Journal of Experimental Psychology:
Learning, Memory, and Cognition
2002, Vol. 28, No. 3, 445–457

0278-7393/02/$5.00 DOI: 10.1037//0278-7393.28.3.445

Concurrent Learning of Temporal and Spatial Sequences

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In a serial reaction time task, stimulus events simultaneously defined spatial and temporal sequences. Responses were based on the spatial dimension. The temporal sequence was incidental to the task, defined by the response-to-stimulus intervals in Experiment 1 and stimulus onset asynchronies in Experiment 2. The two sequences were either of equal length and correlated or of unequal length. In both experiments, spatial learning occurred regardless of sequence length condition. In contrast, temporal learning occurred only in the correlated condition. These results suggest that timing is an integrated part of action representations and that incidental learning for a temporal pattern does not occur independently from the action. Interestingly, sequence learning was enhanced in the correlated condition, reflecting the integration of spatial-temporal information.

Since the seminal article by Lashley (1951) on “the problem of serial order,” (p. 112) much research has been directed toward understanding the cognitive mechanisms underlying the acquisition of skill in performing sequential activities. Fluent performance of many sequential activities, such as speech, music, and sports, requires carrying out component actions in the appropriate order. However, just as important as the order of component activities in performing these tasks is the relative timing of these actions. Sometimes, timing is crucial in explicitly defining the task, as in the case of musical performance. In other tasks, timing impacts the smoothness and skillfulness of performance, as in the case of adjusting the speed and direction of a car when driving down a familiar road. How are the order of actions and their temporal relations represented?

Whether timing is assumed to be represented explicitly in a motor program (Schmidt, 1980; Viviani & Terzuolo, 1980) or considered an emergent property of the actions themselves (Kelso, 1981; Rumelhart & Norman, 1982), existing theories of timing differ widely in terms of the relationship between sequencing and timing. According to Rosenbaum (1985, 1987), the scheduling of actions is based on the joint specification of the order of actions and their timing. Consistent with this view, there is evidence that information about timing can be integrated with information about the action sequence (Summers, 1975, 1977). Such theories assume sequencing and timing of actions are inseparable. In contrast, the notion of a generalized motor program allows one to postulate abstract representations of temporal structure that can be transferred to different movement rates (Heuer, 1988, 1991; Schmidt, 1980, 1985; Terzuolo & Viviani, 1980; see Gentner, 1987, for a critical review). Similarly, MacKay’s (1982, 1987) hierarchical theory of skill acquisition includes temporal representations that are separate from both the representations of the gestures themselves and the sequential order of successive gestures.

The goal of our research was to investigate the relationship between the representation of sequential and temporal information when a new action sequence is learned. Timing in complex actions can be thought of as a sequence of durations or intervals to be learned together with the sequence of gestures. In most situations, sequential and temporal aspects of an action are correlated. For example, a recognizable melody requires that a series of notes be played with a specified temporal relationship across the notes. However, the order and timing of the sequential events can be varied independently; a melody can be played with various rhythms. The experiments reported below were designed to investigate whether a temporal sequence can be learned concurrently with an action sequence. If so, can the temporal sequence be learned independently of the action sequence, or is it learned as an integral part of a specific action sequence?

We used the serial reaction time paradigm (Nissen & Bullemer, 1987) to investigate the representation and acquisition of movement sequences. In this task, a series of stimuli, usually visual, are presented one at a time, and the task is to make a speeded-choice response to each stimulus. The responses might be based on the location of the stimuli or on some other property, such as their color or shape. In separate blocks of trials, the stimuli are either presented randomly or follow a fixed sequence. Reaction time decreases with practice. More important, sequence learning can be assessed by comparing reaction times on sequence blocks with reaction times on random blocks. Faster and more accurate performance in the sequence blocks relative to the random blocks would be indicative of sequence learning.

Numerous studies (e.g., Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Nissen & Bullemer, 1987) have shown that sequence learning with the serial reaction time task can occur both explicitly (i.e., leading to successful report of the sequence after training) and implicitly (i.e., without explicit awareness of the learned sequence). Moreover, participants can implicitly learn multiple sequences presented concurrently along different stimulus dimensions such as vision and audition (Hazeltine, 2001; Schmidtke &

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This work was supported by National Institutes of Health Grants NS33504, NS30256, and NS10666.

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Heuer, 1997) or two different visual dimensions (Mayr, 1996). In the Mayr (1996) study, the participants were required to respond to the shape of each visual stimulus. On sequence blocks, the shapes appeared in a fixed sequence. In addition, the location of the shapes could also follow a sequence or be presented randomly. As expected, randomizing the order of the shapes led to an increase in reaction time. Moreover, a cost in terms of the reaction times to the shapes was also observed when the order of the locations of the objects was randomized. Thus, the results provide evidence that the participants concurrently learned two sequences, one associated with the dimension requiring a response (i.e., shape) and one that was incidental to the task (i.e., spatial location). Of particular interest is the fact that the shape and location sequences in the Mayr study were of different lengths on sequence blocks. Given that the two streams of information were uncorrelated, the results suggest each sequence was learned independently of the other sequence.

Although it is possible for sequences to be learned independently, they may become integrated into a common sequence representation when presented in a correlated fashion. Schmidtke and Heuer (1997) addressed this issue. As in standard serial reaction time tasks, participants responded manually to the spatial location of the stimulus on each trial. Alternating with the visual stimuli were tones varying in pitch. The participants were required to respond to low-pitched tones by pressing a foot pedal and to withhold responses to high-pitched tones (a go/no-go task). The stimuli along both dimensions could occur in sequence. In one condition, the visual and auditory sequences were perfectly correlated; the two sequences were both of length six, and the phase relationship between the two sequences was maintained throughout practice. In the other condition, the two sequences were of different lengths (six elements in the visual sequence and five elements in the auditory sequence). Thus, interdimensional periodicity was only defined over a cycle of 30 elements, ensuring that there was no systematic relationship between the two sequences. In this study, learning was assessed using two types of probes. First, on random probe blocks, either the visual or auditory events were randomized. The second type of probe was a phase-shift probe in which the phase relationship between the two sequences was altered. (The phase-shift probe was possible for the equal-length condition only.) Schmidtke and Heuer found reaction time costs specific to the altered dimension on the random probe blocks. Of greatest interest is that a cost was also evident on the phase-shift probe, indicating that the two sequences had been integrated when they were correlated.

One of the questions addressed in our study was whether a temporal sequence could be learned independently when presented with a spatial sequence. If so, this would be compatible with theories in which timing and sequencing are represented separately. On the other hand, timing might be learned only when integrated with the spatial sequence, at least under incidental conditions. This result would be consistent with theories of timing that assume the representation of temporal information is intimately linked with the representation of the action sequence.

A second question concerned how the presence of a consistent temporal pattern influences the learning of an action sequence. In Schmidtke and Heuer's (1997) study, the effect of stimulus randomization for the spatial sequence was greater when it had been learned along with an auditory sequence than when it had been learned by itself. Furthermore, this benefit, which we will refer to as a *multiple-sequence benefit,* was greater when the spatial and auditory sequences were correlated than when they were uncorrelated. It is important to note that a multiple-sequence benefit has been found not only when responses were required for both dimensions, as in the Schmidtke and Heuer study, but also when the secondary stimulus dimension was incidental to the task, as in Mayr's (1996) study. In our study, we investigated whether learning of an action sequence could be improved by the addition of a correlated temporal sequence.

A third goal of our study was to explore the source of the multiple-sequence benefit. The source of the multiple-sequence benefit found in earlier studies with nontemporal secondary sequences is not well understood. One possibility is that the presence of a secondary sequence facilitated learning of the primary sequence. First, the predictability on the secondary sequence could have reduced the attentional resources directed to that dimension compared with when these events were random. This, in turn, could have resulted in more resources being allocated to the information defining the primary sequence. Furthermore, when the two sequences are correlated (as in Schmidtke and Heuer, 1997), the secondary sequence might have provided information redundant with the primary sequence, allowing participants to elaborate and strengthen the representation for the primary sequence. Both additional resources and redundant information could have led to more efficient learning of the primary sequence.

However, an alternative mechanism that could account for the multiple-sequence benefit is that a secondary sequence might influence expression of already learned sequence information rather than influence learning per se. Particularly when the two sequences are correlated, the redundant information in the secondary dimension might specify advance information about the appropriate response to the primary stimulus dimension, allowing for more efficient response preparation. In the current study, we investigated whether an incidental temporal sequence would impact the learning or the expression of an action sequence.

