



# Are correlated streams of information necessary for implicit sequence learning?

Beat Meier <sup>\*,1</sup>, Josephine Cock

Department of Psychology, University of Bern, Switzerland

## ARTICLE INFO

### Article history:

Received 16 December 2008  
Received in revised form 31 July 2009  
Accepted 6 August 2009  
Available online 29 August 2009

### PsycINFO classification:

2330  
2340  
2343

### Keywords:

Incidental learning  
Implicit learning  
Sequence learning

## ABSTRACT

We investigated whether the existence of correlated streams of information is necessary for incidental sequence learning to occur. We ran three separate experiments with a total of 201 undergraduate students. Each experiment had at least one condition with two streams of sequenced information that were correlated. The correlations differed in terms of the kind of responses that were required, the kind of tasks and stimuli, the on-screen locations at which they occurred and how they were combined. Only in conditions with correlated sequences was implicit sequence learning found. Our results suggest that the presence of correlated streams of information may be the main pre-requisite for implicit sequence learning.

© 2009 Elsevier B.V. All rights reserved.

## 1. Introduction

People do not necessarily need to be aware of sequential regularities in the environment in order to profit from them. A simple example, from driving a car, would be the faster readiness to move off at a road intersection by automatically anticipating the order of traffic light changes. To study implicit learning ability of this kind experimentally, a serial reaction time task (SRTT) is generally used. In the standard sequence learning paradigm, a sequence of correct response key presses follows the sequence of designated target locations (cf. Nissen & Bullemer, 1987). Unbeknownst to participants, the order of target locations follows a sequence predetermined by the experimenter. With practice, performance gets faster compared to a randomised control condition. If the sequence is switched to random, performance is slowed again. These changes are taken as evidence of implicit sequence learning.

Although there has been considerable effort to explain what kind of mental or motor representation drives implicit sequence learning, there is still no consensus on what is involved. We suspect it is related to the fact that in most experiments there is an inevitable correlation between the sequence of stimuli to which partici-

pants must attend and the sequence of motor movements/key presses with which participants must respond. In order to disentangle the correlation between stimuli and responses, we used a task sequence learning paradigm in a previous study (Cock & Meier, 2007). We combined a hidden task sequence with an independent hidden sequence of left (L) vs. right (R) key presses, where hand-side corresponded directly to the binary-choice of the tasks. Specifically, we used three simple binary-choice tasks that involved univalent perceptual stimuli (i.e. “is this fuzzy figure red or blue?”, “is this letter upper- or lowercase?” and “is this shape curved or angular?”). Learning effects were found only when the two sequences were of the same length, that is, when they were correlated. We concluded that in this condition participants became sensitive to the emerging ordering of the six perceptual categories (e.g. “red – curved – uppercase – angular – blue – lower-case”), but not the ordering of the higher level tasks per se (e.g. “colour – shape – letter – shape – colour – letter”). In other words, performance was stimulus driven, but contingent on supportive L vs. R motor key presses. The results of the Cock and Meier study suggested that, in this instance, learning was based on percepts rather than concepts, even though we used a task sequence learning paradigm.

### 1.1. Uncorrelated sequences

To be clear, we would like to point out that we are not claiming that uncorrelated sequences cannot be learned without intention or awareness in an incidental way. Indeed, there is experimental

\* Corresponding author. Address: Department of Psychology, University of Bern, Muesmattstr. 45, 3000 Bern 9, Switzerland. Tel.: +41 31 631 40 39; fax: +41 31 631 82 12.

E-mail address: [beat.meier@psy.unibe.ch](mailto:beat.meier@psy.unibe.ch) (B. Meier).

<sup>1</sup> Both authors contributed equally to this paper.

evidence of the simultaneous implicit learning of separate, that is, concurrent but uncorrelated, sequences (Mayr, 1996; cf. Shin & Ivry, 2002). Mayr, for example, presented two such sequences, one embedded in the ordering of the on-screen locations at which stimuli occurred (locations corresponding to the corners of an imaginary square with side lengths 22 cm), the other identity based (stimuli comprising different graphic shapes presented in a non-obvious sequential order). Participants responded to the identity sequence (and not location) by pressing specific keys, with specific fingers that corresponded to specific stimuli. In this way, there existed a sequence of key presses that correlated with the sequence of different kinds of stimuli. Additionally, by processing the stimuli at different locations, participants made repetitive head movements in the direction of each particular stimulus location on the screen. Mayr found that participants became sensitive to both the spatial sequence (location based) and the non-spatial sequence (identity based), which were of different lengths. Hence, it may appear that sequence correlation is not a pre-requisite to learning. However, we think this is simply a misunderstanding: although the sequences (location based and identity based) were not related, they each correlated separately with other concurrent streams of sequenced information.

### 1.2. Hidden correlated sequences

In order to avoid a hidden sequence of stimulus-related head movements, Willingham (1999) presented the digits “1” to “4” centrally on-screen. They were mapped onto four different response keys from left to right. The results showed transfer from a centrally presented sequence of digits to a corresponding visuo-spatial sequence of locations (i.e. where the far left screen location corresponded to “1” and the far right corresponded to “4”). Although, at first glance, Willingham’s study could be interpreted as evidence of single-sequence learning with no other correlated streams of information present, we would point out that there was actually a concurrent and matching motor key-press response sequence in existence. Furthermore, processing numerical magnitudes and visuo-spatial information are functionally connected (Göbel, Walsh, & Rushworth, 2001). Semantic representations of numbers are spatially defined on an imaginary mental number line and the visuo-spatial coding of numbers along this line has been shown to occur automatically (i.e. spatial-numerical association of response codes or SNARC-effect; Dehaene, Bossini, & Giraux, 1993). Therefore, processing the number stimuli from “1” to “4” would have evoked a corresponding mental number line which was directly consistent with the physical layout of the four response keys. We suggest that the transfer effect depended on this correlation.

