What Matters in Implicit Task Sequence Learning: Perceptual Stimulus Features, Task Sets, or Correlated Streams of Information?

Brigitte Weiermann, Josephine Cock, and Beat Meier
University of Bern

Implicit task sequence learning may be attributed to learning the order of perceptual stimulus features associated with the task sequence, learning a series of automatic task set activations, or learning an integrated sequence that derives from 2 correlated streams of information. In the present study, our purpose was to distinguish among these 3 possibilities. In 4 separate experiments, we replicated and extended a previous study by Heuer, Schmidtke, and Kleinsorge (2001). The presence or absence of a sequence of tasks, as well as that of a sequence of different task-to-response mappings, was manipulated independently within experiments. Evidence of implicit sequence learning was found only when correlated sequences of tasks and mappings were present. No sequence learning effects were found when only a single task sequence or a single mapping sequence was present, even when the structure of the single sequence was identical to the structure of the integrated sequence of task-mapping combinations. These results suggest that implicit task sequence learning is not dependent on either perceptual learning of stimulus features or automatic task-set activation per se. Rather, it appears to be driven by correlated streams of information.

Keywords: sequence learning, incidental learning

Our daily life is characterized by sequential regularities, such as routine sequences of actions or tasks. For example, on a routine workday at the office or lab, we may first check the answering machine and then start up the computer. Next we check our e-mails, respond to the important ones, and postpone responding to the others. Then we continue working at our current project, which almost certainly requires us to switch between different tasks, such as researching, reading, writing, making phone calls, and organizing meetings. We may not notice the regular routines in our daily actions, but unexpected changes can easily disrupt them, for example, when someone suddenly knocks at the door and needs our attention. Routines and regularity make life easier.

There is evidence that individuals benefit from sequential regularity in the environment and their responses to it, even when they are unaware of any ordering—a phenomenon that has widely been investigated with the serial reaction time task (SRTT; Nissen & Bullemer, 1987). In recent studies, the SRTT has been merged with a task-switching paradigm (Cock & Meier, 2007; Gotler, Meiran, & Tzelgov, 2003; Heuer, Schmidtke, & Kleinsorge, 2001; Koch, 2001; Koch, Philipp, & Gade, 2006; Meier & Cock, 2010).

As a result, the task sequence learning paradigm is a more sophisticated version of the SRTT that allows for the separation of the sequences of stimuli and responses. Furthermore, the task sequence learning paradigm enables participants to respond to several intermixed reaction-time tasks in the same experiment. These are usually binary-choice decisions with one pair of response keys used throughout. For example, participants may be required to respond to stimulus color on the first trial, to stimulus shape on the second trial, to stimulus size on the third trial, and so on. To date, in most task sequence learning experiments, either instructional task cues or perceptual features of the stimuli have been used to instruct participants about which type of task to perform next (for example, color, shape, or size). Unbeknownst to the participants, the order of successive tasks is determined by a repeating sequence. However, owing to the binary-choice nature of the tasks and the fact that keys are pressed according to task outcomes and not to the tasks themselves, particular stimuli associated with each task (for example, letter or symbol exemplars) occur at random, and consequently, no repeating sequence of motor responses exists. The task sequence is present during several blocks of trials, during which response times decrease continuously. When the task sequence is replaced by a different sequence or a random order of tasks, response times increase substantially. This increase in response time is taken as indirect evidence of implicit learning of the task sequence. Here, implicit learning may be defined as learning in an incidental way because participants do not know about the presence of a task sequence and, as a consequence, have no deliberate intention to learn it (e.g., Stadler, 1997).

Recently, three theories have been proposed to explain what matters in implicit task sequence learning. First, the learning effect may be attributable to learning a perceptual pattern of external cues or repeated stimulus features that are used to inform the participants which task is to be performed next (Heuer et al.,

2001). Second, the repeated performance of a task sequence may lead to the automatic anticipatory activation of the relevant task set, and this may be at the core of implicit task sequence learning (Koch, 2001). Third, the learning effect may be attributable to the integration of two correlated streams of information, for example, a task sequence together with a same-length sequence of external cues or stimulus features (Cock & Meier, 2007; Meier & Cock, 2010). In the first and second explanations, the kind of information that is learned is specified by a focus on the presence of a single stream of information that is sequenced (i.e., a stream of perceptual stimulus features vs. a stream of task set activations). In contrast, the third explanation holds that the presence of two correlated streams of information is what drives this kind of sequence learning, irrespective of the type of information. Our purpose in the current study was to distinguish among these three explanations. Toward this goal, we used the task sequence learning paradigm introduced by Heuer et al. (2001, Experiment 1). Whereas the study by Heuer et al. (2001) was about task switching and focused on switch costs, we focused specifically on sequence learning.

Heuer et al. (2001) used stimulus location and stimulus color as instructional cues to indicate to participants which task to perform and what kind of task-to-response mapping to use. On each trial, two digits appeared simultaneously on the screen. One was presented directly above or below a fixation mark (*central digit*), and the other was presented to the left or right of the central digit (*peripheral digit*). The vertical location of the stimuli indicated the type of task to be performed (see Figure 1a). When the digits appeared above the fixation mark, participants had to respond to the numerical value of the central digit (larger or smaller than 5; i.e., a numerical task). When the digits appeared below the fixation mark, participants had to respond to the horizontal position of the peripheral digit (to the right or the left of the central digit; i.e., a spatial task). Additionally, the arrangement of the task-to-response mappings changed from trial to trial depending on the digit color. Green digits indicated a *compatible mapping*, that is, a left-hand response to a small number or to a peripheral digit to the left, and a right-hand response to a large number or a peripheral digit to the right. This mapping was compatible both with the spatial arrangement of stimuli and keys for the spatial task, and with the spatial–numerical association of response codes (SNARC) effect for the numerical task (small numbers preferentially elicit a leftward response and large numbers preferentially elicit a rightward response; Dehaene, Bossini, & Giraux, 1993). In contrast, red digits indicated the opposite, that is, a right-hand response to a small number or a peripheral digit to the left, and a left-hand response to a large number or a peripheral digit to the right. This arrangement was referred to as the *incompatible mapping*. In this way, in addition to deciding which type of task was present and which type of response was needed, participants needed to establish which type of mapping was appropriate on each separate trial. The orthogonal combination of tasks and task-to-response mappings resulted in four different combinations, herein after referred to as *task-mapping combinations* (i.e., numerical compatible, numerical incompatible, spatial compatible, and spatial incompatible), which were arranged in sequences of eight elements. Hence, the sequence of task-mapping combinations was associated with a repeating pattern of stimulus features (i.e., color changes and vertical location changes). However, within each task type, particular stimuli (such as small or large digits, left or right positions) were presented

at random, and therefore, no motor response sequence existed in correspondence with either the stimuli or the task-mapping combinations.

Heuer et al. (2001) found substantial sequence learning, which was not accompanied by a reduction of switch costs, irrespective of the length of the response–stimulus interval (200 ms in Experiment 1 vs. 1,200 ms in Experiment 2). Thus, Heuer et al. (2001) argued that sequence learning was restricted to a sequence of uninterpreted stimulus features, that is, stimulus features that are void of their task-associated meanings. Therefore, rather than the sequence of tasks, a sequence of perceptual stimulus features serving as cues for the task-mapping combinations was actually learned.

In a similar study, Koch (2001) reached a different conclusion. The participants were required to identify the form, color, or size of a stimulus, which could be the digit 4 or the letter *A* displayed in red or blue and as small or large. An instructional cue was displayed before the presentation of each stimulus, indicating which of the three tasks was to be performed. Tasks were arranged in sequences of nine elements. Both the sequence of stimuli and the sequence of required left- or right-hand key responses were completely random. Task sequence learning effects were found when the cue–stimulus interval (CSI) was short but not when it was long (100 ms vs. 900 ms). Presumably, in the long CSI condition, the task cues were presented long enough for effective task preparation, and the participants did not have to use, or at least express, task sequence knowledge of any kind. In contrast, in the short CSI condition, it seems more likely that participants had to rely, unknowingly, on incidentally acquired task sequence knowledge in order to prepare effectively for the next task. Furthermore, Koch (2001) found that task sequence learning effects were larger when the response–cue interval (RCI) was short (100 ms vs. 900 ms). He suggested that the formation of an association between the preceding and the following task was more probable in the short RCI condition because of the stronger concurrent activation of the task sets. Task sequence learning did not affect switch costs; that is, the predictability of the upcoming task was advantageous irrespective of whether the task set could be maintained or had to be switched. Unlike Heuer et al. (2001), Koch (2001) argued that task sequence learning depended on *automatic task set activation*, that is, an unspecific automatic priming of task sets.