The role of temporal factors in sequence learning has been examined in a few studies (Frensch & Miner, 1994; Stadler, 1993, 1995). However, these studies did not focus on the role of temporal predictability per se, but rather on how sequence learning may vary as a function of the duration between successive events. Willingham, Greenberg, and Thomas (1997) examined the effect of predictable timing on spatial sequence learning. A location sequence was presented in two conditions. In one condition, the response-to-stimulus interval (RSI) remained constant from trial to trial. In the other condition, the RSI was randomly selected from three possible RSIs on each trial. Although the responses were produced faster in the constant-RSI condition, learning of the spatial location sequence was similar in both RSI conditions, suggesting that temporal predictability did not affect learning of the spatial/key-pressing sequence. Our study is similar to Willingham et al.'s study in that we investigated the effect of temporal learning on spatial sequence learning. However, our study contrasts with Willingham et al. in that we examined the effect of having a patterned series of RSIs rather than a constant or random series of RSIs. Perhaps the structure in such a temporal sequence would allow participants to strengthen their representation of the spatial sequence or to better anticipate the spatial sequence.

In summary, our goal in this research was to explore how earlier findings in visual and auditory sequence learning might be extended to the temporal domain. With the exception of the Willingham et al. (1997) study, the role of the temporal regularity between successive events in the serial reaction time task has been generally ignored. We addressed three questions. First, can an incidental temporal sequence be learned together with an action sequence? Second, can timing be learned independently of the action sequence? Third, can the presence of a temporal sequence facilitate the learning of a concurrent action sequence?

To answer these questions, we conducted two experiments using a modified version of the serial reaction time task in which a series of visual events occurred sequentially in terms of both their spatial position and time. Responses were based on the position of each stimulus; the temporal regularities were incidental to the task. In Experiment 1, the temporal sequence was manipulated by varying the RSI on each trial. In Experiment 2, the temporal sequence was manipulated by varying the stimulus onset asynchrony (SOA) between successive stimulus events. To explore the role of sequence integration, we manipulated the two sequences to be of either equal or unequal length, and we used a phase-shifted probe to assess integration.

To anticipate the main results, in both experiments (a) learning was found for both spatial and temporal sequences; (b) the temporal sequence was learned only when the two sequences were integrated; (c) although the spatial sequence was learned regardless of whether the sequences were integrated, sequence integration enhanced spatial sequence learning; and (d) our data suggest this multiple-sequence benefit was due to the use of integrated information to predict information for the response rather than to a general strengthening of spatial sequence representations per se.

Experiment 1

Method

The Serial Reaction Time Task

Stimuli and equipment. Participants performed a serial reaction time task in which manual responses were required to indicate the location of visual stimuli. An IBM-compatible PC was used for stimulus presentation, collection of responses, and data recording. Stimuli were presented on a computer monitor stationed approximately 60 cm from the participant. On each trial, an *X* (10 mm × 9 mm) was presented at one of four locations along the horizontal meridian. The four locations were continuously marked by four horizontal lines (10 mm long with a 30-mm gap between adjacent lines). The *X* was displayed for a duration of 300 ms or until the participant responded. The *X* appeared at a new location after an RSI of 200 ms, 500 ms, or 800 ms.

The participant responded by pressing one of four keys aligned horizontally on a response board. Each key was 10.2 cm × 2.0 cm with an interkey spacing of 0.6 cm, and a comfortable level of force was required to activate an underlying microswitch. The middle and index finger of the left hands were used to press the two left keys, and the index and middle fingers of the right hand were used to press the two right keys. Each finger was always held directly above the corresponding key in preparation of the response. The mapping between the stimulus locations and keys was compatible (e.g., leftmost key corresponded to leftmost position).

Procedure and design. In each block of 56 trials, the position of the *X* either followed a repeating sequence (*sequenced-location* blocks) or was determined randomly (*random-location* blocks), subject to the constraints outlined below. The RSI was also set to follow a repeating sequence (*sequenced-RSI* blocks) or was determined randomly (*random-RSI* blocks). Thus, there were four types of blocks: sequenced location/sequenced RSI, sequenced location/random RSI, random location/sequenced RSI, and random location/random RSI. There was a total of 27 blocks (see Table 1).

In sequenced-location blocks, the stimulus locations followed a repeating sequence of eight elements. The same syntax, of the form 14213243, was used for all participants. The mapping of numerals to locations was

Table 1
Arrangement of Blocks and Probes in Experiments 1 and 2

Block no.	Locations	RSIs (SOAs)	Probes
1–2	Random	Random	
3–7	Sequenced	Sequenced	
8	Sequenced	Sequenced	Phase shift
9–10	Phase shift	Phase shift	
11	Sequenced	Sequenced	
12	Sequenced	Sequenced	
13	Sequenced	Sequenced (random)	Spatial-RSI (SOA) sequenced (random)
14–15	Random	Sequenced (random)	
16	Sequenced	Sequenced (random)	
17	Sequenced	Sequenced	
18	Sequenced	Sequenced	Timing-location sequenced
19–20	Sequenced	Random	
21	Sequenced	Sequenced	
22–23	Sequenced	Sequenced	
24	Sequenced	Random (Sequenced)	Spatial-RSI (SOA) random (sequenced)
25–26	Random	Random (Sequenced)	
27	Sequenced	Random (Sequenced)	

Note. The timing-location random probe was defined from the random-location blocks of the spatial-RSI (SOA) sequenced probe and the spatial-RSI (SOA) random probe (Blocks 14, 15, 25, and 26). RSI = response-to-stimulus interval; SOA = stimulus onset asynchrony.

counterbalanced across participants subject to the constraint that the sequence did not entail a run in which the stimuli appeared in the four horizontal positions in succession (left to right or right to left). With this syntax, each stimulus was followed by two different stimuli at different points in the sequence (e.g., Stimulus 1 is followed by Stimuli 4 and 3 at different points in the example sequence), a sequence form that has been referred to as “ambiguous” (Cohen, Ivry, & Keele, 1990, p. 23). For each sequenced-location block, the eight-element sequence repeated seven times, starting at a randomly selected position in the sequence. In random-location blocks, the stimulus location was selected randomly from trial to trial with three constraints. First, each position was selected on approximately 25% of the trials, matching the stimulus frequencies for sequence blocks. Second, only the transitions used in the sequence were presented. For example, Position 1 was followed only by Position 3 or 4 but not by Position 1 or 2. Third, a stimulus could not appear at the same position on two successive trials.

For sequenced-RSI blocks, the length of the repeating RSI sequence differed for two groups of participants. In the *matched-length* condition, the RSI sequence was eight elements long, equaling the length of the location sequence. In the *mismatched-length* condition, the RSI sequence was seven elements long, and this sequence repeated eight times in each block. In the matched-length condition, the RSI sequence consisted of ambiguous transitions only, as with the location sequence. Specifically, the syntax of RSIs was ACBCABCB. In the mismatched-length condition, the syntax of RSIs was ACBCABC. The letters here refer to the three different RSIs of 200 ms, 500 ms, and 800 ms, with the mapping of letters to RSIs being counterbalanced across participants. For sequenced-RSI blocks, the RSI sequence started at a random position in the sequence. However, on the sequenced-location/sequenced-RSI training blocks, the same starting point was used for both sequences to ensure that the phase relationship between the two sequences was maintained across blocks. On random-RSI blocks, RSIs were determined randomly under the constraints that the frequency of RSIs approximately matched the frequency of the sequenced-RSI blocks and that an RSI could not be presented on two successive trials.

As shown in Table 1, there were 27 blocks in an experimental session. The first two blocks were random-location/random-RSI blocks. These were followed by five sequenced-location/sequenced-RSI blocks. After these initial training blocks, four sequence-learning probes were presented, separated from one another by one or two sequenced-location/sequenced-RSI training blocks. Each probe consisted of four blocks. In the middle two blocks, the sequenced presentation of at least one dimension was altered. In the surrounding two blocks, the sequenced presentation of these altered dimensions was maintained. Learning was evaluated by comparing performance for the middle two blocks of the probe with performance for the surrounding two blocks. Specifically, if learning occurred, performance would be worse in the altered blocks than in the blocks in which the sequenced presentation was maintained. The properties of the probes are described in detail below and outlined in Tables 1 and 2.