In a modified version of the SRTT, Goschke, Friederici, Kotz, and van Kampen (2001, Experiment 2) found that five patients with Broca’s aphasia were able to learn a key-press sequence but not a phoneme sequence, whilst matched controls learned both. However, we would point out that although the sequences were run independently, both arrangements comprised two correlated streams. For example, for the key-press condition, there was an on-screen visuo-spatial display of 4 letters shown at different locations, as well as a keyboard arrangement of 4 buttons (isomorphic to the letters) for motor responses. For the phoneme condition, there was an instructive vocalized letter stream (different letters having to be attended on different trials), as well as the on-screen perceptual images of the same letters which the participants needed to identify (perhaps with the aid of subvocalizing) before pressing the appropriate key on each trial. In the former condition, the letters and key presses followed a changing location-based sequence, whereas the order of the attended letters (phonemes) was random. In the latter condition, it was the opposite. Goschke et al.

suggested that the difference in results might stem from partially separable brain systems underlying the learning of the different types of sequence. We would suspect that the Broca’s aphasia patients (who performed much more slowly than the controls) were impaired at using the correlation that existed between the auditory letter stream and the visual letter stream.

Shin and Ivry (2002) investigated whether a hidden temporal sequence, linked to the timing of stimulus events and responses, could be learned using the standard implicit sequence learning paradigm. In one condition, but not in another, a temporal sequence was correlated with the motor-spatial response sequence. Shin and Ivry’s results showed motor-spatial response sequence learning in both conditions, but the temporal sequence was learned only in the correlated condition, in which overall sequence learning was also enhanced. We suggest, therefore, that the temporal sequence needed the accompanying motor-spatial stream of information for it to be processed in such a way that it could be learned implicitly. This listing is not exhaustive. However, it is representative and it supports our hypothesis that the presence of correlated sequences is a pre-requisite of implicit sequence learning.

### 1.3. Task sequence learning with bivalent stimuli

In classical SRTT experiments, stimuli and responses are correlated by design. In order to avoid this correlation, we used a sequence of binary decision tasks combined with a separate sequence of L vs. R hand key-press responses. This enabled us to investigate whether the presence of a stream of correlated sequences is a pre-requisite for sequence learning. It is only recently that studies have been conducted on whether it is possible to become sensitive, without awareness, to a sequence of conceptually based tasks (Gotler, Meiran, & Tzelgov, 2003; Heuer, Schmidtke, & Kleinsorge, 2001; Koch, 2001). These studies – rooted in the domain of “task-switching” – have consistently reported sequence learning effects, and these effects did not affect switch costs (i.e. learning is similar for switch and repetition trials). As is usual in most task-switching studies, bivalent stimuli were used (for exceptions see Meier, Woodward, Rey-Mermet, and Graf (in press), Ruthruff, Remington, and Johnston (2001), and Woodward, Meier, Tipper, and Graf (2003)). As bivalent stimuli have properties relevant to more than one task, it was necessary for the experimenters to provide participants with instructional cues about which task to perform next. As a consequence, a sequence of cues also existed and this was correlated with the sequence of tasks. Hence, task sequence learning effects that have been found might be attributable to implicit learning of the task sequence (i.e. automatic task-set activation), learning of the cue sequence (i.e. perceptual learning), or a combination thereof. Inevitably, in task sequence learning studies that use bivalent stimuli, there is always a corresponding correlated sequence of instructional task cues.

Gotler et al. (2003) conducted a study in which two different types of instructional task cues were used (horizontal vs. vertical arrows and horizontal vs. vertical lines). In one condition, cue type was held constant, and in the other it varied at random. The results showed no difference in sequence learning between conditions and were interpreted as evidence for a task-set activation account. However, because the two types of instructional cues were perceptually rather similar, we think it is still possible that the learning of a generalized, perceptually based sequence of cues occurred. Whatever the explanation, we suspect that it is the existence of correlated streams of information that facilitates learning.

### 1.4. Task sequence learning with univalent stimuli

In our recent study on task sequence learning (Cock & Meier, 2007), we introduced univalent stimuli for the first time. As univa-

lent stimuli are unique to each task, no instructional task cues were necessary. We presented participants with three simple binary-choice tasks. For coloured fuzzy figures, a colour decision was required (red vs. blue), for geometrical forms, a shape decision was required (curved vs. angular) and for letters, a case decision was required (uppercase vs. lowercase). Participants responded with a single key-press (one of two specific keys), using their left or right index finger. Using an orthogonal design, we combined the presence or absence of a sequence of tasks with the presence or absence of a sequence of required L vs. R responses. The most important result was that learning occurred only when the task sequence and the response sequence were both present, that is, when there were two concurrent and correlated streams of information in the materials. Sequence learning occurred only in conditions where concurrent sequences were correlated. If sequences were of different lengths, no sequence learning occurred.

