouping condition differed from what would be expected by chance ($\chi^2 = 70.35$), even with a liberal criterion ($p = .20$). Thus, it seems fair to conclude that there was a dissociation between implicit and explicit knowledge in the no-grouping and random-grouping conditions. Although these groups evidenced highly reliable repetition effects, there was no evidence that they could explicitly indicate recognition of the repeating sequence.

The question goes somewhat deeper in the consistent-grouping condition, where as a group, the subjects were able to do better than would be expected by chance. To see what influence their awareness of the repeating sequence might have had on performance, they were divided into groups of (relatively) aware and unaware subjects by a median split based on performance on the recognition test. All subjects ($n=15$) who answered correctly 7 or fewer times and 1 who answered correctly 8 times were assigned to the unaware group; the remaining subjects were assigned to the aware group. The 1 subject who answered correctly 8 times and was assigned to the unaware group was selected on the basis that he or she had the smallest overall repetition effect of those subjects who answered correctly 8 times. This was done so as to tip the balance in favor of finding a larger repetition effect in the aware subgroup.

The RT data for these subjects were then reanalyzed with an awareness × sequence type × block ANOVA, with repeated measures on the last two factors. This analysis revealed no main effect of awareness and no interactions between the awareness factor and any others (all $ps > .25$). The overall difference in RT between the repeating and random sequences was 19.59 msec for the aware group and 19.53 msec for the unaware group. There is no evidence that the repetition effect observed in the RT data in any way depends on subjects' being able to recognize the repeating sequence.

Table 1
Percent of Subjects Who Made a Given Number of Correct Responses in the Recognition Test (n=32), Along With the Percent Expected by Chance

Number of Correct Responses	Grouping Condition: Consistent	No	Random	Expected by Chance
0	0	0	0	0.02
1	0	0	0	0.29
2	0	0	3.13	1.61
3	3.13	3.13	0	5.37
4	0	6.25	6.25	12.08
5	3.13	18.75	6.25	19.34
6	12.5	18.75	28.13	22.56
7	28.13	37.5	34.38	19.34
8	28.13	9.38	12.5	12.08
9	9.38	3.13	6.25	5.37
10	9.38	3.13	3.13	1.61
11	6.25	0	0	0.29
12	0	0	0	0.02

DISCUSSION

A repetition effect resembling the one Hebb reported clearly occurred in these experiments. Of the 132 subjects who participated in Experiments 1 and 2, only 15 responded more slowly to the repeating sequence than to the random ones. The effect is obviously quite reliable, even when relatively small, as in Experiment 2.

The finding that subjects learn the repeating sequence even when it is alternated with random sequences contradicts the idea that the repeating sequence must be continuously active in short-term memory, as if it were being rehearsed, for learning to occur. It is also significant, particularly in illustrating the relation between implicit serial learning and the Hebb effect, that learning was observed even in Block 1. Hebb noted in his report that the advantage for the repeated series of digits emerged very early, and that "a single repetition of a set of digits ... produces a structural trace which can be cumulative" (p. 43). In these two quite different tasks, it is apparent that a single experience with a particular series of elements—whether they are digits or visual-spatial signals—will facilitate later performance with the same series, even when other, quite different, series consisting of those same elements intervene.

The present findings are consistent with the idea that implicit serial learning depends on the number of unique runs of events that appear in a sequence and how often these runs are repeated (Stadler, 1992b). A run is a series of n successive trials in the sequence. Runs of different sizes overlap, so that a run of three trials includes two possible runs of two, and so on. Relative to a random sequence of trials, a continuously repeating sequence imposes strict constraints on the number of possible runs (of all sizes) the subject experiences and the frequency with which those runs are repeated during the experiment. Subjects who practice a random sequence have more runs to practice, and they practice each one less often. Thus, their rate of improvement with practice should be slower than that of subjects in the repeating sequence condition. When subjects who practice a repeating sequence are then transferred to a random sequence, almost all of the runs they must perform are ones that they have not practiced. The idea that implicit serial learning depends on practice with specific runs of events is consistent with the general idea that skills are specific to particular training episodes (e.g., Jacoby & Brooks, 1984; Kolers & Roediger, 1984; Logan, 1988, 1990).

Stadler (1992b) demonstrated that the rate of learning does indeed depend on the number of unique runs practiced by varying the statistical structure of different repeating sequences. The rate of learning increased as the constraints on the number of runs increased. In another experiment, the constraints were imposed on differently sized runs. For example, in one condition, the constraints were imposed only on the frequency with which a particular event (run of one) occurred; in another, the constraints dictated the frequencies of runs of five events. Intermediate conditions were also tested. The results showed that the higher the level of constraint, the greater the learning. Thus, learning does seem to depend on the number of runs to be practiced and the frequency with which they are practiced.