The *phase-shift* probe (Blocks 8–11) measured the extent to which the location sequence and the RSI sequence were integrated into a common representation and was meaningful in the matched-length condition only. All four blocks in this probe were sequenced-location/sequenced-RSI blocks. However, a phase shift was introduced in the two middle blocks (Blocks 9 and 10). To accomplish this, we shifted the RSI sequence forward by one position relative to the surrounding two blocks. Thus, whereas the location–RSI pairs had been 1A, 4C, 2B, 1C, 3A, 2B, 4C, and 3B, during the (middle) phase-shift blocks the pairs were 1C, 4B, 2C, 1A, 3B, 2C, 4B, and 3A. In the case of the matched-length condition, this meant shifting the phase relationship between the 8 different location–RSI pairs that repeated seven times in a block. In the case of the mismatched-length condition, this meant shifting the phase relationship between the 56 different location–RSI pairs in a block. In the mismatched-length condition, it was considered unlikely that participants learned the relationship between the 56 location–RSI pairs. Therefore, we assumed the phase-shift probe would only be relevant in the matched-length condition.

The *spatial-RSI sequenced* probe measured spatial sequence learning in the presence of a temporal sequence. The middle two blocks were random-location blocks, and the surrounding two blocks were sequenced-location blocks. The RSIs in all four blocks in this probe were sequenced. Thus, the outer two blocks preserved the spatial sequence, the timing sequence, and the relationship between the two sequences in the matched-length condition, whereas the middle two blocks only preserved the timing sequence. We expected performance to be worse in the middle blocks than in the outer blocks. We further assumed this cost in performance would reflect learning of both the spatial information and the relational information—the information that was only present in the outer and not in the middle blocks of the probe (see Table 2).

The *timing-location sequenced* probe (Blocks 18–21) measured temporal sequence learning in the presence of the spatial sequence. The middle two blocks were random-RSI blocks (Blocks 19 and 20), and the two surrounding blocks (Blocks 18 and 21) were sequenced-RSI blocks. All four probe blocks were sequenced-location blocks. In this case, the outer two blocks preserved the spatial, timing, and relational information, and the middle two blocks only preserved the spatial sequence information. Therefore, on the basis of the same logic applied in the case of the spatial-RSI sequenced probe, any performance cost in the altered middle blocks of the

Table 2
Sequential Information Measured by Learning Probes

Probe (and blocks)	Maintained blocks	Altered blocks	Difference (learning measured)
Phase shift (8–11)	Spatial Temporal Relational	Spatial Temporal	Relational
Spatial-RSI (SOA) sequenced (13–16 or 24–27)	Spatial Temporal Relational	Temporal	Spatial Relational
Timing-location sequenced (18–21)	Spatial Temporal Relational	Spatial	Temporal Relational
Spatial-RSI (SOA) random (24–27 or 13–16)	Spatial		Spatial
Timing-location random (14, 15, 25, and 26)	Temporal		Temporal

Note. RSI = response-to-stimulus interval; SOA = stimulus onset asynchrony.

timing-location sequenced probe would reflect learning of the timing and relational patterns.

In addition, we examined learning of the spatial and timing sequences when the other dimension was random. In the *spatial-RSI random* probe, the middle blocks of this probe were random-location blocks, and the surrounding blocks were sequenced-location blocks. Whereas the timing in the spatial-RSI sequenced probe was sequenced, timing in the spatial-RSI random probe was random. As a result, in the spatial-RSI random probe, the middle and outer blocks differed only with respect to the presence of the spatial sequence. Therefore, we assumed any performance cost in the middle blocks of this probe would reflect learning of only the spatial sequence and not of other learning components.

Similarly, the *timing-location random* probe measured temporal sequence learning independent of the other sequential components. This probe consisted of a comparison between the middle two blocks of the spatial-RSI sequenced probe (random-location/sequenced-RSI blocks) and the middle two blocks of the spatial-RSI random probe (random-location/random-RSI blocks). These two sets of blocks differed only with respect to the presence of the temporal pattern.[1] Table 2 summarizes the different sequence-learning components measured by the five probes.

For half the participants, the spatial-RSI sequenced probe was presented over Blocks 13–16, before the spatial-RSI random probe that occurred over Blocks 24–27. For the other half of the participants, these two probes were presented in the reverse order (see parentheses in Table 1). The phase-shift and timing-location sequenced probes occurred in the same order for all participants and spanned the first spatial probe.

Instructions and feedback. The instructions stressed accuracy and speed equally. At the end of each block, feedback was visually presented on the computer screen. The feedback indicated the number of errors and the mean reaction time of the correct responses for that block. Participants initiated each block when they were ready. The whole task took about 30–40 min to complete.

Questionnaire of Explicit Sequence Knowledge

Immediately after performing the serial reaction time task, participants filled out a questionnaire designed to evaluate their explicit knowledge about the location and RSI sequences. The first question asked the participants to select which of the following four types of experimental conditions they thought they had been assigned to: (a) both the locations and RSIs were sequenced; (b) only the locations were sequenced, and the RSIs were random; (c) the locations were selected randomly, and only the RSIs were sequenced; or (d) both the locations and RSIs were random. Following this, the participants were asked to list any regularities or patterns they noticed about the location sequence and the RSI sequence. This information allowed us to compare trends in learning between participants who possessed explicit knowledge of either type of sequence and those who did not possess such knowledge. We discuss this issue for both experiments together in the *Results and Discussion* section of Experiment 2.

Data Analysis

For each participant, the median reaction time for each block was calculated from the correct responses obtained during the last 55 trials. From these medians, a learning score was calculated for each probe by subtracting the mean of the median reaction times of the outer two (sequence maintained) blocks from the mean of the median reaction times of the middle two (altered) blocks. Learning scores were also computed for response accuracy, defined as the mean proportion correct in the outer blocks minus the mean proportion correct of the middle blocks. For both reaction time and response accuracy, a positive probe score was considered indicative of learning.

We used two methods to estimate spatial and temporal learning. First, following previous studies of dual-sequence learning (Mayr, 1996; Schmidtke & Heuer, 1997), we evaluated spatial and temporal learning while the sequential presentation of the other dimension was maintained throughout the probe. Specifically, we conducted a one-tailed *t* test on the learning score for both the spatial-RSI sequenced and timing-location sequenced probes to test whether the observed learning scores were significantly greater than zero. Also, we evaluated sequence integration for the matched-length condition with the phase-shift probe. These tests provide basic indicators of learning. We then tested whether sequence integration benefits learning. If so, we expected the learning probes to show greater learning in the matched-length condition than in the mismatched-length condition. Again, we focused on the spatial and the timing probes in which the nonprobed dimension was sequenced throughout the probe.

Second, we complemented the *t* tests with a componential analysis of sequence learning using a model-based analysis to determine the contribution of the different forms of learning to performance. In contrast to the *t* tests described above, this utilized all five probes. The details of this analysis are described below in the *Results and Discussion* section.

Participants

Forty-four college students at the University of California, Berkeley, participated for course credit or $6.00. Twenty-four were in the matched-length condition, and 20 were in the mismatched-length condition.

Results and Discussion

On 0.3% of the trials, a key was depressed at the time of the appearance of the *X*. For these trials, it was not possible to unambiguously determine if the response was for the previous stimulus or an anticipation of the forthcoming stimulus. Thus, they were excluded from the analysis of both the latency and accuracy data.

Reaction Time

t tests. The mean reaction times for each block are plotted separately for the matched- and mismatched-length conditions in Figure 1. Over all blocks, the mean reaction time was 325 ms ($SE = 11$) in the matched-length condition and 332 ms ($SE = 13$) in the mismatched-length condition. The learning scores computed from the five probes are presented in Table 3. Of these, a *t* test was conducted on the spatial-RSI sequenced probe, timing-location sequenced probe, and phase-shift probe. Prior to this, we checked for effects of probe order on these probes with a Sequence Length × Probe Order analysis of variance (ANOVA). This analysis did not reveal any reliable effects of probe order for the spatial-RSI sequenced probe (ps $> .8$), the timing-location sequenced probe (ps $> .1$), nor the phase-shift probe (ps $> .3$). Therefore, we conducted the *t* tests collapsing over probe order.

In both sequence length conditions, analysis of the spatial-RSI sequenced probe revealed robust learning. The relevant statistics for this probe were as follows: matched-length condition ($M = 52$, $SE = 5$), $t(23) = 10.67$, $p < .0001$, and mismatched-length condition ($M = 14$, $SE = 7$), $t(19) = 2.13$, $p < .05$.