### 1.5. The present study

The purpose of the present study was to ascertain whether the existence of correlated streams of information is a pre-requisite for implicit sequence learning. We ran three separate experiments. Each experiment had (at least) one condition with two streams of sequenced information that were correlated. By correlated we mean sequences with mathematically compatible structures (such as identical length) that can be predictably parsed in each cycle of each sequence according to *crosswise* as well as *lengthwise* associations between components. Hence, events in one sequence can predict events in the other and integrative processing is facilitated. The correlations differed in terms of the kind of responses that were required, the kind of tasks and stimuli, the on-screen locations at which they occurred and how they were combined. Our binary-choice design enabled us to unconfound sequence correlation and the isomorphic stimulus–response arrangement that is usually found in SRTT experiments (Nissen & Bullemer, 1987).

In Experiment 1, we examined what happens when a sequence of conceptual rather than perceptual categories arises from the correlation of a task sequence and a key-press response sequence. This was achieved by using written words as stimuli, instead of shapes, letters and figures as in our previous study (Cock & Meier, 2007). The words belonged to three conceptual category decisions, namely, “animal”-decisions, “implement”-decisions, and “plant”-decisions. Each decision task had two stimulus categories, namely, “birds” and “mammals”, “musical instruments” and “kitchen utensils”, and “trees” and “flowers”, respectively. Depending on the stimulus that was presented on any trial, participants made L or R key-press responses, for example, L for a “bird” but R for a “mammal”. The same two keys were used for all three tasks. By task sequence, in this experiment, we refer to the order in which the decision tasks (i.e. “animal”-decision, “implement”-decision, and “plant”-decision) were presented. The task on each trial was to decide which category the stimulus belonged to, and then to respond L or R according to the stimulus category. In addition to the task sequence, we ran a L vs. R binary-choice response sequence. The design of Experiment 1 was, therefore, much the same as in Cock and Meier (2007) even though the materials were very different. The use of conceptual rather than perceptual stimulus categories was entirely new. Each subdivision comprised 16 different exemplars, for example, “oak”, “fir”, “beech” for trees, which varied at random. As a consequence, just looking at a word is not enough to make the relevant response discrimination. Participants must first transform the perceptual symbol into a meaningful concept. For example, “oak” must be understood as belonging to the conceptual category “tree”. In contrast, with more perceptual stimuli such as a red colour patch no further mental transformation is required to perform the colour decision task.

In Experiment 2, we introduced an on-screen stimulus location sequence (left, middle and right presentations). This was separately combined with two different correlated streams of information: first, a correlated sequence of binary-choice tasks together with a random L vs. R key-press response order and second, the opposite, a correlated L vs. R key-press response sequence together with a random binary-choice task order. We also ran a single-sequence condition, in which only the stimulus location order was sequenced, as well as a control condition in which all three streams were random. We predicted that implicit sequence learning effects would only be found in the first two conditions of Experiment 2. In Experiment 3, we replicated the first condition of Experiment 2, but we first removed any association between particular locations and particular tasks, thereby eliminating a potential confound effect in the sequence learning. In all three experiments, learning effects were found exclusively in conditions where correlated sequences were present.

## 2. Experiment 1

The aim of Experiment 1 was to establish whether implicit sequence learning occurs when stimuli are conceptual rather than perceptual (as in Cock & Meier, 2007) and whether two streams of correlated information are a pre-requisite for such learning. By conceptual stimuli, we refer to pre-existent semantic categories, namely “plants”, “animals” and “implements”, exemplars of which are presented to participants as written words, such as “orchid”, “bear”, and “knife”. On each trial, the participant must decide which of the 3 categories is being presented, then make a binary-choice between two subdivisions. For example, if the stimulus is a “plant” (rather than an “animal” or an “implement”), the participant must then press the R key if it is a “flower” but the L key if it is a “tree”. In this way, we are able to run a *task sequence*, a required *response sequence*, and, in the case where these two sequences were correlated, a *sequence of conceptually based stimulus categories*.

### 2.1. Method

#### 2.1.1. Participants and design

Eighty undergraduate students (41 females and 39 males, mean age 24.4 years, SD = 5.5) from the University of Bern took part in return for course credit. Twenty participants were assigned at random to one of four experimental conditions: *correlated sequences (tasks and responses)*, *one sequence (tasks)*, *one sequence (responses)*, and *no sequences (control)*. Task order and response order were manipulated between subjects, whilst block was manipulated within subjects, resulting in a mixed design.

#### 2.1.2. Materials

For the *correlated sequences (tasks and responses)* and the *one sequence (tasks)* conditions, task order was sequenced according to one of two different 6-element repeating cycles (i.e. “plants – animals – implements – animals – plants – implements”, or “implements – plants – animals – plants – implements – animals”, counterbalanced within condition). For the *one sequence (responses)* and the *no sequences (control)* conditions, a pseudo-random, but statistically comparable, order of tasks was created. There were no consecutive task repeats (sequenced or random orders), transitions between tasks were ambiguous, and each task occurred equally often in each block.

For the *correlated sequences (tasks and responses)* and the *one sequence (responses)* conditions, L vs. R key-press response order was sequenced according to one of two different 6-element repeating cycles (i.e. “L–R–L–L–R–R”, or, “R–L–R–R–L–L”, counterbalanced

within condition). For the *one sequence (tasks)* and the *no sequences (control)* conditions, a pseudo-random, but statistically comparable, order of responses was created. This excluded long runs of either L or R key-press responses. Switch and repeat response transitions occurred at the same rate in both the sequenced and the pseudo-random orderings.