In order to avoid the necessity of presenting instructional task cues, Cock and Meier used univalent stimuli (Cock & Meier, 2007; Meier & Cock, 2010). Participants were required to perform case decisions on letters (uppercase vs. lowercase), color decisions on fuzzy figures (red vs. blue), and shape decisions on geometrical forms (curved vs. angular). The presence or absence of a task sequence was orthogonally combined with the presence or absence of a sequence of required left- or right-hand responses, resulting in four experimental conditions: a condition with both a task sequence and a response sequence (correlated sequences condition), a condition with a task sequence but randomly ordered responses, a condition with a response sequence but randomly ordered tasks (single sequence conditions), and a control condition with no sequences. Sequence learning occurred only in the combined task sequence and response sequence condition, that is, when two correlated streams of information were present (Cock & Meier, 2007). Even when a sequence of stimulus locations was combined with either a task sequence or a response sequence (Meier & Cock,
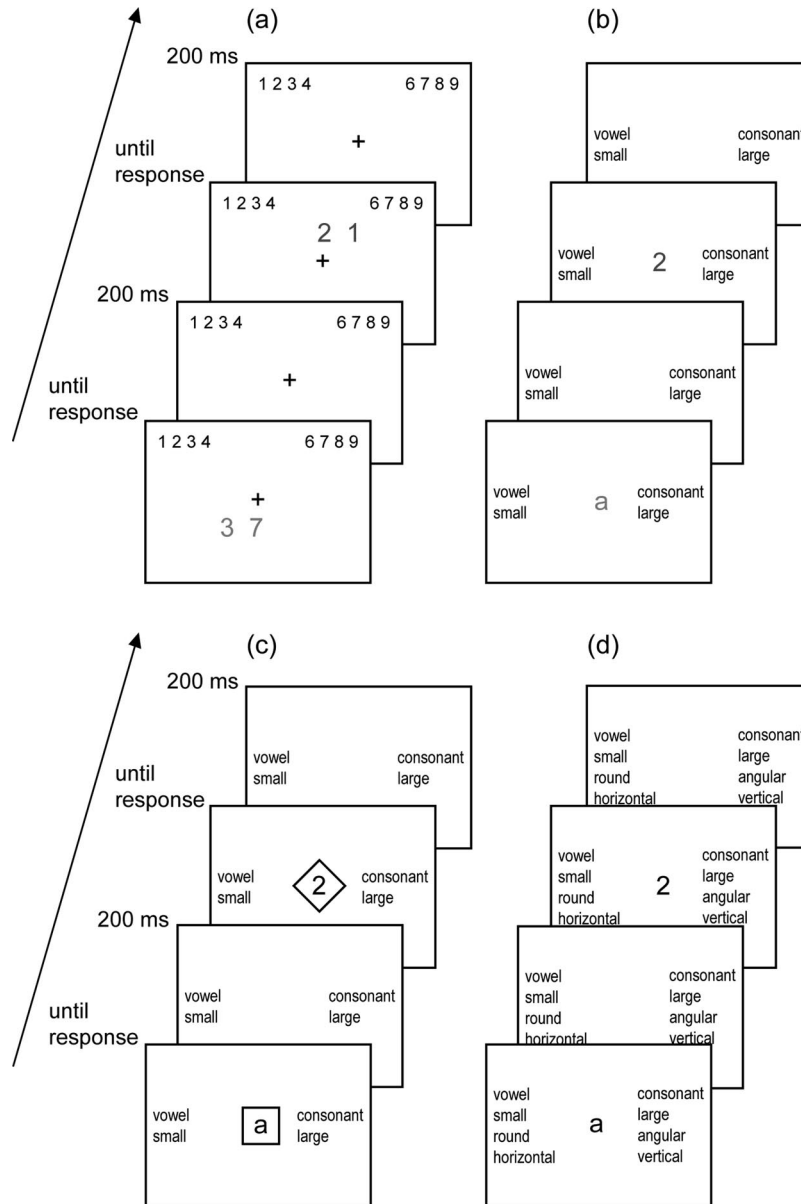
Figure 1. Different procedures of Experiment 1 (a), Experiment 2 (b), Experiment 3 (c), and Experiment 4 (d). In Experiments 1 and 2, the stimuli were printed in either green or red against a black background. In Experiments 3 and 4, the stimuli and frames were presented in white against a black background.

2010), implicit sequence learning was only observed when two correlated streams of information were present (i.e., a task sequence and a response sequence, a location sequence and a task sequence, or a location sequence and a response sequence). Meier and Cock (2010) proposed that the presence of at least two correlated streams of information is at the core of implicit sequence learning and suggested that the information in each stream can be of any kind.

A stream of information may be defined as a temporal flow of data that comprises separable events. The events within a stream of information can be stimuli, stimulus features (e.g., perceptual features, such as the color or size of the stimulus, or conceptual features, such as the categorical identity of the stimulus), or responses. A stream of information can be random or sequenced. In a random stream of information, the successive events occur randomly. In contrast, in a sequenced stream of information, the order of events is determined by a repeating sequence. Correlated streams of information involve two (or more) sequenced streams with mathematically compatible structures, such as sequences of the same length, that can be predictably parsed together in each sequence cycle according to crosswise as well as lengthwise associations between components. The explanation of Meier and Cock (2010) would be consistent with sequence learning effects found by Heuer et al. (2001) and Koch (2001) because in both of

these studies two correlated streams of information were present (i.e., a sequence of tasks and a sequence of mappings in the study by Heuer et al. and a sequence of instructional cues and a sequence of tasks in the study by Koch).

In the present study, we extended the study by Heuer et al. (2001) in four different experiments. Experiment 1 was a replication of the original study. The purpose was to provide evidence for the robustness of sequence learning in this paradigm, which was a prerequisite for further experiments. In Experiments 2 and 3, we orthogonally manipulated the presence or absence of a task sequence and the presence or absence of a task-to-response mapping sequence. The purpose was to investigate whether the sequence learning effect found in the Heuer et al. study (2001) is based on learning perceptual stimulus features, automatic task-set activation, or the integration of two correlated streams of information (i.e., the task sequence and the mapping sequence). In Experiment 4, we investigated the learning of a single task sequence with an invariant task-to-response mapping. The purpose was to test whether a single task sequence with a sequence structure identical to that of the integrated sequence (i.e., as in Experiments 2 and 3, resulting from the correlation between the task and mapping sequences) was learned or not. Stimuli and procedures of Experiments 1–4 are shown in Figure 1.

Experiment 1

Method

Participants. Sixteen volunteers (10 women and six men, two left-handed) participated in Experiment 1. Mean age was 22.1 years ($SD = 0.9$).

Materials. Stimuli and tasks were composed according to Heuer et al. (2001). The target stimuli were the digits 1, 2, 3, 4, 6, 7, 8, and 9. They were presented in 26-point Arial font and were displayed, depending on the trial, in either green or red. Two target digits were presented simultaneously, one of which was either directly above or below the fixation mark (central digit) and the other of which was to the left or right of it (peripheral digit). The gap between the digits and between the central digit and the fixation mark was 4 mm.

Two features of the stimuli were used as cues for different tasks and for different task-to-response mappings. The vertical location of the digits was the cue for the type of task (numerical task vs. spatial task) and the color of the digits was the cue for the type of mapping (compatible vs. incompatible, as will be defined). The orthogonal combination of tasks and mappings resulted in four different task-mapping combinations (numerical compatible, numerical incompatible, spatial compatible, and spatial incompatible). If the digits appeared above the fixation mark, the central digit had to be classified as small (1–4) or large (6–9) and the peripheral digit had to be ignored (numerical task). If the digits were shown below the fixation mark, the peripheral digit had to be classified as being to the left or right of the central digit, and the central digit had to be ignored (spatial task). Green digits indicated that a left-hand response (key "1") was to be made when the central number was small or when the peripheral digit was to the left, and a right hand response (key "5") was to be made when the central digit was large or when the peripheral digit was to the right. This arrangement is referred to as the compatible task-to-

response mapping because it was compatible both with the spatial arrangement of stimuli and keys for the spatial task and with the SNARC effect (Dehaene et al., 1993) for the numerical task. Additionally, it was compatible with the instructional reminders shown on screen. Red digits indicated the opposite mapping, and this arrangement is referred to as the incompatible task-to-response mapping. Here, a left-hand response had to be made for a large central number or for a right peripheral digit, and a right-hand response had to be made for a small central number or for a left peripheral digit.

Sequences. Task-mapping combinations were arranged in repeating sequences of eight elements according to the sequences used by Heuer et al. (2001). Sixteen sequences of task-mapping combinations were derived from four abstract sequences of nominal relations between successive task-mapping combinations shown in Table 1. In each of these abstract sequences, the four possible trial-to-trial relations (task: same vs. different, and mapping: same vs. different) occurred twice. From each of the four abstract sequences, four different sequences of task-mapping combinations were derived with each of the four task-mapping combinations as the initial element (see Table 2 for an example). Each task-mapping combination occurred twice in the sequence. Each of the 16 participants was trained on one particular sequence. For each participant, each kind of trial-to-trial relation was associated with only two specific pairs of task-mapping combinations rather than four due to the sequence length of eight.

For the pseudorandom ordering (104 trials per block), we randomized the order of task-mapping combinations with the following constraints: First, each of the four possible trial-to-trial relations (task: same vs. different, and mapping: same vs. different) occurred with equal frequency. Second, the same transition occurred maximally twice in a row. Third, the four different task-mapping combinations occurred with nearly equal frequency.

Procedure. Participants were tested individually. They were instructed to respond as quickly and as accurately as possible to the stimuli that appeared on screen. They were not informed about the presence of the sequence of task-mapping combinations. The experiment consisted of 21 blocks of 104 trials each. A white fixation mark was presented continuously at the center of the black screen. At the top of the screen, the digits 1–4 were displayed throughout in a row at the left corner and the digits 6–9 in a row at the right corner. They served as reminders for small and large numbers, respectively, and were written in 26-point Arial font in white against a black background. On each trial, two digits were presented on the screen until the participant pressed one of the two response keys with the left or right index finger, respectively. The response–stimulus interval was 200 ms. Blocks were separated by intervals of 5 s during which the monitor switched several times between the colors blue and gray. The next block started immediately after these 5 s. To prevent fatigue, we scheduled longer breaks of 5 min for participants after Blocks 3, 11, and 18. After these longer breaks, the next block was started when the participant pressed the spacebar.

When numerical tasks were required, the relevant central digit was chosen randomly from one of the sets (1–4 or 6–9), whereas the peripheral digit was chosen randomly from both sets. When spatial tasks were required, both digits were chosen randomly from both sets. The horizontal position of the peripheral digit was

Table 1
Abstract Sequences 1–4 of Relations Between Successive Task–Mapping Combinations

Sequence characteristic	Transition between successive trials							
	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–1
1								
Task	≠	≠	=	=	≠	=	=	≠
Mapping	=	≠	=	≠	≠	=	≠	=
2								
Task	=	≠	=	≠	≠	=	≠	=
Mapping	≠	≠	=	=	≠	=	=	≠
3								
Task	≠	≠	=	=	≠	=	=	≠
Mapping	=	=	≠	=	≠	≠	=	≠
4								
Task	=	=	≠	=	≠	≠	=	≠
Mapping	≠	≠	=	=	≠	=	=	≠

Note. For each transition between successive trials within a sequence, it is specified whether the type of task remains the same (=) or is changed (≠) and whether the task-to-response mapping remains the same (=) or is changed (≠). Adapted from "Implicit Learning of Sequences of Tasks," by H. Heuer, V. Schmidtke, & T. Kleinsorge, 2001, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* p. 970. Copyright 2001 by the American Psychological Association.

randomly assigned to the left or to the right, with similar frequency of both positions. Thus, the order of responses was always random.