The results of Experiments 1 and 2 are consistent with this account. The interposed random trials increased the number of runs to be practiced, but those runs in the repeating sequence were still practiced more than all the others. To observe a repetition effect, the runs in the repeating sequence need not be the only runs the subjects practice, they just need to be practiced more.

The effects of grouping are also consistent with the proposed account. Learning clearly depended on the consistency with which the repeating sequence was organized. Consistent grouping was significantly better for performance than no grouping or random grouping in both experiments. In any case, if the pauses are assumed to define runs by automatic organizational processes that more or less follow the Gestalt laws of organization (cf. Kahneman & Henik, 1981), then there would be fewer unique runs to practice in the consistent-grouping condition and many more in the random-grouping condition. The observed pattern would thus be expected.

Note that this account does not necessarily predict that random grouping would produce no learning. A benefit from repetition could still occur in the random-sequence condition because there is a finite number of ways (10 or 220, respectively) that one grouping cue can be inserted into 10 trials, or three into 12. Furthermore, those groupings would not all create completely unique runs. For example, a sequence with grouping cues after Trials 4, 6, and 9 would produce a run in common with a sequence with grouping cues after Trials 4, 9, and 12. Thus, even in the random-grouping condition, runs from the repeating sequence would be somewhat more frequently practiced.

From the present perspective, it also makes sense that implicit serial learning begins to occur very early in practice. Response time typically decreases most early in practice (Newell & Rosenbloom, 1981). Thus, if implicit serial learning is basically a practice effect, then one would expect that it would be apparent fairly early in practice.

Implicit Serial Learning and Attention

It has been claimed that learning requires attention (Cohen et al., 1990; Hartman, Knopman, & Nissen, 1989; Nissen & Bullemer, 1987). One of the present findings raises a possible question about some of the evidence that has been used to argue that learning requires attention. Much of that evidence comes from dual-task studies in which the choice RT task is performed in conjunction with a tone-counting task, as described previously (Cohen et al., 1990; Nissen & Bullemer, 1987). The tone-counting task has been assumed to draw on attentional resources that are needed for learning. When those resources are taken up by the counting task, learning cannot occur. However, there is another possible explanation.

The counting task might also disrupt organization of the sequence (see also Jacoby, Woloshyn, & Kelly, 1989; Stadler, 1990). After every trial, subjects must discriminate which tone occurred, add one to their old count if it was a low tone, and then hold the count in memory until the next trial. The act of discriminating the tone might disrupt organization, or having to update their count on half the trials (the probability of a low tone has usually been .5) and not do so on the other half might be an even bigger disruption. This grouping effect, if it exists, might be more disruptive than the random-grouping condition used here because grouping cues (low tones) occurred more often. Thus, learning might not occur when the tone-counting task is performed, because the counting task prevents consistent organization of the sequence rather than because the counting task competes with the learning mechanism for attentional resources. Evidence supporting this alternative account has been obtained (Stadler, 1992a, 1993).

Implicit Serial Learning and Awareness

Finally, there is the issue of awareness. The practice account of implicit serial learning is more or less silent on this point. Subjects might or might not be aware of the effects of practice, the number of unique runs they have practiced, and so on. There was no evidence in the present experiments that subjects must have explicit awareness of the repeating sequence before learning, as indexed by the RT measures, can occur. In Experiment 2, subjects in the no-grouping and random-grouping conditions responded at chance levels on the recognition test, but clearly showed a repetition effect. In the consistent-grouping condition, some of the subjects were able to recognize the repeating sequence, but the size of the repetition effect did not depend upon whether subjects were aware. There is always the potential problem that the measure of awareness, recognition in this case, was not sensitive enough to detect subjects' awareness of the sequence, so appropriate caution should be exercised in accepting this conclusion. However, it is reasonable to adopt the provisional conclusion that, although subjects are sometimes able to explicitly recognize the repeating sequence, this is not a necessary requirement for learning.

REFERENCES

Bower, G. H., & Winzenz, D. (1969). Group structure, coding, and memory for digit series. *Journal of Experimental Psychology Monographs*, **80**(3, Pt. 2).

Cheesman, J., & Merikle, P. M. (1986). Distinguishing conscious from unconscious perceptual processes. *Canadian Journal of Psychology*, **40**, 343-367.

Cohen, A., Ivry, R. I., & Keele, S. W. (1990). Attention and structure in sequence learning. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **16**, 17-30.