Learning, as measured by the timing-location sequenced probe, was reliable in the matched-length condition ($M = 23$, $SE = 5$),

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[1] The form of this probe differs from the other probes and, in fact, was not part of our initial design. We thank one of the reviewers for bringing to our attention the possibility of using this comparison as a measure of temporal sequence learning in the absence of a location sequence.

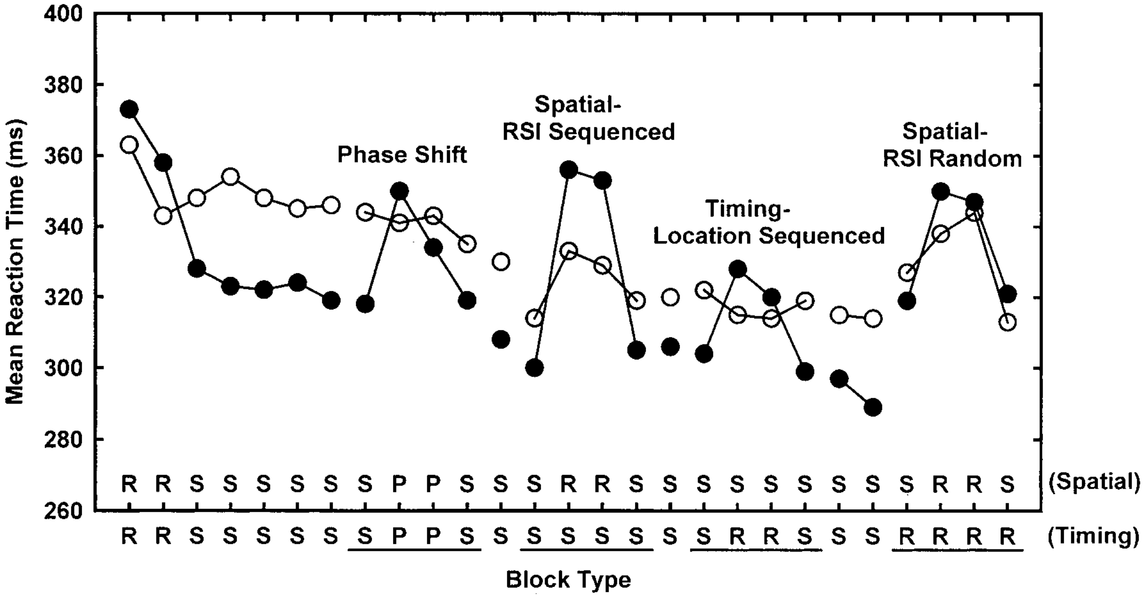

Figure 1. Mean of median reaction times in each block for the matched-length condition (black circles; n = 24) and mismatched-length condition (white circles; n = 20) in Experiment 1. The data are presented by probe type, although the actual order of blocks in the experiment was counterbalanced for the spatial-RSI sequenced and spatial-RSI random probes. There are three types of blocks for both the spatial and temporal dimensions: S = sequenced; R = random; P = phase shift. RSI = response-to-stimulus interval.

$t(23) = 4.89$, $p < .0001$, but not in the mismatched-length condition ($M = -6$, $SE = 4$), $t(19) = -1.29$, $p > .1$. The fact that incidental learning for the temporal sequence occurred only when the location and temporal sequences were correlated suggests that the temporal sequence was difficult to learn independent of the location sequence. The fact that the phase-shift probe was significant in the matched-length condition confirms that participants integrated the spatial and temporal sequences ($M = 24$, $SE = 5$), $t(23) = 4.38$, $p < .001$.

Next, we compared learning in the matched- and mismatched-length conditions. For both the spatial-RSI sequenced and timing-location sequenced probes, learning was greater in the matched- than in the mismatched-length condition. The mean difference between conditions was 38 ms for the spatial-RSI sequenced probe, $t(42) = 4.66$, $p < .0001$, and 29 ms for the timing-location sequenced probe, $t(42) = 4.39$, $p < .0001$.

Table 3
Mean and Standard Error (in ms) of Learning Scores in Experiments 1 and 2

Length condition	Phase shift		Spatial-RSI (SOA) sequenced		Tim-loc seq.		Spatial-RSI (SOA) random		Tim-loc ran.	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
					Experiment 1					
Matched	24	5	52	5	23	5	29	4	−6	5
Mismatched	3	4	14	7	−6	4	21	4	10	11
					Experiment 2					
Matched	23	5	35	8	32	7	19	4	16	7
Mismatched	9	15	17	6	−5	4	26	5	0	9

Note. Tim-loc seq. = timing-location sequenced; Tim-loc ran. = timing-location random.

Model-based analysis. The results of the t tests suggest that the potential for sequence integration significantly affected learning. However, these results alone do not tell us whether to attribute this multiple-sequence benefit to a facilitation of independent learning for the spatial or timing sequences or to the anticipatory use of relational information. As described above and summarized in Table 2, the spatial-RSI sequenced (or timing-location sequenced) probe not only reflects spatial (or temporal) learning but also learning of the spatial-temporal relationship. Thus, an increase in this probe in the matched-length condition over the mismatched-length condition could either be attributed to learning of the individual sequence or to sequence integration.

To clarify this issue, we complemented the t tests with a more extensive componential analysis of sequence learning. Because each learning probe reflected learning of a subset of the three sequential components (spatial, temporal, and relational information), one can estimate the learning for each component by conducting an analysis of all five probes using a series of linear equations:

$$\begin{aligned}
Y_{1j} &= \beta_3 + \varepsilon_{1j},\\
Y_{2j} &= \beta_1 + \beta_3 + \varepsilon_{2j},\\
Y_{3j} &= \beta_2 + \beta_3 + \varepsilon_{3j},\\
Y_{4j} &= \beta_1 + \varepsilon_{4j}, \text{ and}\\
Y_{5j} &= \beta_2 + \varepsilon_{5j}.
\end{aligned}$$

Here, Y_{ij} ($i = 1, 2, \ldots, 5$) represents the learning probes for the jth participant, where Y_{1j} represents the learning score from the phase-shift probe, Y_{2j} represents the learning score from spatial-RSI sequenced probe, Y_{3j} represents the learning score from the timing-location sequenced probe, Y_{4j} represents the learning score from the spatial-RSI random probe, and Y_{5j} represents the learning score from the timing-location random probe. The βs represent the effects of the three hypothesized sequential components on the learning scores: β_1 is the effect of the spatial sequence component on the learning score, β_2 is the effect of the temporal sequence component on the learning score, and β_3 is the effect of the relational component on the learning score. Thus, as summarized in Table 2, the learning scores from the five probes are assumed to reflect learning of different subsets of sequential information. It is important to note that we assumed the sequential components were additive (see the Appendix).

The analysis involved simultaneously solving for the three β values from the five observed values of Y using a least squares method. For a given participant j, the least squares estimators of the three βs (b_1, b_2, and b_3) were computed from the following equations:

$$b_1 = [(3Y_{2j} + 5Y_{4j}) - (2Y_{1j} + Y_{3j} - Y_{5j})]/8, \qquad (1)$$

$$b_2 = [(3Y_{3j} + 5Y_{5j}) - (2Y_{1j} + Y_{2j} - Y_{4j})]/8, \text{ and} \qquad (2)$$

$$b_3 = [(2Y_{1j} + Y_{2j} + Y_{3j}) - (Y_{4j} + Y_{5j})]/4. \qquad (3)$$

Thus, the b values were estimators of learning for the three sequential components and were measured in milliseconds.

Following the calculation of the bs for each participant, we tested the reliability of each of the bs with one-tailed t tests The mean and standard errors of the bs are presented in Table 4. For both the matched- and mismatched-length conditions, b_1, the estimator representing spatial sequence learning, was significant in the matched-length condition ($M = 28$, $SE = 4$) and in the mismatched-length condition ($M = 20$, $SE = 4$), ts > 5, ps $<$ .0001. In contrast, b_2, the estimator representing learning of the timing sequence, was not reliable in the matched-length condition ($M = -4$, $SE = 4$), $t(23) = -1.07$, $p > .1$, nor in the mismatched-length condition ($M = 4$, $SE = 8$), $t(19) = .55$, $p > .2$. This suggests the participants did not form a representation of the temporal sequence that was independent of the spatial sequence.