The stimulus categories had sixteen exemplars each (i.e. 16 “trees”, 16 “flowers”, 16 “birds”, 16 “mammals”, 16 “kitchen utensils”, and 16 “musical instruments”). Depending on tasks and trials, presentation of these exemplars varied at random.

Stimuli were presented in German and shown in black 18-point courier new font, against a pale grey background, at the centre of a 15 in. monitor, connected to an IBM-compatible computer with an external response pad. Viewing distance was approximately 50 cm. The experiment was programmed in E-Prime (<http://www.pst-net.com/e-prime>).

### 2.1.3. Procedure

For the *implements* task, participants pressed a designated L key (with their left index finger) for a “musical instrument” and a designated R key (with their right index finger) for a “kitchen utensil”. For the *plants* task, participants pressed the (same) designated L key (with their left index finger) for a “tree” and the (same) designated R key (with their right index finger) for a “flower”. For the *animals* task, they pressed the (same) L key (with their left index finger) for a “bird” and the (same) R key (with their right index finger) for a “mammal”. Two initial practice blocks (one comprising 48 random trials and one comprising 96 random trials) were used to train participants on the stimulus to response key mappings. The participants were instructed to respond as quickly and as accurately as possible. They were told that if they made mistakes, they should simply continue. When the participant was ready, the experimenter pressed a key to initiate the blocks of trials. Each stimulus remained on-screen until the participant pressed a response key, followed by an interval of 250 ms before presentation of the next stimulus. The practice blocks were followed by four experimental blocks (blocks 3–6, each comprising 96 trials) and one pseudo-random block (block 7, 96 trials). In block 8, the original ordering was reinstated. There was a brief pause between blocks. No feedback on performance was provided. After the test session, which lasted approximately 20 min, a *structured interview* was carried out to assess explicit knowledge of the sequences. Participants were first asked about the possible presence of sequenced information. Next, as appropriate, they were asked to verbally reproduce whatever they could still remember or guess of each of the sequences they had received (*sequence generation trials*). For data analysis, responses were individually compared to the actual sequences that were presented.

### 2.1.4. Data analysis

Decision-task trials on which errors were made were excluded from analysis. Average error rate was less than 5% throughout and comparable between conditions. Reaction time (RT) data for the three tasks were aggregated and median RTs per block were computed for each participant. Decreasing RTs over blocks 3–6 were taken as directly indicative of a general training effect, also possibly including some sequence learning. *Training scores* were calculated, in milliseconds, for each participant, as the RT difference between performance at block 3 and performance at block 6. Increased RTs at block 7 (where sequences were simultaneously changed to separately created pseudo-random ordering) were taken as indirectly indicative of sequence learning. *Disruption scores* were calculated, in milliseconds, as the RT difference between performance at block 7 and mean performance at surrounding blocks 6 and 8. For statistical analyses, an alpha level of .05 was used. De-

grees of freedom and MSE values were Greenhouse-Geisser adjusted where appropriate. Effect sizes are partial  $\eta^2$  values.

## 2.2. Results

The results are shown in Fig. 1. RTs decreased initially for all groups. Mean *training scores* (mean difference in RTs between blocks 3 and 6) were 136 ms (SE = 45) for the *correlated sequences (tasks and responses)* condition, 67 ms (SE = 21) for the *one sequence (tasks)* condition, 110 ms (SE = 21) for the *one sequence (responses)* condition, and 74 ms (SE = 17) for the *no sequences (control)* condition. Inspection of blocks 6–8 indicates that only participants in the *correlated sequences (tasks and responses)* condition appear to have been significantly disrupted by random block 7. Mean *disruption scores* (difference in RTs between mean of block 7 and mean of surrounding blocks 6 and 8, individually averaged) were 125 ms (SE = 39) for the *correlated sequences (tasks and responses)* condition, 5 ms (SE = 9) for the *one sequence (tasks)* condition, 13 ms (SE = 11) for the *one sequence (responses)* condition, and 0 ms (SE = 13) for the *no sequences (control)* condition. *Training and disruption scores* are also summarized in Supplementary Table 1.

Statistical analyses were conducted separately for blocks 3–6 and blocks 6–8. A mixed two-factorial ANOVA with blocks 3–6 as within-subjects factor and conditions as between-subjects factor, revealed a significant main effect of block  $F(3, 228) = 26.6$ ,  $MSE = 5034$ ,  $p < .01$ ,  $\eta^2 = .26$ . No other effect was significant,  $F_s < 1.2$ .

Another mixed two-factorial ANOVA comparing RTs at block 7 to mean RTs of surrounding blocks 6 and 8 revealed a significant main effect of block,  $F(1, 76) = 10.67$ ,  $MSE = 4725$ ,  $p < .01$ ,  $\eta^2 = .12$ , and a significant block  $\times$  condition interaction,  $F(3, 76) = 7.54$ ,  $p < .01$ . To locate the source of this interaction, we conducted post hoc Tukey HSD tests on the *disruption scores*. This revealed that the *correlated sequences (tasks and responses)* condition differed from the three other conditions (all  $t_s(38) > 2.7$ ,  $p_s < .01$ ), but the latter did not differ from one another (all  $t_s < 1$ ).