Curran, T., & Keele, S. W. (1993). Attentional and nonattentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **19**, 189-202.

Dulany, D. E., Carlson, R. A., & Dewey, G. I. (1984). A case of syntactic learning and judgment: How conscious and how abstract? *Journal of Experimental Psychology: General*, **113**, 541-555.

Dulany, D. E., Carlson, R. A., & Dewey, G. I. (1985). On consciousness in syntactic learning and judgment: A reply to Reber, Allen, and Regan. *Journal of Experimental Psychology: General*, **114**, 25-32.

Fendrich, D. M., Healy, A. F., & Bourne, L. E., Jr. (1991). Long-term repetition effects for motoric and perceptual procedures. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **17**, 137-151.

Greenwald, A. G. (1992). New Look 3: Unconscious cognition reclaimed. *American Psychologist*, **47**, 766-779.

Hartman, M., Knopman, D. S., & Nissen, M. J. (1989). Implicit learning of new verbal associations. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **15**, 1070-1082.

Hebb, D. O. (1961). Distinctive features of learning in the higher animal. In J. F. Delafresnaye (Ed.), *Brain mechanisms and learning* (pp. 37-46). Oxford: Blackwell.

Holender, D. (1986). Semantic activation without conscious identification in dichotic listening, parafoveal vision, and visual masking: A survey and appraisal. *Behavioral & Brain Sciences*, **9**, 1-23.

Jacoby, L. L., & Brooks, L. R. (1984). Nonanalytic cognition: Memory, perception, and concept learning. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 18; pp. 1-47). New York: Academic Press.

Jacoby, L. L., Woloshyn, V., & Kelley, C. (1989). Becoming famous without being recognized: Unconscious influence of memory produced by dividing attention. *Journal of Experimental Psychology: General*, **118**, 115-125.

Kahneman, D., & Henik, A. (1981). Perceptual organization and attention. In M. Kubovy & J. R. Pomerantz (Eds.), *Perceptual organization* (pp. 181-211). Hillsdale, NJ: Erlbaum.

Kolers, P. A., & Roediger, H. L. (1984). Procedures of mind. *Journal of Verbal Learning & Verbal Behavior*, **23**, 425-449.

Lewicki, P., Hill, T., & Bizot, E. (1988). Acquisition of procedural knowledge about a pattern of stimuli that cannot be articulated. *Cognitive Psychology*, **20**, 24-37.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, **95**, 492-528.

Logan, G. D. (1990). Repetition priming and automaticity: Common underlying mechanisms? *Cognitive Psychology*, **22**, 1-35.

Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 1-55). Hillsdale, NJ: Erlbaum.

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, **19**, 1-32.

Perruchet, P., & Amorim, M. (1992). Conscious knowledge and changes in performance in sequence learning: Evidence against dissociation. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **18**, 785-800.

Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **118**, 219-235.

Reber, A. S., Allen, R., & Regan, S. (1985). Syntactic learning and judgments: Still unconscious and still abstract. *Journal of Experimental Psychology: General*, **114**, 17-24.

Richardson-Klavehn, A., & Bjork, R. A. (1988). Measures of memory. *Annual Review of Psychology*, **39**, 475-543.

Stadler, M. A. (1989). On learning complex procedural knowledge. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **15**, 1061-1069.

Stadler, M. A. (1990). Chunking and implicit pattern learning in a serial reaction time task (Doctoral dissertation, Purdue University, 1989). *Dissertation Abstracts International*, **50**, 5357-5358.

Stadler, M. A. (1992a, May). *Attention and implicit serial learning*. Paper presented at the meeting of the Midwestern Psychological Society, Chicago.

Stadler, M. A. (1992b). Statistical structure and implicit serial learning. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **18**, 318-327.

Stadler, M. A. (1993). *Attention and implicit serial learning*. Manuscript in preparation.

Willingham, D. B., Nissen, M. J., & Bullemer, P. (1989). On the development of procedural knowledge. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **15**, 1047-1060.

NOTE

1. These sequences were selected to avoid confounding practice with sequence type. That is, it was important to compare the repeating sequence to the random sequences that followed it because early in practice a difference might emerge between one set of 10 trials and the following 10 trials simply because of a practice effect; subjects might be faster on the second set of trials just because they had received more practice. Because the repeating sequence was compared in each case to the random sequence that followed it, a practice effect would cause RT to be slower on the repeating sequence, which is contrary to the hypothesis.

(Manuscript received December 3, 1991;
revision accepted for publication April 5, 1993.)