Table 4
Mean and Standard Error (in ms) of Effect Sizes for Different Sources of Sequential Representation in Experiments 1 and 2

Length condition	b_1 (S) *M*	b_1 (S) *SE*	b_2 (T) *M*	b_2 (T) *SE*	b_3 (R) *M*	b_3 (R) *SE*
			Experiment 1			
Matched	28	4	−4	4	25	4
Mismatched	20	4	4	8	−4	5
			Experiment 2			
Matched	17	3	14	6	20	5
Mismatched	21	6	−3	10	1	11

Note. S = spatial; T = temporal; R = relational.

As expected, b_3, the estimator representing relational learning between the spatial and temporal sequences, was significantly greater than zero only in the matched-length condition ($M = 25$, $SE = 4$), $t(23) = 6.00$, $p < .0001$, but not in the mismatched-length condition ($M = -4$, $SE = 5$), $t(19) = -.80$, $p > .2$.

Next, we explored the source of the multiple-sequence benefit found in the spatial-RSI sequenced and timing-location sequenced probes. We sought to do this by identifying the learning components that were greater in the matched- than in the mismatched-length condition. We found that the estimator of spatial learning, b_1, was similar in the matched- and mismatched-length conditions (28 vs. 20 ms), $t(42) = 1.58$, $p < .07$. In contrast, b_3, the estimator of relational learning, was significantly greater in the matched- than in the mismatched-length condition (25 vs. −4 ms), $t(42) = 4.38$, $p < .0001$. Together, these results suggest the multiple-sequence benefit found in the spatial-RSI sequenced probe was due primarily to the formation of integrated spatial-temporal representations. Because the estimator of temporal learning, b_2, was not significant in either the matched- or mismatched-length condition, the multiple-sequence benefit regarding the timing-location sequenced probe can also be attributed to an increase in the relational learning component in the matched-length condition relative to the mismatched-length condition rather than to an increase in the timing component per se.

Proportion Correct

The results concerning proportion correct show a generally high level of performance. Overall, the proportion of correct trials was .97 ($SE = .004$) in the matched-length condition and .95 ($SE = .006$) in the mismatched-length condition. This difference was significant, $t(44) = 2.19$, $p < .05$. Consistent with the latency results, the learning score for the spatial-RSI sequenced probe was significant in both the matched-length condition ($M = .028$, $SE = .008$), $t(23) = 3.53$, $p < .001$, and the mismatched-length condition ($M = .034$, $SE = .015$), $t(19) = 2.28$, $p < .05$. The spatial-RSI sequenced probe did not differ significantly between the two conditions, $t(44) = -.37$, $p > .3$. The timing-location sequenced probe and the phase-shift probe were not reliable in either sequence length condition.

Taken together, the latency and accuracy data indicate significant learning of the spatial sequence as well as the incidental temporal sequence. Furthermore, when correlated, the two sequences were integrated. Similar to earlier studies (Mayr, 1996; Schmidtke & Heuer, 1997), a multiple-sequence benefit was found for both the spatial and timing probes. Based on the model-based analysis, we attributed this benefit to the use of relational information to enhance performance rather than to improved learning of the individual sequences by themselves.

The central finding in Experiment 1 was that whereas learning of the spatial sequence was robust in both length conditions, the temporal sequence was learned only in the condition that allowed the temporal information to be integrated with the spatial sequence. This latter result suggests sequence integration was critical for temporal learning. This finding contrasts with the results reported in Mayr (1996) in which incidental spatial learning was obtained even when the length of this spatial sequence differed from that of the task-relevant dimension (shape).

Why was the temporal sequence learned only when the location and RSI sequences were integrated in our study? One possibility is that timing is special; the representation of temporal information may need to be embedded in a sequence of specific events rather than exist independently of such events. However, an alternative explanation is that the temporal intervals in our study were not salient enough. In Experiment 1, we manipulated timing by varying the RSIs. Under such conditions, the actual intervals between successive stimulus events are variable given that these are composites of the reaction time intervals and the RSIs. Perhaps temporal sequence learning requires more consistent timing of the successive events.

Moreover, the time intervals presented in Experiment 1 were not simple ratios of one another. People are strongly biased to represent temporal differences in terms of simple ratios (Collier & Wright, 1995; Povel & Collard, 1982). Indeed, explicit learning of timed sequences is extremely difficult with complex temporal patterns (Jagacinski, Marshburn, Klapp, & Jones, 1988; Klapp, Nelson, & Jagacinski, 1998). Perhaps the extent of incidental temporal learning in Experiment 1 was limited given the complexity of the temporal sequence. Experiment 2 was designed to provide conditions more conducive to extracting the temporal sequence.

Experiment 2

Two changes were adopted in Experiment 2. First, instead of varying the response-to-stimulus intervals (RSIs), we directly controlled the stimulus onset asynchronies (SOAs). Thus, the timing of the successive stimulus events was fixed at all points within the sequence. Second, the two longer SOAs were simple integer ratios (2:1 and 3:1) of the shortest SOA (550 ms).

Method

SOAs of either 550 ms, 1,100 ms, or 1,650 ms separated the onset of successive stimuli. On sequence blocks, the series of SOAs followed the syntax for sequenced RSIs in Experiment 1. For the matched-length condition, the SOA sequence was eight elements long, and for the mismatched-length condition, the SOA sequence was seven elements long. On random blocks, the three SOAs were selected with the same constraints as in Experiment 1 (matched frequency and no immediate repetitions). The shortest SOA was chosen based on the expectation that on almost all trials the response to the stimulus on a given trial would be completed prior to the onset of the stimulus on the next trial.

All other aspects of Experiment 2 were identical to Experiment 1. Forty-nine college students at the University of California, Berkeley, participated for course credit or $8.00. Twenty-six were in the matched-length condition and 23 were in the mismatched-length condition. None had participated in Experiment 1.

Results and Discussion

As in Experiment 1, we excluded from analysis data from the first trial of each block as well as trials in which the *X* was presented while a key was being pressed. The proportion of this latter type of trial was exceptionally high for 2 participants in the matched-length condition and 1 participant in the mismatched-length condition (over 26% of trials), and we excluded the data of these participants from further analysis. Also excluded was the data from 1 participant in the matched-length group who had an exceptionally high error rate (28%). This left 45 participants' data, 23 in the matched-length condition and 22 in the mismatched-length condition.

In this experiment, the key related to the previous stimulus on a given trial remained depressed on 7.7% of trials ($SE = 0.88\%$), a high proportion relative to Experiment 1. This was due to the use of the SOAs and was especially pronounced on trials following the shortest SOA (550 ms). The key related to the previous stimulus remained depressed on 23.4% of the trials with a 550-ms SOA, constituting 96.8% of all the rejected trials. Although this high rate of data loss for the short-SOA condition was regrettable, we did not have any a priori reason to suspect SOA should interact with sequence length for any of our probes. Therefore, we pooled the trials from different SOA conditions in the following analysis.

Reaction Time

t tests. The mean reaction times for each block are plotted separately for the matched- and mismatched-length conditions in Figure 2. Over all blocks, the mean reaction time was 353 ms ($SE = 12$) in the matched-length condition and 365 ms ($SE = 13$) in the mismatched-length condition. The learning scores computed from the five probes are presented in Table 3. As in Experiment 1, we conducted a Sequence Length × Probe Order ANOVA on the spatial-SOA sequenced probe, the timing-location sequenced probe, and the phase-shift probe. This analysis did not reveal any significant effects of probe order for the spatial-SOA sequenced probe ($p\text{s} > .2$), the timing-location sequenced probe ($p\text{s} > .1$), nor the phase-shift probe ($p\text{s} > .4$). Therefore, *t* tests on these probes were collapsed over probe order.

As we found in Experiment 1, the spatial-SOA sequenced probe was significantly greater than zero in the matched-length condition ($M = 35$, $SE = 8$), $t(22) = 4.48$, $p < .0001$, and in the mismatched-length condition ($M = 17$, $SE = 6$), $t(21) = 2.63$, $p < .01$. Also, the timing-location sequenced probe was reliably greater than zero only in the matched-length condition ($M = 32$, $SE = 7$), $t(22) = 4.34$, $p < .001$, but not in the mismatched-length condition ($M = -5$, $SE = 4$), $t(21) = -1.18$, $p > .1$. In addition, participants integrated the spatial and temporal sequences when the two were correlated ($M = 23$, $SE = 5$), $t(22) = 4.71$, $p < .0001$.

Next, we compared learning in the matched- and mismatched-length conditions. Both the spatial-SOA sequenced and timing-location sequenced probes were greater in the matched- than in the mismatched-length condition (a difference of 18 ms for the spatial-SOA sequenced probe, $t(43) = 1.77$, $p < .05$, and 37 ms for the timing-location sequenced probe, $t(43) = 4.33$, $p < .0001$).