Blocks 1–4 were practice blocks with the task-mapping combinations presented according to pseudorandom sequencing (104 trials per block). In Blocks 5–12, the sequence of task-mapping combinations was presented such that it was repeated 13 times per block. After this phase, we administered two tests in order to assess indirect effects of implicit learning. The *random test* (Blocks 13–18) consisted of two sequenced blocks (13 and 14), two pseudorandom blocks (15 and 16), and again two sequenced blocks (17 and 18). The random test was followed by a second test phase, the *specificity test* (Blocks 19–21), which was designed to

Table 2
Sequences of Task–Mapping Combinations for One of the Four Abstract Sequences of Trial-to-Trial Relations From Table 1

Sequence	Serial position							
	1	2	3	4	5	6	7	8
1a	G[a]		R[c]	R	G			
		G[b]				R[d]	R	G
1b	R		G	G	R			
		R				G	G	R
1c		G				R	R	G
	G		R	R	G			
1d		R				G	G	R
	R		G	G	R			

Note. Task–mapping combinations are indicated by the color cue green (G) or red (R) in the upper or lower position; color and location were the stimulus features that indicated task and mapping in Experiment 1. Adapted from "Implicit Learning of Sequences of Tasks," by H. Heuer, V. Schmidtke, & T. Kleinsorge, 2001, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* p. 971. Copyright 2001 by the American Psychological Association.
[a] Numerical task, compatible mapping. [b] Spatial task, compatible mapping. [c] Numerical task, incompatible mapping. [d] Spatial task, incompatible mapping.

test whether participants learned the abstract structure of trial-to-trial relations. However, Heuer et al. (2001) obtained inconsistent results and doubted the reliability of this test. In the present study, we administered the specificity test in order to maintain the procedure of Heuer et al. (2001); however, we will not report the results. The experiment was programmed with E-Prime Version 1.2 (Psychology Software Tools, Pittsburgh, PA) on an IBM-compatible notebook computer.

After the last block of trials, participants were informed that there had been a repeating sequence of task-mapping combinations. In order to assess their explicit knowledge of the sequence, experimenters asked the participants to reproduce the sequence, as best they could, on a sheet of paper showing a series of eight boxes. Each box represented the screen, and they had to write a stimulus either above or below the fixation mark (thereby indicating the type of task) in green or red (thereby indicating the type of mapping). They were allowed to start the reproduction of the sequence with any task-mapping combination and were encouraged to guess when necessary. The maximal number of consecutively correct task-mapping combinations (combinations of stimulus location and stimulus color) was calculated.

Data analysis. In order to assess learning effects, we computed median response times (RTs) per block and participant for the four task-mapping combinations and the four trial-to-trial relations (task: same vs. different, and mapping: same vs. different) separately. Then, the median RTs were averaged per block and participant. In random blocks, 16 median RTs were available. In sequenced blocks, only eight of the 16 median RTs were available for each participant because of the structure of the individual sequence of task-mapping combinations. Across participants, however, all 16 median RTs were available (see Heuer et al., 2001). The first trial of each block, trials on which errors were made, and trials that followed an error were excluded from analysis. Perfect prediction of the next stimulus–response pair was not possible because only the task and the stimulus feature that cued it followed a repeating sequence, whereas the response was deter-

mined randomly. Therefore, consistent with Heuer et al. (2001), the data were screened for anticipatory responses (i.e., RTs of less than 100 ms), and these trials were also excluded from analysis. Among all participants and blocks, altogether 5.7 % of the trials were excluded. For all statistical analyses, an alpha level of .05 was used. Unless stated otherwise, *t* tests were two-tailed. Degrees of freedom were adjusted where appropriate. Effect sizes are expressed as η^2 values.

Results

RTs. RT results are shown in Figure 2. During Blocks 5–12, there was a continuous decrease in RTs, reflecting a general practice effect. The *training score* (i.e., the RT reduction from Block 5 to Block 12) was 162 ms (*SE* = 24), and the RTs in Blocks 5 and 12 were significantly different as revealed by a paired-samples *t* test, $t(15) = 6.82, p < .001, \eta^2 = .76$. Sequence specific learning was revealed in the random test (Blocks 13–18). The mean *disruption score* (i.e., the RT difference between random Blocks 15 and 16 and adjacent sequenced Blocks 13, 14, 17, and 18) was 175 ms (*SE* = 22). RTs were significantly slower in random blocks compared with RTs in sequenced blocks as revealed by a paired-samples *t* test, $t(15) = 8.01, p < .001, \eta^2 = .81$. This was taken as evidence of sequence learning.

Explicit knowledge. The mean number of consecutive task-mapping combinations that were reproduced in the correct order was 4.5 out of 8.0 (*SD* = 2.0). Five participants scored conspicuously high on the explicit knowledge test and were suspected of having potentially relevant explicit knowledge. One of them reported five elements, two reported seven elements, and two reported eight elements of their sequences.

To investigate whether the sequence learning effect was attributable to those participants who scored high on the explicit knowledge test, we performed the random test separately for the five participants who correctly reproduced five or more elements of the sequence and the remaining 11 participants. The mean disruption score was 133 ms (*SE* = 28) for the participants with explicit knowledge and 194 ms (*SE* = 28) for the remaining participants. The two groups did not differ in their disruption scores, as revealed in an independent-samples *t* test (*p* = .201). The disruption score of the remaining participants remained significantly different from zero, as shown by a one-sample *t* test, $t(10) = 6.97, p < .001, \eta^2 = .83$. This indicates substantial sequence learning in the group of participants with little or no explicit knowledge.

Error rates. The mean error rate across Blocks 4–18 was .02 (*SD* = .02), and no further analyses were conducted. Further error and RT analyses on switch costs are presented in the Appendix.

Discussion

Experiment 1 provides clear evidence of sequence learning. When the sequenced order of task-mapping combinations was replaced by a random order, RTs increased substantially. However, some of the participants also gained relevant explicit sequence knowledge as indicated by their performance in the reproduction test. As we used a less restrictive reproduction task than Heuer et al. (2001), who predefined the first two elements of the sequence, this may explain why our participants scored higher on the explicit knowledge test. At present, the debate regarding whether sequence learning can proceed independently of awareness is far from resolved (e.g., Destrebecqz & Cleeremans, 2001; Jiménez, Méndez, & Cleeremans, 1996; Jiménez, Vaquero, & Lupiáñez, 2006; Perruchet & Amorim, 1992; Shanks & St. John, 1994), and this study was not designed to contribute to this dispute. When the five participants who correctly reported conspicuously long sequence fragments were excluded from the analysis, the sequence-specific learning effect was still very substantial. Furthermore, the disruption score of the participants with more explicit knowledge did not
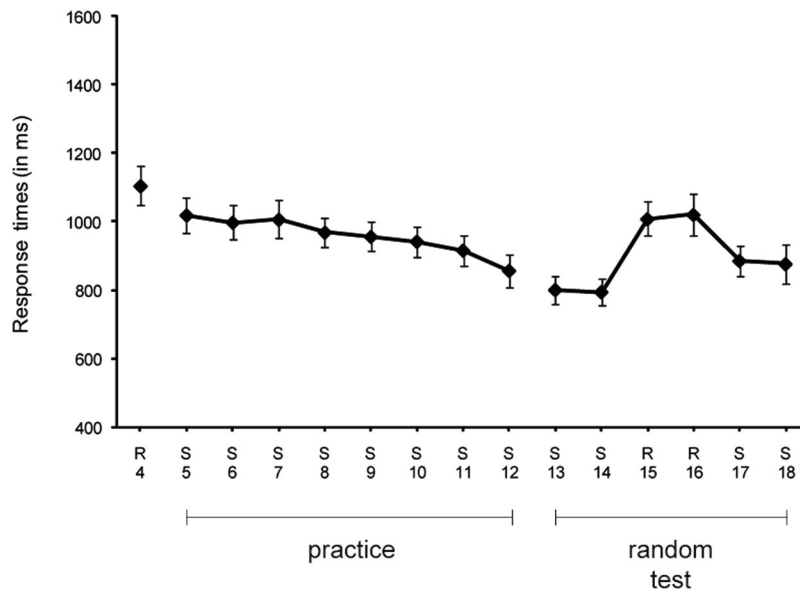

Figure 2. Reaction time results for Experiment 1 (R = random block; S = sequenced block). Error bars represent standard errors.

differ from that of the participants with little or no explicit knowledge. Thus, even though there was evidence for explicit knowledge, its amount did not affect the performance score. Therefore, sequence learning cannot be solely attributed to explicit knowledge.

The present results clearly replicate the RT findings of Heuer et al. (2001), and therefore, the precondition to further test the source of task sequence learning with this paradigm was met. From the present results, we could not distinguish whether sequence learning was due to perceptual learning of surface features, to automatic task-set activation or to the integrated sequence learning resulting from two correlated sequences of tasks and task-to-response mappings. The goal of Experiment 2 was to separate these possibilities. We achieved this by using a between-subjects design, with the order of tasks (sequenced vs. random) and the order of mappings (sequenced vs. random) manipulated independently (Cock & Meier, 2007). Four different conditions were tested: The first condition was similar to Experiment 1; that is, tasks and changes in mappings were sequenced in unison (i.e., different streams with different structures but with same cycle length and hence correlated). In the second condition, tasks were sequenced, whereas changes in mappings were random. In the third condition, tasks were random, whereas changes in mappings were sequenced. Finally, the fourth condition was a control condition in which both streams were randomly ordered.

Furthermore, in Experiment 2, stimuli that were univalent with regard to the different tasks were used in order to eliminate the sequence of stimulus positions that correlated with the sequence of tasks by design. Two different types of tasks were used, namely number and letter tasks. The number task was identical to the numerical task in Experiment 1; that is, participants had do decide whether the digit shown on screen was smaller or larger than 5. For the letter task, participants had to decide whether the letter shown on screen was a vowel or a consonant. Because the stimulus itself (i.e., a digit or a letter) indicated directly which task was to be performed, it was possible to present the stimuli centrally. The vertical location cue (indicating the type of task in Experiment 1) was no longer necessary.

With regard to these changes, the three explanations for implicit task sequence learning would predict different results. If task sequence learning is restricted to learning the regular order of perceptual stimulus features (Heuer et al., 2001), then learning should occur in the first condition, which has both a task and a task-to-response mapping sequence, and also in the third condition, which has just a single mapping sequence. This is because there is a salient stream of repeating perceptual stimulus features. Here, perceptual stimulus features are understood as unique surface characteristics, such as the color of the stimulus that indicates the type of mapping. However, no sequence learning would be expected in the second condition, which has just a single task sequence. Here, there is no repeating pattern of perceptual stimulus features, because each task type comprises eight different exemplars (i.e., eight digits or eight letters), the presentation of which varies at random. The stimulus has to be transformed into a meaningful concept in order to make the relevant task. For example, the letter *a* has to be understood as belonging to the category "vowel." On the other hand, if task sequence learning is to be attributed to automatic task-set activation (Koch, 2001), then sequence learning should occur in those conditions in which a task

sequence is present, that is, in the first condition, which has both a task and a mapping sequence, and also in the second condition, which has just a single task sequence. This is because different task types (i.e., the letter or the number task) imply different task sets. In contrast, our third condition, which has just a single mapping sequence, should not show any sequence learning effects because different mapping types (i.e., compatible vs. incompatible) do not imply different task sets. Finally, if the presence of correlated streams of information is at the core of task sequence learning (Cock & Meier, 2007; Meier & Cock, 2010), then sequence learning should occur only in the first condition, which has two correlated sequences: the task and the mapping sequence. No sequence learning effects would be expected in the conditions that have only a single task sequence or a single mapping sequence.