When questioned afterwards, 10% of all participants suspected that there was a task sequence, *correlated sequences (tasks and responses)* = 10%, *one sequence (tasks)* = 15%, *one sequence (responses)* = 5%, and *no sequences (control)* = 10%. Forty-five percent of all participants suspected that there was a L vs. R response sequence, *correlated sequences (tasks and responses)* = 14%, *one sequence (tasks)* = 7%, *one sequence (responses)* = 14%, and *no sequences (control)* = 10%. One participant in the *correlated sequences (tasks and responses)* condition correctly reported the whole task sequence, the whole L vs. R response sequence, and, when probed, the whole *stimulus groups* sequence (i.e. sequence of category subdivisions) (*disruption score* = 437 ms). Two other participants in the *correlated sequences (tasks and responses)* condition, one of whom suspected that there was a task sequence and one of whom did not, reported it correctly (*disruption scores* = 199 and 301 ms). Yet two other participants in the *correlated sequences (tasks and responses)* condition, who suspected that there was a L vs. R response sequence (but not a task sequence), reported it correctly (*disruption scores* = 22 and 172 ms). Two participants in the *one sequence (tasks)* condition, who did not suspect that there was a task sequence, reported it correctly (*disruption scores* = 60 and –23 ms). Three participants in the *one sequence (responses)* condition, who suspected that there was a L vs. R response sequence, reported it correctly (*disruption scores* = –22, 33 and –110 ms).

Next, all participants with potentially relevant explicit knowledge (i.e. those who correctly generated one or more of the sequences they had received either with or without reporting that there was a sequence at all) were excluded from the analysis. This resulted in mean *disruption scores* of 91 ms (SE = 45) for the *corre-*

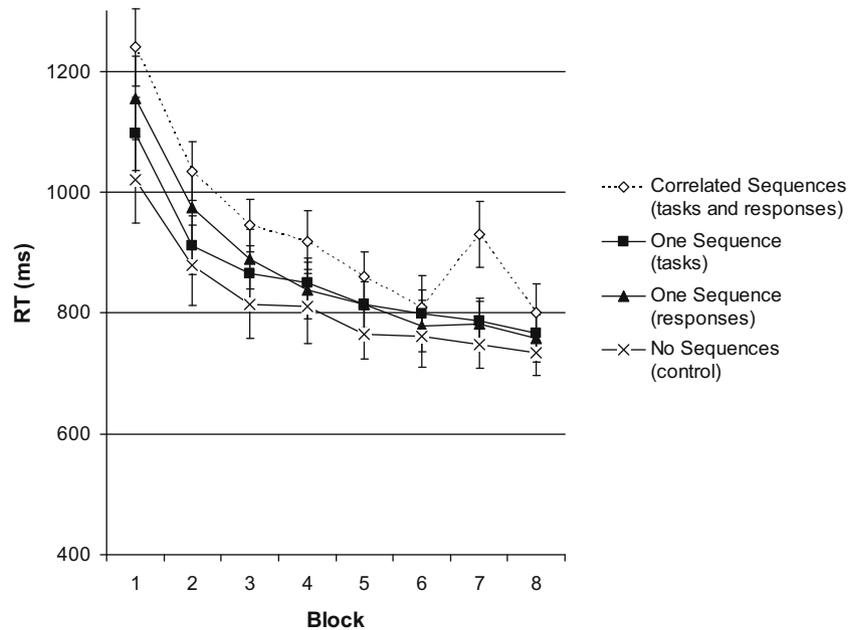


Fig. 1. Mean reaction times in Experiment 1. Error bars represent standard errors.

lated sequences (tasks and responses) condition ( $n = 15$ ), 3 ms ( $SE = 10$ ) for the one sequence (tasks) condition ( $n = 18$ ), and 21 ms ( $SE = 9$ ) for the one sequence (responses) condition ( $n = 17$ ). A one-way ANOVA on these revised disruption scores gave  $F(3, 69) = 3.59, p = .018$ . Directed comparisons showed that the correlated sequences (tasks and responses) condition was significantly different from the one sequence (tasks) and the no sequences (control) conditions ( $ps < .01$ ), and marginally different from the one sequence (responses) condition ( $p = .07$ ). The one sequence (tasks), the one sequence (responses) and the no sequences (control) conditions did not differ from one another (all  $ps > .88$ ).

In order to assess chance level performance, “sequence knowledge” of participants in those conditions without sequences was also analyzed. Thirty percent of those who did not receive any task sequences still generated at least 4 elements in the same order as one of the experimental task sequences, with two persons per condition guessing all 6 elements correctly. On average these participants guessed, in the correct order, 3 out of 6 elements of a relevant task sequence. For the LR responses, 80% of those participants who did not receive any sequencing in this stream still generated at least 4 elements in the same order as one of the experimental response sequences, with 1 or 2 persons per condition guessing all 6 elements correctly. On average these participants guessed, in the correct order, 4 or 5 out of 6 elements of a relevant LR response sequence. Taken together, these figures show that it would be possible to achieve an apparently high score for explicit knowledge without any explicit knowledge being present.

### 2.3. Discussion

The purpose of Experiment 1 was to test whether implicit sequence learning effects can be found when conceptual rather than perceptual tasks are used and whether the existence of correlated streams of information is important. There was no indication that either the task sequence itself, or the L vs. R response sequence itself, was learned in an incidental way. In fact, the two single-sequence experimental conditions, one sequence (tasks) and one sequence (responses), were statistically indistinguishable from the no sequences (control) condition. However, as predicted, in the combined-streams condition, correlated sequences (tasks and responses), we found implicit sequence learning effects in terms of

significant disruption of RTs at block 7, and this was not easily attributable to explicit rather than implicit knowledge.