In summary, the results concerning reaction time in Experiment 2 replicated those of Experiment 1. Robust spatial learning was found in both sequence length conditions, whereas the timing sequence was learned only when participants integrated the two sequences. Furthermore, sequence learning was greater when the spatial and timing sequences were integrated than when they were not integrated.

Model-based analysis. As in Experiment 1, we used the model-based analysis to evaluate the contribution of different forms of learning, again assuming the spatial, temporal, and relational sequential components were additive (see the Appendix). As in Experiment 1, the learning components were estimated separately for each participant. The mean and standard errors of the *b*s

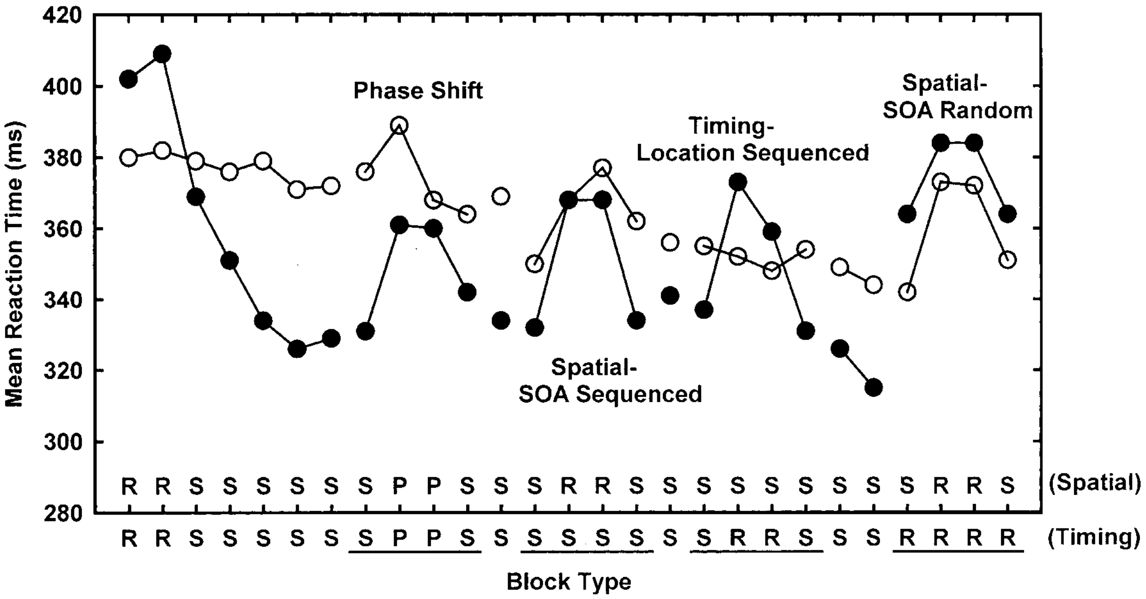

Figure 2. Mean of median reaction times in each block for the matched-length condition (black circles; n = 23) and mismatched-length condition (white circles; n = 22) in Experiment 2. There are three types of blocks for both the spatial and temporal dimensions: S = sequenced; R = random; P = phase shift. SOA = stimulus onset asynchrony.

are presented in Table 4. Again, the reliability of the b values was evaluated with t tests. The results were similar to those of Experiment 1. The estimator of spatial sequence learning, b_1, was significant both in the matched-length condition ($M = 17$, $SE = 3$), $t(22) = 6.19$, $p < .0001$, and in the mismatched-length condition ($M = 21$, $SE = 6$), $t(21) = 3.78$, $p < .001$.

Temporal learning, as estimated by b_2, was significant in the matched-length condition ($M = 14$, $SE = 6$), $t(23) = 2.42$, $p < .05$, but not in the mismatched-length condition ($M = -3$, $SE = 10$), $t(21) = -.29$, $p > .3$. As expected, learning of the relationship between spatial and temporal sequences, as reflected in b_3, was significant only in the matched-length condition ($M = 20$, $SE = 5$), $t(22) = 3.49$, $p < .01$, and not in the mismatched-length condition ($M = 1$, $SE = 11$), $t(21) = .09$, $p > .4$. In contrast to the results of Experiment 1, the results concerning b_2 and b_3 suggest the temporal sequence was represented both independently and in an integrated manner. In Experiment 1, timing was only represented in an integrated manner. Together, the results of the two experiments point to the possibility that sequence integration can facilitate the formation of an independent temporal representation when the temporal intervals themselves are salient.

Next, as in Experiment 1, we compared the b values between the matched- and mismatched-length conditions. b_1 was similar for both conditions (17 and 21 ms in the matched- and mismatched-length conditions, respectively), $t(43) = .61$, $p > .2$. In contrast, b_2 tended to be greater in the matched-length condition (14 ms) than in the mismatched-length condition (-3 ms), $t(43) = 1.49$, $p < .08$. The difference in b_3 for the two conditions (19 ms) was marginally significant, $t(43) = 1.58$, $p < .07$. These results suggest the multiple-sequence benefit for the spatial-SOA sequenced probe was due to the use of relational information. However, both temporal and relational components appear to have contributed to the multiple-sequence benefit for the timing-location sequenced probe.

In general, the model-based analysis replicates the analysis reported in Experiment 1. Whereas the spatial sequence could be learned independently of the temporal sequence, the reverse was not true. The temporal sequence was learned only when spatial and temporal sequences could be integrated.

Comparison between Experiments 1 and 2. Did the presence of more salient time intervals affect sequence learning? To answer this question, we directly compared the two experiments by conducting an Experiment × Sequence Length ANOVA for the spatial-RSI(SOA) sequenced probe, timing-location sequenced probe, and the phase-shift probe. Although the overall reaction time was significantly greater in Experiment 2 (359 ms) than in Experiment 1 (328 ms), $F(1, 85) = 6.25$, $MSE = 3{,}263$, $p < .05$, the analyses did not reveal any effects of experiment on the learning probes (ps $> .1$, for the spatial-RSI(SOA) sequenced probe; ps $> .3$, for the timing-location sequenced probe; and ps $> .7$, for the phase-shift probe).

The same analysis was conducted on the model-derived estimators of the components of sequence learning. A marginally significant Experiment × Sequence Length interaction was found for b_2, the estimator of learning of the timing sequence, $F(1, 85) = 3.20$, $MSE = 1{,}110$, $p < .08$. This interaction reflected a greater difference in b_2 between the matched- and mismatched-length conditions in Experiment 2 (17 ms) than in Experiment 1 (–8 ms).

Comparison of learning with and without explicit sequence knowledge. Another interesting issue concerns the role of awareness in sequence learning. The salient time intervals of Experiment 2 might be more conducive to awareness of the temporal sequence than the time intervals of Experiment 1. Contrary to these expectations, the results from the debriefing questionnaire indicate that none of the participants in either experiment were aware of the temporal sequence. Most commented that there were different intervals between successive events, although the most common response was that there were two intervals, one short and one long, rather than the actual three.

A few participants exhibited explicit knowledge about the spatial sequence, reporting at least four consecutive elements of the eight-element spatial sequence. In Experiment 1, there were 7 such participants, 4 in the matched-length condition and 3 in the mismatched-length condition. In Experiment 2, 10 participants exhibited explicit knowledge of the spatial sequence, 6 in the matched-length condition and 4 in the mismatched-length condition. We compared the learning scores and model-derived coefficients for the subgroups of participants with explicit knowledge of the spatial sequence and those not possessing such knowledge. In Experiment 1, awareness of the spatial sequence did not influence the probes or model-based estimators; the pattern of results was essentially identical for the aware and nonaware subgroups.

However, in Experiment 2, for the matched-length condition, participants who evidenced explicit knowledge of the spatial sequence tended to have greater learning scores for the spatial-SOA sequenced probe than those not showing such knowledge (60 vs. 26 ms, respectively), $t(21) = 1.58$, $p < .09$, although learning for this probe was significant for both the aware and nonaware subgroups (ts > 2.9, ps $< .05$). Similarly, the timing-location sequenced probe was greater in the aware (52 ms) than in the nonaware (25 ms) group, $t(21) = 1.72$, $p < .06$. In terms of the model-based analysis, the estimator of spatial learning, b_1, was significantly greater in the aware participants (25 ms) than in the nonaware participants (14 ms), $t(21) = 1.84$, $p < .05$, as was the estimator of relational learning, b_3 (32 ms in the aware group vs. 15 ms in the nonaware group), $t(21) = 1.35$, $p < .1$. However, the estimator of temporal learning, b_2, did not differ reliably as a function of awareness (21 ms in the aware group vs. 12 ms in the nonaware group), $t(21) = .65$, $p > .2$. In neither experiment did awareness influence the results for the mismatched-length condition.