Experiment 2

Method

Participants and design.   Eighty-four participants were randomly assigned to one of four experimental conditions: *seqseq* (order of tasks and order of mappings sequenced), *seqran* (tasks sequenced, mappings random), *ranseq* (tasks random, mappings sequenced), and *ranran* (control condition with no sequences). Five participants did not finish the experiment for technical reasons. Eight participants with error rates higher than 10% (averaged over Blocks 4–21) were excluded from the analysis. The final sample consisted of 71 participants: 18 participants in the *seqseq*, 17 in the *seqran*, 17 in the *ranseq*, and 19 in the *ranran* conditions. The participants' mean age was 24.1 years ($SD = 4.2$). Thirty-one participants were men and 40 were women. Five participants were left-handed. Sequence was manipulated between subjects, and block was manipulated within subject, resulting in a mixed design.

Materials.   The target stimuli were the digits 1, 2, 3, 4, 6, 7, 8, and 9 and the letters *a*, *e*, *i*, *u*, *c*, *n*, *r*, and *s*. The target stimulus appeared at the center of the black screen in 32-point Arial font in either green or red. The stimulus determined the type of task (a digit for the number task vs. a letter for a letter task), and the color of the stimulus was the cue for the type of mapping (green for compatible vs. red for incompatible). The orthogonal combination of tasks and mappings resulted in four different task-mapping combinations. For a number task, participants had to decide whether the digit was small (1–4) or large (6–9). For a letter task, participants had to decide whether the letter was a vowel (*a*, *e*, *i*, *u*) or a consonant (*c*, *n*, *r*, *s*). The color green signaled compatible mapping, which required a left-hand response (key "1") for a small number or a vowel and a right-hand response (key "5") for a large number or a consonant. This mapping was compatible with the instructional reminders shown on the screen (see Figure 1b). The color red signaled incompatible mapping, which required a left-hand response for a large number or a consonant and a right-hand response for a small number or a vowel. This mapping was incompatible with the instructional reminders shown on the screen.

Sequences.   For the *seqseq* condition, the order of tasks (number vs. letter) and the order of mappings (compatible vs. incompatible) were sequenced according to the 16 sequences used in Experiment 1. For the *seqran* condition, sequences of tasks were constructed in the following way. First, two different sequences of nominal relations between successive tasks (same vs. different)

were identified in the abstract sequences of Experiment 1. The abstract sequences were "different–different–same–same–different–same–same–different" and "same–different–same–different–different–same–different–same." From each of these sequences, two different task sequences were derived with the initial element counterbalanced. The four different task sequences are shown in Table 3. The order of mappings was pseudorandom, such that each of the four possible transitions between successive trials occurred with the same frequency during a block of 104 trials and with similar frequencies of the four different task-mapping combinations (number compatible, number incompatible, letter compatible, letter incompatible). The same transition did not occur more than twice in a row. For the *ranseq* condition, the order of successive mappings was sequenced. Four different mapping sequences were derived from the same two abstract sequences of relations as in the *seqran* condition (see Table 3). The order of tasks was pseudorandom, with the same constraints as those used in the *seqran* condition for the order of mappings. For the *ranran* condition, both the order of tasks and the order of mappings were pseudorandom. Each of the four possible transitions between successive task-mapping combinations occurred with equal frequency within a block. The same transition did not occur more than twice in a row. The frequencies of the four possible task-mapping combinations were marginally different. In the *seqseq*, the *seqran*, and the *ranseq* conditions, pseudorandom orders of task-mapping combinations fulfilling the same criteria were used for random blocks.

Procedure. The procedure was the same as in Experiment 1 except for a few adjustments. Throughout each block of trials, four instructional reminder words were presented continuously on the left and right sides of the black screen in white 26-point Arial font (see Figure 1b). On the left, the German words for "vowel" and "small" were shown. On the right, the German words for "consonant" and "large" were shown. On each trial, one stimulus appeared centrally on the screen.

The course of the 21 blocks was identical to that in Experiment 1, with the only difference being that in sequenced blocks, either a sequence of task-mapping combinations (*seqseq* condition), a sequence of tasks (*seqran* condition), a sequence of mappings (*ranseq* condition), or no sequence (*ranran* condition) was present. For the *ranran* condition, all blocks were in pseudorandom order. After the last block of trials, all participants were informed that there had been a repeating sequence of tasks and were asked to

Table 3
Four Different Sequences of Tasks and Mappings Used in Experiments 2 and 3

Sequence	Serial position							
	1	2	3	4	5	6	7	8
1a	A	B	A	A	A	B	B	B
1b	B	A	B	B	B	A	A	A
2a	A	A	B	B	A	B	B	A
2b	B	B	A	A	B	A	A	B

Note. Tasks and mappings are indicated by the letters A (number task or compatible mapping) and B (letter task or incompatible mapping).

reproduce this sequence in a paper-and-pencil reproduction task similar to Experiment 1. They were asked to generate a series of letters and numbers (indicating different tasks) in either green or red (indicating different mappings) in eight boxes.

Data analysis. Data analysis was the same as that in Experiment 1. In the *seqseq* condition, only eight of 16 median RTs were available in the sequenced blocks. In all other conditions and blocks, 16 median RTs were available. Among all participants and blocks, 7.9 % of the trials were excluded from analysis.

Results

RTs. RT results of Experiment 2 are shown in Figure 3. In all conditions, RTs decreased during the practice blocks (Blocks 5–12). The mean training score (i.e., the RT difference between Blocks 5 and 12) was 189 ms ($SE = 44$) for the *seqseq*, 97 ms ($SE = 64$) for the *seqran*, 148 ms ($SE = 41$) for the *ranseq*, and 140 ms ($SE = 57$) for the *ranran* conditions. We analyzed the RT difference between Blocks 5 and 12 in a 2×4 mixed analysis of variance (ANOVA) with the within-subject factor block (5 vs. 12) and the between-subjects factor sequence (*seqseq*, *seqran*, *ranseq*, *ranran*). RTs decreased significantly from Block 5 to Block 12, $F(1, 67) = 29.77, p < .001, \eta^2 = .31$. The effect of sequence and the interaction term was not significant ($ps > .65$), indicating similar general practice effects in all conditions.

In the random test, sequence-specific learning is indicated by an increase in RTs when the sequence is changed to random in Blocks 15 and 16. This was observed only in the *seqseq* condition. Sequence-specific learning was assessed with the disruption score (i.e., the RT difference between random Blocks 15 and 16 and adjacent sequenced Blocks 13, 14, 17, and 18), shown in Table 4. A 2×4 mixed ANOVA with the within-subject factor block (sequenced vs. random) and the between-subjects factor sequence (*seqseq*, *seqran*, *ranseq*, *ranran*) revealed a significant main effect of block, $F(1, 67) = 17.60, p < .001, \eta^2 = .21$. The effect of sequence was not significant ($p = .501$), but the Block × Sequence interaction was significant, $F(3, 67) = 11.78, p < .001, \eta^2 = .35$. To locate the source of this interaction, we conducted post hoc Tukey's honestly significant difference test on the disruption scores. The *seqseq* condition differed significantly from the three other conditions (all $ps < .01$), but the latter did not differ from one another (all $ps > .45$).

Explicit knowledge. In the *seqseq* condition, the mean number of correctly reproduced task-mapping combinations was 3.8 out of 8.0 ($SD = 1.6$). In the *seqran* condition, the mean number of correctly reproduced tasks was 5.4 out of 8.0 ($SD = 1.3$). In the *ranseq* condition, the mean number of correctly reproduced task-to-response mappings was 4.9 out of 8.0 ($SD = 1.3$). For each participant in the *ranran* condition, we compared the generated sequence to each possible sequence of task-mapping combinations (16 comparisons per participant), tasks (four comparisons per participant), and mappings (four comparisons per participant). The mean number of correctly reproduced elements was 2.9 ($SD = 0.2$) for the sequence of task-mapping combinations, 5.6 ($SD = 0.9$) for the task sequence, and 5.3 ($SD = 1.1$) for the mapping sequence.