Our finding for the correlated sequences condition, using conceptual rather than perceptual tasks and stimuli, would appear to relate to the fact that the streams could be successfully integrated (Schmidtke & Heuer, 1997). Unlike the other conditions in Experiment 1, the correlated sequences (tasks and responses) arrangement gives rise to perfect predictability of each consecutive task and of each consecutive L or R response. In this condition only, there arises another perfectly predictable sequence of stimulus categories (e.g. “tree” – “mammal” – “instrument” – “bird” – “flower” – “utensil”). This third sequence comprises a repeating cycle with unique transitions. We think that it is this sequence of stimulus categories that is learned, with learning facilitated by the synchronised motor key-press responses. Furthermore, the learning is unlikely to be purely perceptual because each subdivision has 16 different word exemplars which vary at random. Participants may produce a series of semantic labels for the conceptual stimulus categories, and as a consequence learn the order of these (i.e. “tree” – “mammal” – “instrument” – “bird” – “flower” – “utensil”). We conclude, therefore, that participants in the correlated sequences group learned the ordering of the conceptual stimulus categories and this learning was dependent on the existence of correlated streams of information.

In our previous study, using the same basic design but letters, shapes and colours rather than words, we argued in favour of a more perceptual kind of learning. However, in view of the results presented here, it would seem that the effect can generalize to conceptual stimulus categories as well. An alternative possibility, however, would be that instead of the existence of a sequence of stimulus categories with an isomorphic sequence of corresponding key-press responses the presence of two correlated streams of any kind of information would be sufficient to give rise to implicit sequence learning. We addressed this hypothesis in Experiment 2.

### 3. Experiment 2

If the mere presence of two correlated sequences is sufficient for the occurrence of implicit sequence learning, then it will be found even when there is no direct correspondence between a se-

quence of stimuli and a concurrent sequence of responses, provided there are, at least, two correlated streams of some kind are present. To do this, we introduced an on-screen stimulus location sequence (left, middle and right presentations). This was separately combined with either a sequence of binary-choice tasks together with a random L vs. R key-press response order or with the opposite, a sequence of L vs. R key-press responses together with a random binary-choice task order. We also ran a single-sequence condition, in which only the stimulus location order was sequenced, as well a control condition in which all three streams were random. We predicted that implicit sequence learning effects would only be found in the first two conditions of Experiment 2. We did not expect to find implicit sequence learning in a single-sequence condition in which only the locations were sequenced (i.e. sequences of tasks and responses both random), nor in a control condition in which all three streams were random. For practical reasons we used the perceptual stimuli and tasks as in our previous study, that is, red and blue figures for colour decisions, lowercase and uppercase letters for letter decisions and rounded and angular shapes for shape decisions (cf. Cock & Meier, 2007).

### 3.1. Method

#### 3.1.1. Participants and design

Ninety five participants (74 females, 21 males, mean age = 23 years, SD = 4, range 19–45 years) from the University of Bern took part in return for course credit. Participants were assigned at random to one of four conditions. In one condition we presented a series of three binary-choice decision tasks in a pseudo-random order, with required L vs. R key-press responses also in a separate pseudo-random order. We refer to this condition as the *one sequence (locations)* condition. The on-screen locations at which the stimuli occurred (left, middle and right) were, unbeknownst to participants, in a sequenced order. In two other experimental conditions, either stimulus locations and tasks (but not L vs. R key-press responses) or stimulus locations and L vs. R key-press responses (but not tasks) were sequenced in a counterbalanced way. These are referred to as the *correlated sequences (locations and tasks)* and the *correlated sequences (locations and responses)* conditions. In the fourth condition, referred to as the *no sequences (control)* condition, presentation order of all three streams of information was entirely pseudo-random. Conditions were manipulated between subjects. Blocks of trials were manipulated within subjects, giving a mixed design.

#### 3.1.2. Materials

Stimuli were approximately 4 × 3 cm in size, and shown against a white background (cf. Cock & Meier, 2007). For the *letter task* (“lowercase” vs. “uppercase”), 6 different letters were used, for the *shape task* (“rounded” vs. “angular”), 6 different geometric shapes were used, and for the *colour task* (“red” vs. “blue”), 6 different fuzzy figures were used. An example of each type is shown in Fig. 2. Where sequenced, task order followed one of two repeating 6-element cycles (i.e. “letter – colour – shape – colour – letter – shape” and “colour – shape – letter – shape – colour – letter” for counterbalancing). There were no consecutive task repeats. Transitions between tasks were ambiguous (cf. Cohen, Ivry, & Keele, 1990; Shanks & Channon, 2002). In terms of frequency and distribution of transitions, the pseudo-random task order was made statistically comparable to the sequenced task order. Where sequenced, the required L vs. R key-press response order followed a repeating 6-element cycle (“L–R–L–L–R–R” or the reverse “R–L–R–R–L–L” for counterbalancing). In terms of frequency, distribution and consecutive response repeats, the pseudo-random L–R response order was made statistically comparable to the sequenced L vs. R response order. Where sequenced (both experimental con-