Summarizing the effects of temporal salience and awareness, the two experiments show similar patterns of results. Interestingly, explicit knowledge of the spatial pattern was accompanied by enhanced spatial and relational knowledge relative to when participants lacked such knowledge in the matched-length condition of Experiment 2. Such an effect of awareness was not found in Experiment 1 nor in the mismatched-length condition of Experiment 2.

Proportion Correct

Overall, the participants responded correctly on 94% of the trials. The proportion correct was .92 ($SE = .008$) in the matched-length condition and .94 ($SE = .006$) in the mismatched-length condition. This difference was statistically significant, $t(43) = 1.72$, $p < .05$. In the matched-length condition, the spatial-SOA sequenced probe was statistically reliable ($M = .028$, $SE = .008$), $t(22) = 3.65$, $p < .001$, as was the timing-location sequenced probe ($M = .025$, $SE = .010$), $t(22) = 2.47$, $p < .05$. However, neither probe was reliable in the mismatched-length condition (Ms $< .01$, ts < 1, ps $> .2$). The proportion correct indicated sequence integration in the matched-length condition ($M = .027$, $SE < .010$), $t(22) = 2.57$, $p < .01$.

In summary, the results for the latency and accuracy measures replicate Experiment 1. The timing sequence was learned only when it was integrated with the location sequence, even when salient stimulus intervals with integer ratios were used in Experiment 2.

General Discussion

Two experiments were conducted to investigate whether a spatial sequence and a temporal sequence could be learned concurrently in a serial reaction time task. Learning in each dimension was examined when the two sequences were correlated as well as when they were uncorrelated. Spatial sequence learning was evident regardless of the relationship between the two sequences. In contrast, incidental learning of the temporal sequence was observed only when the two sequences were correlated.

Our finding that the temporal sequence was learned only in the correlated condition suggests that incidental temporal patterns are learned only when these intervals are associated with concrete events, such as specific visual stimuli or finger movements. This interpretation is consistent with theories of timing that assume temporal information is represented in an integrated form with event sequence information rather than as an abstract entity. That is, the temporal properties of an action representation convey when particular events are to occur rather than provide a generic representation of when the next event should be triggered. One implication of this view is that temporal representations are linked to specific action systems (Ivry, 1996).

Our conclusion that incidental temporal sequences could not be learned in the abstract does not preclude the possibility for independent temporal representations. Once learned, salient temporal intervals can perhaps be represented in an independent fashion. Congruent with this idea, the modeling results suggest that independent sequence representations of the SOAs were acquired but only when spatial-temporal integration was possible. Such independent representations might allow for the transfer of a temporal pattern to different actions, such as when a well learned melody and rhythm are sung to a new set of lyrics. Another example of temporal transfer is in the domain of speech. Speech errors often involve consonants being transposed between words while the relative timing among phonemes remains constant. Similarly, typing errors often involve letters being transposed while the timing of keystrokes is maintained (MacKay, 1987). These examples—the song, the word, and the typing—represent well practiced skills, suggesting the independence of temporal representation emerges at later stages in learning.

A second factor that may encourage the independent representation of temporal and action patterns is the structure of the temporal pattern itself. It may be easier to learn a temporal sequence when it forms a hierarchical pattern akin to musical rhythms with identifiable beats. A hierarchical representation might also contribute to enhanced awareness of the temporal sequence. The role of practice, hierarchical representation, and awareness in temporal sequence learning are topics for future research.

Although it appears possible for timing to be represented independently from action sequences, our data indicate timing must initially be learned in relation to a correlated action sequence. Our failure to observe independent learning of an incidental timing sequence is at odds with the findings of Mayr (1996). In that study, an incidental spatial sequence was learned when the spatial sequence was presented in an uncorrelated fashion with a response-relevant shape sequence. Mayr's explanation was that spatial learning is carried out in an independent learning system. This modular account does not appear viable for the current experiments given the lack of independent spatial and temporal learning.

We consider three alternative explanations for the discrepancy between the two studies. First, as suggested above, temporal information may be special in that it must be integrated with the primary dimension to be learned. This hypothesis would predict that incidental temporal sequence learning would not occur regardless of whether the primary dimension was spatial or nonspatial.

Second, although the spatial dimension was used for assessing incidental learning in Mayr (1996), the participants may still have generated overt or covert responses based on this dimension, such as making covert or overt shifts of attention to the successive stimulus positions. In other words, an attentional response to the spatial aspects of the task may have been necessary for making identity judgments required for the task-relevant response (Nissen, 1985). In contrast, temporal information in our task may not have had the same kind of relevance to the responses as spatial information did in Mayr's task, making it a truly incidental dimension. Future research is required to determine if space has a special informational status as a secondary dimension. For example, one might ask whether incidental learning would occur for sequences based on a nonspatial object property (e.g., color).

A third hypothesis for why we did not find independent learning of an incidental temporal sequence is that participants were not aware of the distinct temporal intervals used in our study. The time intervals in our experiments may not have been sufficiently distinct. Many participants in the current study were not aware that there were three different temporal intervals; most reported they were aware of only two—short and long. This was true for the RSIs in Experiment 1 and the SOAs in Experiment 2, despite the fact that the intervals would have been easily discriminated under standard psychophysical procedures (e.g., Allan, 1979; Getty, 1975). It is possible that independent learning of an incidental sequence (regardless of whether it is in the temporal dimension) is possible only if participants are aware of the distinct sequence elements as they arise in that sequence. Indeed, the individual elements of both the shape and spatial sequences in Mayr's (1996) study were easily distinguishable and recognized explicitly by the participants.

The central finding in our study was that temporal sequences were learned only in association with a spatial sequence. Equally important is the issue of how temporal learning affected performance. In our study, we found sequence learning was greater in the matched- than in the mismatched-length condition when the learning probe retained the timing sequence. This suggests performers used the temporal information to benefit performance. Such a benefit of having a secondary sequence is similar to those found in previous work with concurrent sequences (Schmidtke & Heuer, 1997). How did performers use temporal information? Our results are consistent with the interpretation that participants used the information about the relationship between the two sequences to better express knowledge about the learned spatial sequence rather than to elaborate the spatial representation itself.

At first glance, the fact that predictable timing facilitated sequence learning in our study would appear to contradict the results of Willingham et al. (1997). In that study, spatial sequences were learned in two conditions. In one condition the RSI was constant (500 ms), and in the other the RSI was random. In contrast to the difference we observed between the matched- and mismatched-length conditions, Willingham et al. observed equal spatial learning in the constant and random conditions. The discrepancy between the two studies can be explained by assuming the temporal information was not integrated with the spatial pattern in a meaningful way in the Willingham et al. study. Why would this be the case? The timing in the Willingham et al. study was constant, whereas in our study a complex temporal pattern was used in which the RSIs varied from trial to trial. Thus, although both experiments involved predictable RSIs, only in the current study was the timing structured and correlated with the spatial sequence. It makes sense that a variegated pattern would provide information facilitating the anticipation of sequenced movement, whereas a constant series of RSIs, although predictable in itself, would not.

In conclusion, the studies reported in this article demonstrate that people can incorporate a structured temporal pattern as part of an action sequence. Furthermore, temporal sequence learning was observed only when the temporal regularities were correlated with the action sequence. The coupling of spatial and temporal information enhanced learning and performance and likely reflects an essential aspect of motor skills.

References

Allan, L. G. (1979). The perception of time. *Perception & Psychophysics, 26,* 340–354.

Cohen, A., Ivry, R. I., & Keele, S. W. (1990). Attention and structure in sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 17–30.

Collier, G. L., & Wright, C. E. (1995). Temporal rescaling of simple and complex ratios in rhythmic tapping. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 602–627.

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

Frensch, P. A., & Miner, C. S. (1994). Effects of presentation rate and individual differences in short-term memory capacity on an indirect measure of serial learning. *Memory & Cognition, 22,* 95–110.

Gentner, D. R. (1987). Timing of skilled motor performance: Tests of the proportional duration model. *Psychological Review, 94,* 255–276.