The reproduction performance of the *ranran* condition with no sequences provided an empirical baseline for comparison. Neither participants in the *seqran* condition ($p = .552$) nor those in the *ranseq* condition ($p = .437$) reported more elements of the task or
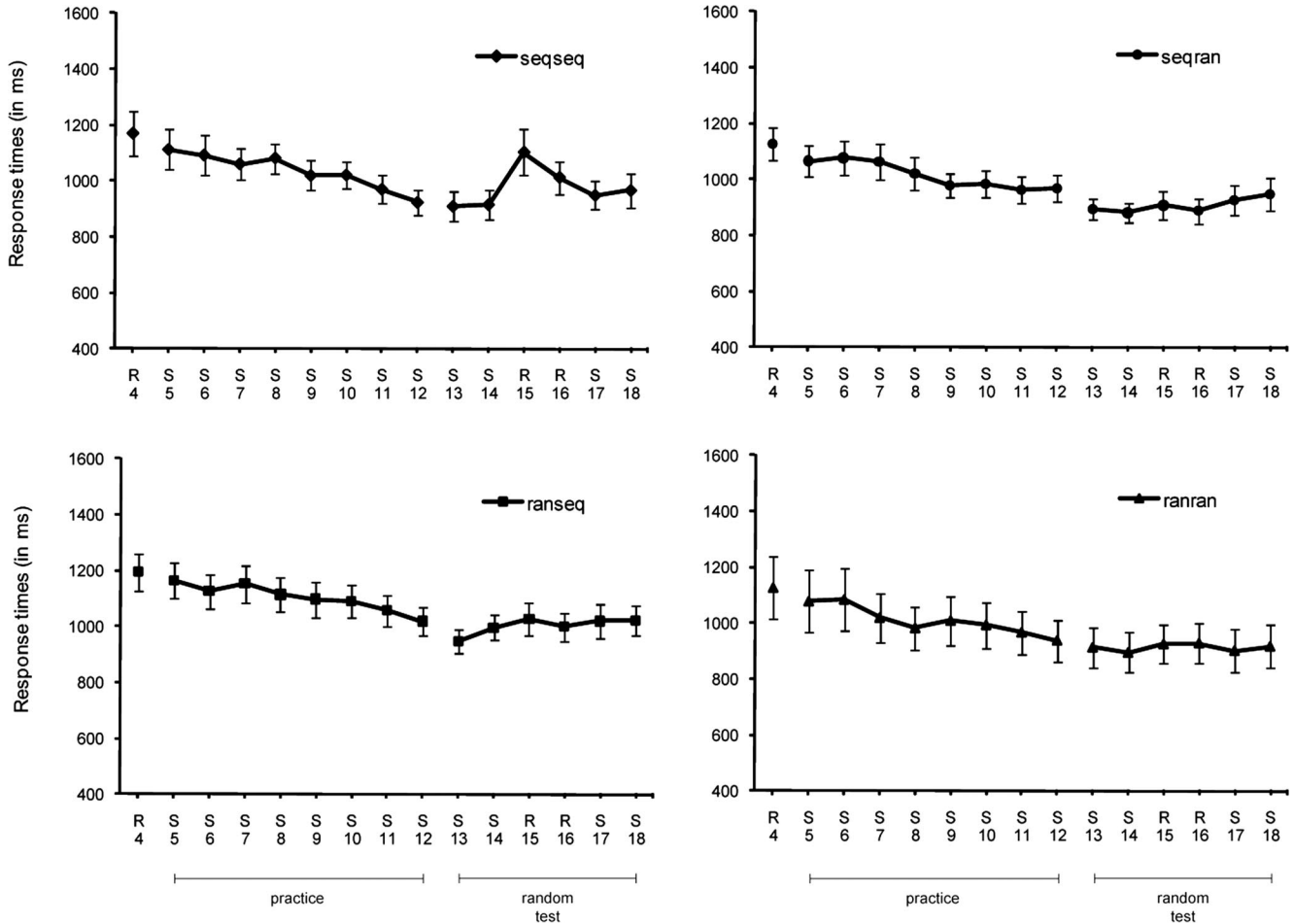
Figure 3. Reaction time results for Experiment 2 (R = random block; S = sequenced block). Separate graphs are shown for the correlated sequences condition (*seqseq*: correlated sequences of tasks and mappings), the single sequence conditions (*seqran*: single sequence of tasks; *ranseq*: single sequence of mappings), and the control condition (*ranran*: no sequences). Error bars represent standard errors.

mapping sequence than those in the *ranran* condition. This indicates no substantial above-chance explicit sequence knowledge in these conditions. In contrast, participants in the *seqseq* condition reported significantly more elements of the sequence of task-

Table 4
Disruption Scores for the Random Tests (Blocks 13–18) Conducted Separately for Experimental Conditions in Experiments 2 and 3

Sequence condition	Experiment 2		Experiment 3	
	M	*SE*	*M*	*SE*
seqseq	123**	21	89**	20
seqran	−14	14	19	17
ranseq	18	23	−1	10
ranran	20*	8	−12	12

Note. *seqseq* = correlated sequences of tasks and mappings; *seqran* = single task sequence; *ranseq* = single mapping sequence; *ranran* = no sequences.
* $p < .05$. ** $p < .01$.

mapping combinations than those in the *ranran* condition, $t(17.52) = 2.36$, $p = .030$, $\eta^2 = .24$. For subsequent follow-up analyses, the reproduction of five or more elements was taken as the cutoff for potentially relevant explicit knowledge in the *seqseq* condition because this was more than 2 standard deviations higher than the mean number of reproduced task-mapping combinations in the *ranran* condition and thus very unlikely to occur merely by guessing. Five participants were suspected of having relevant explicit knowledge (two reproduced five elements, one reproduced six elements, and two reproduced seven elements of the task sequence).

To investigate whether sequence learning in the *seqseq* condition was attributable to those participants scoring high on the explicit knowledge test, we computed the disruption scores of the random test separately for the five participants with potentially relevant explicit knowledge and the remaining participants. The mean disruption score was 133 ms ($SE = 25$) for the participants with potentially relevant explicit knowledge and 119 ms ($SE = 18$) for the remaining participants. The two groups did not differ in their disruption scores, as revealed in an independent-samples *t*

test, $p = .771$. The disruption score of the remaining participants was significantly different from zero, $t(12) = 4.18$, $p = .001$, $\eta^2 = .59$. This indicates that sequence learning in the *seqseq* condition occurred even in participants with little or no explicit knowledge.

Error rates. The mean error rate across Blocks 4–18 was .03 ($SD = .02$) for the *seqseq*, .03 ($SD = .02$) for the *seqran*, .04 ($SD = .02$) for the *ranseq*, and .04 ($SD = .02$) for the *ranran* condition. A one-way ANOVA on error rates revealed no significant effect of sequence condition ($p = .942$). Further error and RT analyses on switch costs are presented in the Appendix.

Discussion

In Experiment 2, sequence learning was observed in the correlated sequences condition (*seqseq*). Participants in this condition slowed down substantially when the sequence of task-mapping combinations was changed to random, and the learning effect was not easily attributable to explicit sequence knowledge. In contrast, in the single sequence conditions (*seqran* and *ranseq*), participants did not slow down when the task or mapping sequence was changed to random. This suggests that the single sequences were not learned at all. These results are inconsistent with the predictions derived from the perceptual learning explanation (Heuer et al., 2001) and the explanation of automatic task-set activation (Koch, 2001). However, they are consistent with the prediction derived from the explanation of correlated streams of information (Meier & Cock, 2010).

The lack of perceptual learning in the single mapping sequence condition is at odds with a recent study in which researchers found evidence of learning a sequence of colors in a serial color-matching task (Gheysen, Gevers, De Schutter, Van Waelvelde, & Fias, 2009). Participants were asked to match the colors of three small squares with the color of a subsequently presented large square. The color of the large square was determined by a sequence, whereas the colors of the small squares and the responses were selected randomly from trial to trial. Participants incidentally learned the color sequence, as indicated by slower RTs in random blocks than in sequenced blocks. However, as the color-matching task is based on a two-step procedure, it differs substantially from the task sequence learning paradigm. Learning of a color sequence may be possible under the conditions given in the study by Gheysen et al. (2009) but not under the conditions given in our experiment.

Experiment 3 was designed to replicate Experiment 2 but with the use of a different cue to indicate the type of mapping. In order to make the perceptual salience of the mapping cue less conspicuous, we replaced the color cue by a simple line frame around the stimulus. The stimulus was either framed by a square (for a compatible mapping) or a diamond (for an incompatible mapping), the two frames being perceptually less distinct than the colors green and red. If the presence of correlated streams of information is at the core of task sequence learning, then learning should still occur irrespective of the cue used for different mapping types.

Experiment 3

Method

Participants and design. Eighty participants were randomly assigned to one of the four experimental conditions: *seqseq* (order

of tasks and order of mappings sequenced), *seqran* (tasks sequenced, mappings random), *ranseq* (tasks random, mappings sequenced), and *ranran* (control condition with no sequences). Four participants with error rates higher than 10% (averaged over Blocks 4–21) were excluded from the analysis. The final sample consisted of 76 participants: 20 participants in the *seqseq* condition, 19 in the *seqran* condition, 20 in the *ranseq* condition, and 17 in the *ranran* condition. Mean age was 22.5 years ($SD = 2.1$). Thirty-two participants were men and 44 were women. Five participants were left-handed. Sequence was manipulated between subjects, and block was manipulated within subjects, resulting in a mixed design.

Materials and procedure. The materials and procedure were the same as those used in Experiment 2, except that the color cue for different types of task-to-response mappings was replaced by a simple line frame around the stimulus. All stimuli were presented in white against a black background, and they were framed by either a white square or a white diamond. For both square and diamond, the side length was approximately 2 cm, and the thickness of the line approximately 1 mm. The square signaled a compatible task-to-response mapping, whereas the diamond signaled an incompatible mapping. In the reproduction task, the participants had to indicate the type of mapping by drawing a frame instead of using the colors green or red as in Experiment 2.

Data analysis. The data analysis was the same as before. Among all participants and blocks, altogether 8.2 % of the trials had to be excluded.

Results

RTs. RT results of Experiment 3 are shown in Figure 4. RTs decreased initially in all conditions. The mean training score (i.e., the RT difference between Block 5 and Block 12) was 234 ms ($SE = 37$) for the *seqseq*, 240 ms ($SE = 42$) for the *seqran*, 179 ms ($SE = 23$) for the *ranseq*, and 172 ms ($SE = 37$) for the *ranran* condition. The RT difference between Blocks 5 and 12 was analyzed in a 2×4 mixed ANOVA with the within-subject factor block (5 vs. 12) and the between-subjects factor sequence (*seqseq* vs. *seqran* vs. *ranseq* vs. *ranran*). RTs decreased significantly from Block 5 to Block 12, $F(1, 72) = 134.63$, $p < .001$, $\eta^2 = .65$. The effect of sequence and the interaction term were not significant (ps $> .35$), indicating no differences between sequence conditions in the general training effect.