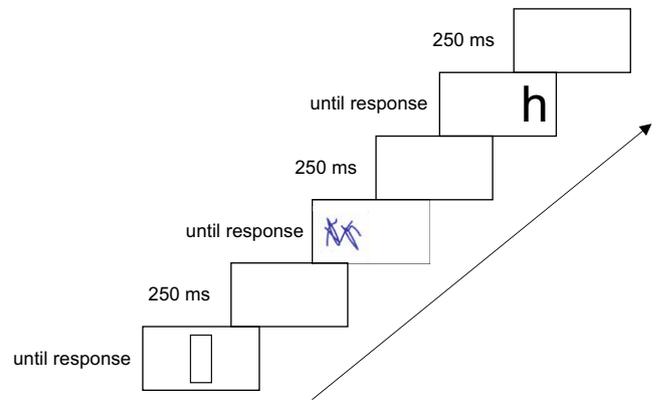


Fig. 2. Example of procedure and stimuli for Experiment 2. The fuzzy figures for the colour decision were printed in either red or blue. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

ditions), stimulus location order followed a repeating 6-element cycle which determined where the stimuli were physically presented on the screen (“left-middle-right-middle-left-right”). The middle on-screen stimulus location was centred vertically and horizontally. Left and right side locations were positioned approximately three degrees of visual angle left and right of the middle location.

#### 3.1.3. Procedure

Participants were tested individually, with instructions given verbally and on-screen. They were told that we were interested in the effects of practice on speed of performance in simple decision tasks. They were informed that on some trials they would be required to identify the colour of fuzzy figures (“red” vs. “blue”), on other trials the form of geometric shapes (“curved” vs. “angular”), and on yet other trials the format of letters (“lowercase” vs. “uppercase”). For red fuzzy figures, uppercase letters and curved geometric shapes, participants were instructed to press a designated right-hand side key with their right index finger. For blue fuzzy figures, lowercase letters and angular geometric shapes, the participants were instructed to press a designated left-hand side key with their left index finger. The same two keys were used for all three tasks. No mention was made of the changing locations at which the stimuli were presented. Two initial practice blocks (one comprising 48 random trials and one comprising 96 random trials) were used to train participants on the stimulus to response key mappings. As in Experiment 1, these were followed by four experimental blocks (blocks 3–6) and one pseudo-random block (block 7). In block 8, the original ordering was reinstated.

Participants were instructed to respond as quickly and as accurately as possible. They were told that if they made mistakes, they should simply continue. When the participant was ready, the experimenter pressed a key to initiate the blocks of trials. Each stimulus remained on-screen until the participant pressed a response key, followed by an interval of 250 ms before presentation of the next stimulus. There was a brief pause between blocks.

After the test session, which lasted approximately 20 min, a *structured interview* was carried out to assess explicit knowledge of the sequences (i.e. tasks, L vs. R responses and stimulus locations). This included three *sequence generation trials* (for each kind of sequence) in which participants reproduced verbally whatever they thought they could still remember or guess of the sequences they had received. For data analysis, the responses were individually compared to the actual sequences that were presented.

### 3.2. Results

The RT results are shown in Fig. 3. RTs decreased initially for all groups. Mean training scores (mean difference in RTs between blocks 3 and 6) were 52 ms (SE = 13) for the *correlated sequences (locations and tasks)* condition, 51 ms (SE = 11) for the *correlated sequences (locations and responses)* condition, 88 ms (SE = 20) for the *one sequence (locations)* condition, and 51 ms (SE = 13) for the *no sequences (control)* condition.

Mean *disruption scores* (mean difference in RTs between block 7 and the average of blocks 6 and 8) were 34 ms (SE = 7) for the *correlated sequences (locations and tasks)* condition, 25 ms (SE = 8) for the *correlated sequences (locations and responses)* condition, 0 ms (SE = 5) for the *one sequence (locations)* condition, and –3 ms (SE = 5) for the *no sequences (control)* condition. Training and disruption scores are also summarized in [Supplementary Table 1](#).

Statistical analyses of the RTs were conducted separately for blocks 3–6 and 6–8. A mixed two-factorial ANOVA with blocks 3–6 as within-subject factor and condition as between-subject factor revealed a significant main effect of block,  $F(3, 273) = 46.14$ ,  $MSE = 1433$ ,  $p < 0.001$ ,  $\eta^2 = 2.34$ . No other effect was significant, all  $F_s < 1.3$ .

Another mixed two-factorial ANOVA comparing mean RTs at block 7 to the mean RTs of surrounding blocks 6 and 8 revealed a significant main effect of block,  $F(1, 91) = 19.38$ ,  $MSE = 473$ ,  $p < .01$ ,  $\eta^2 = .18$ , and a significant block  $\times$  group interaction,  $F(3, 91) = 8.34$ ,  $p = .01$ ,  $\eta^2 = .22$ . Post hoc Tukey HSD tests on the *disruption scores* at block 7 revealed that the significant difference between conditions pertained to both *correlated sequences conditions* compared to the *one sequence (locations)* condition,  $t_s(46) > 2.7$ ,  $p_s < .01$ , as well as compared to the *no sequences (control)* condition,  $t_s(45) > 3$ ,  $p_s < .01$ . There was no significant difference between the two conditions with *correlated sequences*, and no difference between the *one sequence (locations)* condition and the *no sequences (control)* condition (all  $t_s < 1$ ).