Getty, D. J. (1975). Discrimination of short temporal intervals: A comparison of two models. *Perception & Psychophysics, 18,* 1–8.

Hazeltine, R. E. (2001). The representational nature of implicit sequence learning. Evidence for goal-based codes. In *Attention and Performance: Common mechanisms in perception and action. Oxford, England: Oxford University Press.*

Heuer, H. (1988). Testing the invariance of relative timing: Comment on Gentner (1987). *Psychological Review, 95,* 552–557.

Heuer, H. (1991). Invariant relative timing in motor-program theory. In J. Fagard & P. H. Wolff (Eds.), *The development of timing control and temporal organization in coordinated action: Invariant relative timing, rhythms and coordination* (pp. 37–68). Amsterdam: North-Holland.

Ivry, R. (1996). The representation of temporal information in perception and motor control. *Current Opinion in Neurobiology, 6,* 851–857.

Jagacinski, R. J., Marshburn, E., Klapp, S. T., & Jones, M. R. (1988). Tests of parallel versus integrated structures in polyrhythmic tapping. *Journal of Motor Behavior, 20,* 416–442.

Kelso, J. A. S. (1981). Contrasting perspectives on order and regulation of movement. In J. Long and A. Baddeley (Eds.), *Attention and performance* (Vol. 9, pp. 437–457). Hillsdale, NJ: Erlbaum.

Klapp, S. T., Nelson, J. M., & Jagacinski, R. J. (1998). Can people tap concurrent bimanual rhythms independently? *Journal of Motor Behavior, 30,* 301–322.

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–136). New York: Wiley.

MacKay, D. G. (1982). The problems of flexibility, fluency, and speed–accuracy trade-off in skilled behavior. *Psychological Review, 89,* 483–506.

MacKay, D. G. (1987). *The Organization of perception and action: A theory for language and other cognitive skills.* New York: Springer-Verlag.

Mayr, U. (1996). Spatial attention and implicit sequence learning: Evidence for independent learning of spatial and nonspatial sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 350–364.

Nissen, M. J. (1985). Accessing features and objects: Is location special? In M. Posner & O. Marin (Eds.), *Attention and performance XI* (pp. 41–62). Hillsdale, NJ: Erlbaum.

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

Povel, D.-J., & Collard, R. (1982). Structural factors in patterned finger tapping. *Acta Psychologica, 52,* 107–124.

Rosenbaum, D. A. (1985). Motor programming: A review and scheduling theory. In H. Heuer, U. Kleinbeck, & K. H. Schmidt (Eds.), *Motor behavior: Programming, control, and acquisition* (pp. 1–33). Berlin: Springer-Verlag.

Rosenbaum, D. A. (1987). Successive approximations to a model of human motor programming. *The Psychology of Learning and Motivation, 21,* 153–182.

Rumelhart, D. E., & Norman, D. A. (1982). Simulating a skilled typist: A study of skilled cognitive-motor performance. *Cognitive Science, 6,* 1–36.

Schmidt, R. A. (1980). On the theoretical status of time in motor program representations. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 145–166). Amsterdam: North-Holland.

Schmidt, R. A. (1985). The search for invariance in skilled movement behavior. *Research Quarterly for Exercise and Sport, 56,* 188–200.

Schmidtke, V., & Heuer, H. (1997). Task integration as a factor in secondary-task effects on sequence learning. *Psychological Research, 60,* 53–71.

Stadler, M. A. (1993). Implicit serial learning: Questions inspired by Hebb (1961). *Memory & Cognition, 21,* 819–827.

Stadler, M. A. (1995). Role of attention in implicit learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 674–685.

Summers, J. J. (1975). The role of timing in motor program representation. *Journal of Motor Behavior, 7,* 229–241.

Summers, J. J. (1977). The relationship between the sequencing and timing components of a skill. *Journal of Motor Behavior, 9,* 49–59.

Terzuolo, V. A., & Viviani, P. (1980). Determinants and characteristics of motor patterns used for typing. *Neuroscience, 5,* 1085–1103.

Viviani, P., & Terzuolo, C. (1980). Space–time invariance in learned motor skills. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 525–533). Amsterdam: North-Holland.

Willingham, D. B., Greenberg, A. R., & Thomas, R. C. (1997). Response-to-stimulus interval does not affect implicit motor sequence learning, but does affect performance. *Memory & Cognition, 25,* 534–542.

Appendix

Non-Additive Model-Based Analysis

Initially, we included interactive terms in our model-based analysis. We estimated the learning components by conducting an analysis of all five probes using a series of linear equations:

$$\begin{aligned}
Y_{1j} &= \beta_3 + \varepsilon_{1j},\\
Y_{2j} &= \beta_1 + \beta_3 + \beta_{13} + \varepsilon_{2j},\\
Y_{3j} &= \beta_2 + \beta_3 + \beta_{23} + \varepsilon_{3j},\\
Y_{4j} &= \beta_1 + \varepsilon_{4j}, \text{ and}\\
Y_{5j} &= \beta_2 + \varepsilon_{5j}.
\end{aligned}$$

Here, Y_{ij} ($i = 1, 2, \ldots, 5$) represents the learning probes for the jth participant, where Y_{1j} represents the learning score from the phase-shift probe, Y_{2j} represents the learning score from the spatial-RSI sequenced probe, Y_{3j} represents the learning score from the timing-location sequenced probe, Y_{4j} represents the learning score from the spatial-RSI random probe, and Y_{5j} represents the learning score from the timing-location random probe. βs represent the effects of the hypothesized sequential components on the learning score. β_1 is the effect of the spatial sequence component on the learning score, β_2 is the effect of the temporal sequence component on the learning score, β_3 is the effect of the relational component on the learning score, β_{13} is the interaction between the spatial and relational information, and β_{23} is the interaction between the temporal and relational information.

We computed the least squares estimators of the βs using the following formulas based on the general linear model:

$$\begin{aligned}
b_1 &= Y_{4j},\\
b_2 &= Y_{5j},\\
b_3 &= Y_{1j},\\
b_{13} &= -Y_{4j} + Y_{2j} - Y_{1j}, \text{ and}\\
b_{23} &= -Y_{5j} + Y_{3j} - Y_{1j}.
\end{aligned}$$

The results of this analysis are shown in Table A1. In the matched-length condition, b_1, the estimator of the spatial component, and b_3, the estimator of the relational component, were significant (ts > 4, ps $< .001$). b_2, the estimator of the temporal component, was not reliable, $t(23) = -1.23$, $p > .2$. In the mismatched-length condition, only b_1 was statistically significant, $t(19) = 5.75$, $p < .0001$. The estimators of the temporal and relational components were not reliable in the mismatched-length condition (ps $> .3$). For both conditions, the estimators of the interaction between the relational component and the spatial and temporal components, b_{13} and b_{23}, were not reliable (ps $> .6$ in the matched-length condition, and ps $> .2$ in the mismatched-length condition). Therefore, in subsequent analyses of

Table A1

Mean and Standard Error (in ms) of Effect Sizes for Different Sources of Sequential Representation Including Interactive Effects in Experiments 1 and 2

Length condition	b_1 (S)		b_2 (T)		b_3 (R)		b_4 (S-R)		b_5 (T-R)	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Experiment 1										
Matched	29	4	−6	5	24	5	0	7	5	10
Mismatched	21	4	10	11	3	4	−10	9	−19	14
Experiment 2										
Matched	19	4	16	7	23	5	−8	9	−8	12
Mismatched	26	5	0	9	9	15	−18	12	−13	11

Note. S = spatial; T = temporal; R = relational; S-R = spatial–relational interaction; T-R = temporal–relational interaction.

data from Experiment 1, we assumed the spatial, temporal, and relational components were additive.

The same type of analysis was conducted for Experiment 2, yielding similar results, shown in Table A1. In the matched-length condition, the estimators of the spatial and relational components were statistically significant (*t*s > 4, *p*s < .001). In addition, the estimator of the temporal component was also significant, $t(22) = 2.14$, $p < .05$. In the mismatched-length condition, only the estimator of the spatial component was significant, $t(21) = 5.61$, $p < .0001$, but the estimators of the relational and temporal components were not reliable (*p*s > .5). In both sequence-length conditions, the estimators representing the interaction between the relational component and the spatial or temporal component were not positive values, and these values did not deviate reliably from zero (*p*s > .1). Given this, we assumed the spatial, temporal, and relational learning components were additive in further analyses of data from Experiment 2.

Received March 20, 2000
Revision received September 27, 2001
Accepted September 27, 2001 ■