When the sequence was changed to random in Blocks 15 and 16, RTs increased only in the *seqseq* condition, suggesting sequence-specific learning, but not in the three other conditions. The disruption scores of the random test (i.e., the RT difference between random Blocks 15 and 16 and adjacent sequenced Blocks 13, 14, 17, and 18) are shown in Table 4. A 2×4 mixed ANOVA with the within-subject factor block (sequenced vs. random) and the between-subjects factor sequence (*seqseq*, *seqran*, *ranseq*, *ranran*) revealed no effect of sequence ($p = .747$) but a significant effect of block, $F(1, 72) = 9.39$, $p = .003$, $\eta^2 = .12$, and a significant Block × Sequence interaction, $F(3, 72) = 8.72$, $p < .001$, $\eta^2 = .27$. To locate the source of the interaction, we conducted post hoc Tukey's honestly significant difference tests on the disruption scores. The *seqseq* condition differed significantly from the three other conditions (all ps $< .05$), but the latter did not differ from each other (all ps $> .50$).
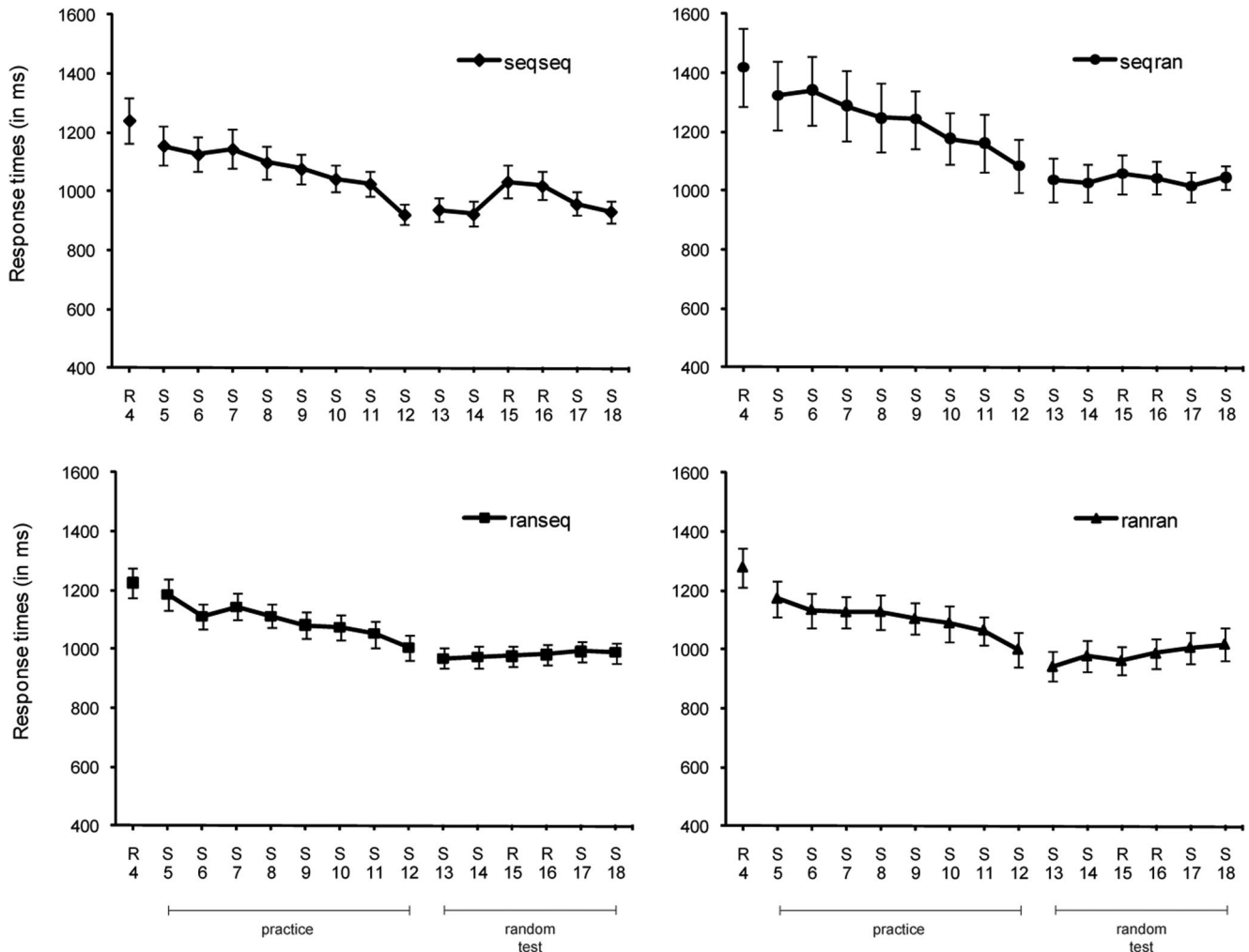
Figure 4. Reaction time results for Experiment 3 (R = random block; S = sequenced block). Separate graphs are shown for the correlated sequences condition (*seqseq*: correlated sequences of tasks and mappings), the single sequence conditions (*seqran*: single sequence of tasks; *ranseq*: single sequence of mappings), and the control condition (*ranran*: no sequences). Error bars represent standard errors.

Explicit knowledge. In the *seqseq* condition, the mean number of correctly reproduced task-mapping combinations was 3.4 out of 8.0 (*SD* = 1.2). In the *seqran* condition, the mean number of correctly reproduced tasks was 6.0 out of 8.0 (*SD* = 1.5). In the *ranseq* condition, the mean number of correctly reproduced mappings was 5.8 out of 8.0 (*SD* = 1.0). For each participant in the *ranran* condition, the generated sequence was compared to each possible sequence of task-mapping combinations, tasks, and mappings. The mean number of correctly reproduced elements was 2.9 (*SD* = 0.2) for the sequence of task-mapping combinations, 5.7 (*SD* = 0.4) for the task sequence, and 5.4 (*SD* = 0.6) for the mapping sequence.

Neither participants in the *seqran* condition (*p* = .386) nor those in the *ranseq* condition (*p* = .186) reported more elements of the task or mapping sequence, respectively, than those in the *ranran* condition. Similarly, participants in the *seqseq* condition did not reproduce significantly more elements of the sequence of task-mapping combinations than those in the *ranran* condition

(*p* = .093). As in Experiment 2, the reproduction of five or more elements was taken as the cutoff for potentially relevant explicit knowledge in the *seqseq* condition. Three participants reported five elements and one participant reported seven elements of the sequence of task-mapping combinations, and they were therefore suspected of having explicit knowledge.

To investigate whether the sequence learning effect in the *seqseq* condition was attributable to the participants scoring high on the explicit knowledge test, we computed the disruption scores of the random test separately for participants with potentially relevant explicit knowledge and the remaining participants. The mean disruption score was 100 ms (*SE* = 20) for the participants with explicit knowledge and 86 ms (*SE* = 25) for the remaining participants. The two groups did not differ in their disruption scores, as indicated by an independent-samples *t* test (*p* = .790). The disruption score of the remaining participants was still significantly different from zero, *t*(15) = 3.43, *p* = .003, η^2 = .44, which indicates that sequence learning

occurred even in participants with little or no explicit knowledge.

Error rates. The mean error rate across Blocks 4–18 was .04 (*SD* = .03) for the *seqseq*, .04 (*SD* = .02) for the *seqran*, .03 (*SD* = .02) for the *ranseq*, and .04 (*SD* = .02) for the *ranran* condition. A one-way ANOVA on error rates revealed no significant effect of sequence (*p* = .431). Further error and RT analyses on switch costs are presented in the Appendix.

Discussion

Experiment 3 provides further evidence for sequence learning in the correlated sequences condition (*seqseq*) only. Participants slowed down substantially when the sequence of task-mapping combinations was changed to random, and this sequence learning effect was not attributable to explicit knowledge. In contrast, no sequence learning was observed in the single sequence conditions (*seqran* and *ranseq*) or in the control condition (*ranran*). These findings provide further evidence for the hypothesis that correlated streams of information are necessary for implicit task sequence learning (Meier & Cock, 2010). However, there are two alternative explanations as to why sequence learning might occur in the correlated sequences condition but not in the single sequence conditions.

First, in the correlated sequences condition, the correlated streams of tasks and mappings can be integrated into a sequence of task-mapping combinations that is defined by specific stimulus types (e.g., a letter within a square or a diamond, or a digit within a square or a diamond). This integrated sequence of task-mapping combinations is, by design, less complex than the single task or mapping sequences. Previous SRTT studies have shown that the sequential structure affects implicit learning, with greater statistical structure resulting in higher sequence learning effects (e.g., Stadler, 1992; Stadler & Neely, 1997). Thus, it is possible that the single sequences were not learned simply because their structure was too difficult, whereas the integration of two correlated streams provided a useful source of simplification.

Second, in the single sequences conditions, learning the single sequence may have been disrupted by the presence of an accompanying random stream of information. Specifically, the random order of mappings may have interrupted the coherence between successive elements of the task sequence, similar to secondary-task effects on sequence learning in the SRTT (e.g., Heuer & Schmidtke, 1996; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Schmidtke & Heuer, 1997). In the single sequence conditions, the random stream of mappings (or tasks) may weaken the association between successive tasks (or mappings), whereas in the correlated sequences condition, the association between successive task-mapping combinations is strengthened. Hence, it is possible that it is not the presence of two correlated streams of information that is responsible for sequence learning but that in the single-stream conditions the "de-correlation" resulting from the uncorrelated stream of information may have prevented learning. If this alternative explanation would hold, then learning of a single sequence may occur as long as there is no random stream interfering with the sequenced stream of information.

We designed Experiment 4 to investigate whether sequence learning in the single task sequence condition occurs when these two alternative explanations are controlled. A single task sequence with a structure identical to the structure of the sequences of task-mapping combinations in Experiments 1–3 (*seqseq* conditions) was used. We achieved this by replacing the four different task-mapping combinations (e.g., number compatible, number incompatible, letter compatible, letter incompatible) by four different task types. In addition to the number and the letter tasks, a line task and a shape task were introduced. For the line task, participants had to decide whether horizontal or vertical lines were presented. For the shape task, they had to decide whether a form was round or angular. Only a compatible mapping was used; therefore, there was no additional random stream of mappings that might disrupt learning of the task sequence. According to the correlated streams explanation (Meier & Cock, 2010), we would not expect to find sequence learning effects in Experiment 4 because there is only a single task sequence present. However, if either sequence complexity or the presence of a random stream of mappings (or tasks) prevented sequence learning from occurring in the single sequence conditions in Experiments 2 and 3, we would expect to find sequence learning in Experiment 4.

Experiment 4

Method

Participants. Twenty volunteers (nine men and 11 women, 1 left-handed) participated in Experiment 4. Mean age was 25.6 years (*SD* = 4.1).

Materials. Stimuli were approximately 1.0 × 1.2 cm and shown in white against a black background. For the number and the letter tasks, stimuli were the same used in Experiments 2 and 3, and participants had to decide whether the digit was small or large (number task) and whether the letter was a vowel or a consonant (letter task), respectively. For the shape task, four different round shapes and four different angular shapes were used, and participants had to decide whether the presented figure was round or angular. For the line task, four different figures consisting of horizontal lines and four different figures consisting of vertical lines were used, and participants had to decide whether the lines were horizontal or vertical. The stimuli for the shape task and the line task are shown in Figure 5. The stimulus determined the task type. Only the compatible task-to-response mapping type was used. Participants had to press a designated key with their left index finger for small numbers, vowels, round shapes, and horizontal lines and another designated key with their right index finger for large numbers, consonants, angular shapes, and vertical lines. This mapping was compatible with the instructional reminders shown on the screen.
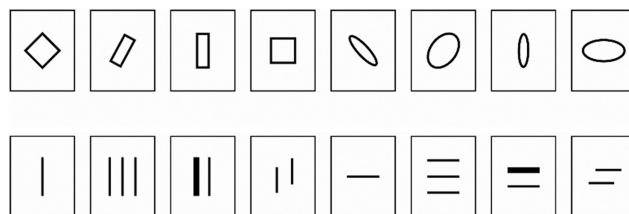

Figure 5. Shape figures and line figures used in Experiment 4. Figures were presented in white against a black background.

Sequences. The order of tasks (number, letter, shape, or line) was sequenced according to the 16 sequences of task-mapping combinations used in Experiment 1. Each of the four task-mapping combinations was replaced by one of the four task types. For the pseudorandom ordering (104 trials per block), we adapted the order of tasks from the pseudorandom order of task-mapping combinations in Experiment 1. Each task occurred with nearly equal frequency, and task repetitions did not occur more than twice in a row.

Procedure. The procedure was the same as in the *seqran* condition in Experiments 2 and 3 except that throughout each block of trials, eight instructional reminder words were presented continually on the left and right sides of the black screen (see Figure 1d). On the left, the German words for "vowel," "small," "round," and "horizontal" were shown. On the right, the German words for "consonant," "large," "angular," and "vertical" were shown. Within each task, stimuli were chosen randomly.

After the last block of trials, all participants were informed that there had been a repeating sequence of tasks and were asked to reproduce this sequence in a paper-and-pencil reproduction task similar to that in Experiment 1. They were asked to generate a series of letters, numbers, shapes and lines (indicating different types of tasks) in eight boxes.

Data analysis. The data analysis was the same as before except that we computed median RTs per block and participant for the four tasks separately for task repetition and task switch trials, and then we averaged these median RTs per block and participant. Only six median RTs were available in sequenced blocks, but eight median RTs were available in random blocks. Among all participants and blocks, 5.8 % of the trials were excluded from analysis.

Results

RTs. RT results are shown in Figure 6. During Blocks 5–12, there was a continuous decrease in RTs, reflecting a general practice effect. The training score (i.e., the RT reduction from Block 5 to Block 12) was 67 ms ($SE = 13$), and the RTs in Blocks 5 and 12 were significantly different as revealed by a paired-samples t test, $t(19) = 5.15$, $p < .001$, $\eta^2 = .58$. Sequence specific learning was investigated in the random test (Blocks 13–18). The mean disruption score (i.e., the RT difference between random Blocks 15 and 16 and adjacent sequenced Blocks 13, 14, 17, and 18) was 4 ms ($SE = 5$). The difference between random and sequenced blocks was not significant, as revealed by a paired-samples t test, $t(19) = 0.97$, $p = .342$, $\eta^2 = .05$. This indicates that no sequence specific learning occurred.

Explicit knowledge. The mean number of correctly reproduced tasks was 2.9 out of 8.0 ($SD = 1.0$). As no sequence specific learning was found, no further analyses were conducted.

Error rates. The mean error rate across Blocks 4–18 was .03 ($SD = .02$), and no further analyses were conducted.

Discussion

In Experiment 4, participants did not slow down when the single task sequence was replaced by a random order. This indicates that the task sequence was not learned, although its structure was identical to the structure of the sequences of task-mapping combinations in Experiment 1 and in the correlated sequences conditions (*seqseq*) in Experiments 2 and 3. Furthermore, there was no additional random stream of mappings present that may have disrupted learning of the task sequence. Therefore, we conclude that the absence of sequence learning in the single task sequence condition (*seqran*) in Experiments 2 and 3 is neither attributable to the complexity of the single sequence being higher than that of the integrated sequence nor to the presence of an additional stream of randomly ordered mappings.

It may be argued that the lack of sequence learning in Experiment 4 is due to the presence of a random stream of motor responses. However, even in Experiment 1 and in the correlated
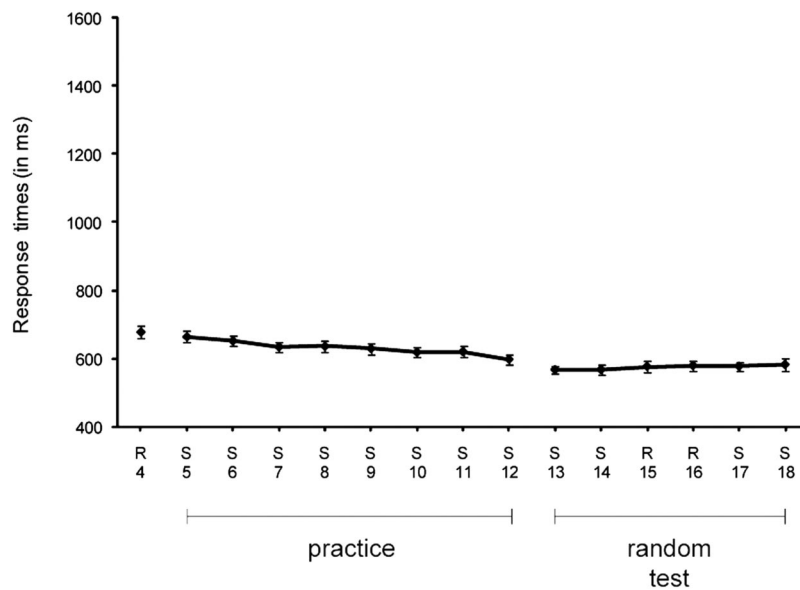

Figure 6. Reaction time results for Experiment 4 (R = random block; S = sequenced block). Error bars represent standard errors.

sequences conditions of Experiments 2 and 3, a random stream of responses was present. Nevertheless, sequence learning was found as long as two correlated sequences of tasks and mappings were present. Therefore, it is very unlikely that sequence learning in Experiment 4 was prevented by the presence of the random response stream.

It may also be argued that Experiment 4 simply presents a null result. However, the lack of learning a single-stream task sequence is in line with the results of Experiments 2 and 3 and with findings from previous studies (Cock & Meier, 2007; Meier & Cock, 2010). The multiple replication of a null result across a variety of different tasks and experiments becomes convincing evidence for the absence of single-stream task sequence learning.

General Discussion

Our purpose in the present study was to distinguish among the three explanations put forward to explain what matters in task sequence learning. The first holds that the learning effect is attributable to learning a pattern of repeated perceptual stimulus features (Heuer et al., 2001). The second suggests that task sequence learning depends on automatic task-set activation (Koch, 2001). Both explanations focus on single-stream learning (i.e., learning a stream of perceptual stimulus features and learning a stream of task-set activations, respectively). In contrast, the third explanation holds that two correlated streams of information are necessary for sequence learning to occur, irrespective of the kind of information (Meier & Cock, 2010).

In four different experiments, we extended the task sequence learning paradigm by Heuer et al. (2001). In Experiment 1, we replicated the incidental learning condition and found substantial sequence learning. In Experiments 2 and 3, the presence and absence of the task and of the task-to-response mapping sequence were orthogonally manipulated. Sequence learning effects were restricted to the correlated sequences conditions with both a task sequence and a mapping sequence present. In contrast, no sequence learning was observed in the single sequence conditions with either just a single task sequence or just a single mapping sequence. In Experiment 4, we found no learning of a single task sequence despite the simplification of the sequence structure and despite the absence of an additional random stream of mappings that might have impeded learning.

The present findings are at odds with the perceptual learning explanation proposed by Heuer et al. (2001). If sequence learning effects were attributable to learning of the single stream of uninterpreted perceptual stimulus features, then the perceptual pattern of repeating colors or frames produced by the mapping sequence (*ranseq* conditions in Experiments 2 and 3) should have been sufficient for sequence learning to occur. The present findings are also at odds with the explanation of automatic task-set activation (Koch, 2001). If task sequence learning depended on automatic task-set activation, then the presence of a single task sequence (*seqran* conditions in Experiments 2–4) should have been sufficient for sequence learning to occur. In contrast, the present findings support the account that two correlated streams of information are necessary for implicit task sequence learning to occur (Meier & Cock, 2010). In each condition in which two correlated streams of information were present (i.e., a sequenced stream of tasks and a sequenced stream of mappings), sequence learning

occurred. When two correlated sequences are integrated, a new less complex sequence emerges, and as a consequence, an alternative explanation would be that differences in sequence complexity may have caused the results. However, Experiment 4 shows that sequence complexity is not sufficient to explain why no sequence learning occurred in the single sequence conditions. In addition, the lack of sequence learning in the single sequence conditions cannot be attributed to a potentially disruptive effect of the presence of a random stream of information. There was no accompanying random stream of mappings present in Experiment 4, and yet the task sequence was not learned.

Altogether, the present findings add to previous evidence showing that correlated streams of information are a prerequisite for implicit task sequence learning to occur (Cock & Meier, 2007; Meier & Cock, 2010). However, it remains an open issue whether correlated streams of information are at the core of implicit sequence learning in general. In the SRTT (e.g., Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Nissen & Bullemer, 1987), the sequenced stream of stimulus locations is always correlated with a sequenced stream of motor responses. Accordingly, evidence for sequence learning in the standard SRTT seems to be consistent with the correlated streams explanation.

The coexistence of a perceptual sequence and a motor sequence in the standard SRTT has provoked an ongoing debate as to whether implicit sequence learning is based on the perceptual or motor characteristics of the sequence structure (see Goschke, 1998, for an overview). Thus, a number of researchers have examined whether sequence learning is primarily perceptual based or response based. Such studies are of particular interest for evaluation of the generality of the correlated streams account because they focus on learning based on a single sequenced stream of information.

The observation paradigm has been used to separate the perceptual stimulus sequence from the motor response sequence in the SRTT. In this paradigm, participants are typically instructed to observe the stimuli on the screen or to watch a model (i.e., another participant or the experimenter) performing the SRTT during the acquisition phase but without making overt motor or vocal responses themselves. Only afterwards, in a test phase, do the observers respond for themselves to the same stimuli as the model participant. In this way, evidence for implicit sequence learning by observation alone has been found (e.g., Bird, Osman, Saggerson, & Heyes, 2005; Heyes & Foster, 2002; Howard, Mutter, & Howard, 1992; Seger, 1997; Song, Howard, & Howard, 2008; Willingham, 1999). However, some observational sequence learning is in fact attributable to active hypothesis testing, as evoked by an intentional instruction (e.g., in the study of Song et al., 2008). In other studies, explicit sequence knowledge was elevated, indicating that learning may have been explicit rather than implicit. In fact, no observational sequence learning has been reported to date in studies specifically designed to eliminate explicit knowledge, for example by having participants perform a secondary (nonassociated) tone-counting task (Kelly & Burton, 2001; Kelly, Burton, Riedel, & Lynch, 2003). Therefore, there is no evidence for implicit sequence learning by observation alone without intention or without emergence of substantial explicit knowledge.

Another way to investigate the learning of a single stream of information is the simultaneous presentation of separate, uncorrelated sequences. For example, in a study by Mayr (1996), partic-

ipants responded to a target's identity rather than its location. Both the target identities and the target locations were determined by repeating sequences. These sequences were of different lengths and, thus, were uncorrelated. This arrangement was intended to allow for separate learning of a perceptual–motor sequence (stimulus identity is attended and linked to key presses), and, more important, a single-stream perceptual sequence (stimulus locations are ignored and not linked to key presses). Mayr (1996) found evidence for learning the single-stream location sequence. However, it appears that there may actually have been a secondary sequenced stream of information that correlated with the location sequence. An additional occulomotor sequence existed in the form of eye movements associated with the stimulus location changes on the screen. Although the locations were not relevant for making responses, participants needed to see where the stimuli were in order to identify what they were. Similarly, Dennis, Howard, and Howard (2006) provided evidence for learning a single-stream auditory sequence. However, the auditory sequence was, in fact, composed of both a sequenced stream of stimulus exemplars and a correlated sequenced stream of speaker identities, as each stimulus word was spoken by a different voice. In other studies in which purely single-stream sequences were used, no evidence was found of implicit learning of single-stream visual sequences (Deroost & Soetens, 2006; Willingham, Nissen, & Bullemer, 1989), single-stream auditory sequences (Riedel & Burton, 2006), or single-stream temporal sequences (Shin & Ivry, 2002). Therefore, these studies provided no evidence for implicit learning based on a single sequenced stream of information.

Taken together, findings from these studies are largely consistent with the correlated streams account (Meier & Cock, 2010). However, an alternative model has been proposed by Keele et al. (2003). In their comprehensive framework of the cognitive and neural architecture of sequence learning, Keele et al. (2003) distinguished between a unidimensional learning system and a multidimensional learning system. The unidimensional learning system is thought to consist of a set of modules, each of which is restricted to learning information along a single dimension (i.e., a single stream of information). In contrast, the multidimensional system is thought to build associations between events from different dimensions. However, it operates only when there is a reliable prediction among events of different dimensions, that is, when the dimensions are correlated (i.e., correlated streams of information). The multidimensional system is constrained by a selective attention mechanism, and only task-relevant streams are integrated. Randomly varying events within a task-relevant stream of information are thought to be disruptive and to prevent learning within the multidimensional system but not within the unidimensional system. The dual-system approach is mainly supported by evidence from dual-task SRTT studies (Keele et al., 2003), in which performing an SRTT on its own is compared with performing an SRTT with an accompanying tone-counting task. The presence of a secondary tone-counting task with randomly ordered stimuli is supposed to have a disruptive effect on the multidimensional system but not on the unidimensional system. However, the evidence cited by Keele et al. (2003) does not rule out the correlated streams account. Even under dual-task conditions, at least two sets of modules within the unidimensional system seem to be activated whenever sequence learning effects are reported: one to process the spatial information stream and a second to process the

motor information stream. Thus, Keele et al. (2003) provided no evidence for learning within only one module of the unidimensional system. Therefore, we suggest that even within the unidimensional system, the presence of two correlated streams might be essential for implicit sequence learning to occur.

There is also evidence against the generality of the correlated streams account. For example, statistical learning studies have provided evidence for single-stream sequence learning (e.g., Saffran, Aslin, & Newport, 1996; Saffran, Johnson, Aslin, & Newport, 1999; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). In these studies, participants were exposed to a stream of continuous and highly structured sounds while performing another task. Later, they were asked to make forced-choice recognition decisions between old and new sequence fragments. The results showed that participants became sensitive to the statistical properties of the material. There are obvious similarities between implicit sequence learning and statistical learning. For example, structured material is learned in incidental learning situations and without engaging analytical processes or hypothesis-testing strategies (Perruchet & Pacton, 2006). However, statistical learning studies focus on learning statistical properties rather than on learning the more complex kind of sequences that are typically used in SRTT and task sequence learning studies.

Clearly, further research is needed to test the limitations of the correlated streams account. For example, it is possible that single-stream sequences can be learned with more training, an intentional learning orientation, or other paradigms. In conclusion, the present findings provide evidence that implicit task sequence learning is related to the presence of correlated streams of information and is neither attributable to learning a single stream of perceptual stimulus features nor to learning a single stream of task sets. Thus, at least in implicit task sequence learning, the presence of two correlated streams of information seems to be a prerequisite for learning to occur.

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(*Appendix follows*)

Appendix

Switch Cost Analyses

Switch costs analyses were restricted to the random test blocks and to the *seqseq* conditions because sequence learning occurred only in these conditions. Mean error rates and RTs are shown in Table A separately for sequenced blocks (13, 14, 17, and 18) and random blocks (16 and 17). Within each experiment, we analyzed error rates and RTs in separate $2 \times 2 \times 2$ ANOVAs with within-subject factors relation of tasks (same vs. different), relation of mappings (same vs. different), and block (sequenced vs. random).

Switch Costs in Experiment 1

For error rates, the effect of task was significant, indicating higher error rates in task switch trials compared to task repetition trials, $F(1, 15) = 10.11, p = .006, \eta^2 = .40$. The Task $\times$ Mapping interaction was also significant, $F(1, 15) = 9.15, p = .009, \eta^2 = .38$. The difference between task repetition and task switch trials was larger when the mapping was repeated than when it was switched. Importantly, no interactions with the factor block were significant (all ps > .40). This indicates that there was no difference in error switch cost profiles between sequenced and random blocks.

For RTs, the effect of task was significant, indicating higher RTs in task switch trials compared with task repetition trials, $F(1, 15) = 44.59, p < .001, \eta^2 = .75$. The Task $\times$ Mapping interaction

was also significant, $F(1, 15) = 34.70, p < .001, \eta^2 = .70$. The RT difference between task repetition and task switch trials was larger when the mapping was repeated than when it was switched. The effect of block was also significant, indicating slower RTs in random than in sequenced blocks, $F(1, 15) = 61.69, p < .001, \eta^2 = .80$. No interaction with the factor block was significant (all ps > .25). This indicates that there was no difference in RT switch cost profiles between sequenced and random blocks.

Switch Costs in Experiment 2

For error rates, the effect of mapping was significant, $F(1, 17) = 14.91, p = .001, \eta^2 = .47$, indicating higher error rates in mapping switch trials than in mapping repetition trials. The Task $\times$ Mapping interaction was also significant, $F(1, 17) = 4.68, p = .045, \eta^2 = .22$. The difference between mapping repetition and mapping switch trials was larger when the task was repeated than when it was switched. No other effects and no interactions with the factor block were significant (all ps > .45). This indicates that the error switch cost profiles of sequenced and random blocks were similar.

For RTs, the effect of task and the effect of mapping were significant, $F(1, 17) = 13.19, p = .002, \eta^2 = .44$, and $F(1, 17) = 27.72, p < .001, \eta^2 = .62$, indicating slower RTs in task switch than in task repetition trials and slower RTs in mapping switch than in mapping repetition trials. The Task $\times$ Mapping interaction

Table A

Switch Costs in Experiments 1, 2, and 3: Mean Error Rates and Response Times in Sequenced (13, 14, 17, 18) and Random (15, 16) Blocks Shown as a Function of Relations Between Successive Task–Mapping Combinations

Experiment/ combination	Error rates (proportion)				Response times (ms)			
	Sequenced blocks		Random blocks		Sequenced blocks		Random blocks	
	M	SE	M	SE	M	SE	M	SE
Experiment 1								
T = M =	.008	.003	.016	.007	555	48	773	35
T = M ≠	.024	.007	.028	.006	819	34	987	46
T ≠ M =	.032	.008	.043	.014	1,077	96	1,206	79
T ≠ M ≠	.021	.005	.020	.005	912	57	1,091	75
Experiment 2								
T = M =	.025	.003	.026	.004	717	35	822	32
T = M ≠	.045	.004	.047	.005	1,035	78	1,132	78
T ≠ M =	.032	.003	.035	.004	988	86	1,096	90
T ≠ M ≠	.039	.004	.039	.005	1,001	56	1,181	89
Experiment 3								
T = M =	.019	.002	.022	.003	737	24	863	42
T = M ≠	.048	.004	.058	.005	1,007	54	1,078	57
T ≠ M =	.029	.003	.031	.004	978	63	1,038	53
T ≠ M ≠	.036	.004	.041	.004	1,030	49	1,127	67

Note. For Experiments 2 and 3, only data of the *seqseq* conditions are shown. T = task; M = mapping; same (=); different (≠).

was also significant, $F(1, 17) = 11.66$, $p = .003$, $\eta^2 = .41$. The RT difference between task repetition and task switch trials was larger when the mapping was repeated than when it was switched. The effect of block was also significant, indicating slower RTs in random blocks than in sequenced blocks, $F(1, 17) = 33.13$, $p < .001$, $\eta^2 = .66$. No interactions with the factor block were significant (all ps > .35). This indicates that the RT switch cost profiles of sequenced and random blocks were similar.

Switch Costs in Experiment 3

For error rates, the effect of mapping was significant, indicating higher error rates in mapping switch trials than in mapping repetition trials, $F(1, 19) = 13.23$, $p = .002$, $\eta^2 = .41$. The Task $\times$ Mapping interaction was also significant, $F(1, 19) = 5.43$, $p = .031$, $\eta^2 = .22$. The difference between mapping repetition and mapping switch trials was larger when the task was repeated than when it was switched. Additionally, the effect of block was significant, $F(1, 19) = 7.29$, $p = .014$, $\eta^2 = .28$. Generally, error rates were higher in random blocks than in sequenced blocks.

There were no significant interactions with the factor block (all ps > .05), which indicates that the error switch cost profiles were similar between blocks.

For RTs, the effect of task and the effect of mapping were significant, $F(1, 19) = 18.07$, $p < .001$, $\eta^2 = .49$, and $F(1, 19) = 36.33$, $p < .001$, $\eta^2 = .66$, indicating slower RTs in task switch than in task repetition trials and slower RTs in mapping switch than in mapping repetition trials. The Task $\times$ Mapping interaction was also significant, $F(1, 19) = 14.89$, $p = .001$, $\eta^2 = .44$. The RT difference between task repetition and task switch trials was larger when the mapping was repeated than when it was switched. The effect of block was also significant, indicating slower RTs in random blocks than in sequenced blocks, $F(1, 19) = 19.58$, $p < .001$, $\eta^2 = .51$. No interactions with the factor block were significant (all ps > .25). This indicates that the RT switch cost profiles of sequenced and random blocks were similar.