Thirty-four percent of all participants suspected that there was a task sequence, with *correlated sequences (locations and tasks)* 25%, *correlated sequences (locations and responses)* 28%, *one sequence (locations)* 46%, and *no sequences (control)* 38%. Fifty-two percent of

all participants suspected that there was a L vs. R response sequence, with *correlated sequences (locations and tasks)* 41%, *correlated sequences (locations and responses)* 58%, *one sequence (locations)* 58%, and *no sequences (control)* 52%. Thirty-two percent of all participants suspected that there was a stimulus location sequence, with *correlated sequences (locations and tasks)* 38%, *correlated sequences (locations and responses)* 29%, *one sequence (locations)* 33%, and *no sequences (control)* 26%.

In the *correlated sequences (locations and tasks)* condition, one participant, who suspected that there was a task sequence, reported it correctly (*disruption score* = 78 ms). A different participant, who suspected that there was a stimulus location sequence, reported it correctly (*disruption score* = 82 ms). Still in this condition, two other participants reported the stimulus location sequence correctly (*disruption scores* = 26 and 56 ms). In the *correlated sequences (locations and responses)* condition, six participants, who suspected that there was a L vs. R response sequence, reported it correctly (*disruption scores* = 96, –22, 85, –68, 16, and 27 ms), as did another three participants (*disruption scores* = 8, 45, and 22 ms). None of the participants in the *correlated sequences (locations and responses)* condition reported the stimulus location sequence correctly. In the *one sequence (locations)* condition, one participant, who suspected that there was a stimulus location sequence, reported it correctly, as did one other participant (*disruption scores* = 2 and –7 ms, respectively).

When all participants with potentially relevant explicit knowledge (i.e. those who correctly generated one or more of the sequences they had received either with or without reporting that there was a sequence at all) were excluded from the analysis, mean *disruption scores* became 29 ms (SE = 8) for the *correlated sequences (locations and tasks)* condition ( $n = 20$ ), 27 ms (SE = 7) for the *correlated sequences (locations and responses)* condition ( $n = 15$ ), and 0 ms (SE = 5) for the *one sequence (locations)* condition ( $n = 22$ ). A one-way ANOVA on these revised *disruption scores* revealed a significant effect, with  $F(3, 76) = 7.23$ ,  $p < .01$ . Directed comparisons showed that the significant difference between conditions, in terms of the disruption at block 7, pertained to both *correlated sequences conditions* compared to the *one sequence (locations)* condition, as well as compared to the *no sequences (control)* condition

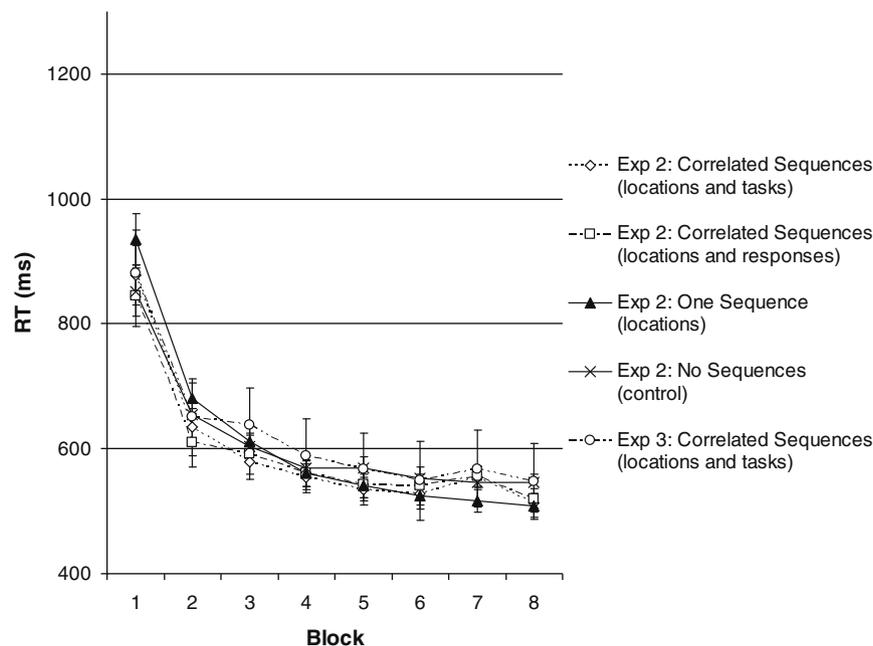


Fig. 3. Mean reaction times in Experiments 2 and 3. Error bars represent standard errors.

(both  $ps < .05$ ). There was no significant difference between the two conditions with *correlated sequences*, and no difference between the *one sequence (locations)* condition and the *no sequences (control)* condition ( $ps > .90$ ).

As in Experiment 1, to assess chance level performance, “sequence knowledge” of participants in those conditions without sequences was also analyzed. Forty percent of those participants who did not receive any task sequence still generated at least 4 elements in the same order as one of the experimental task sequences, with one person per condition guessing all 6 elements correctly. On average they guessed, in the correct order, 3 out of 6 elements of a relevant task sequence. For the L R responses, 100% of those participants who did not receive any sequencing in this stream still generated at least 4 elements in the same order as one of the experimental response sequences, with 2–3 persons per condition guessing all 6 elements correctly. On average they guessed, in the correct order, 4 or 5 out of 6 elements of a relevant L R response sequence. Finally, for the randomly ordered location sequence (control condition), 43% of the participants generated at least 4 elements in the same order as the experimental location sequence but none of them guessed all 6 elements correctly. On average they guessed, in the correct order, 3 or 4 out of 6 elements of the relevant location sequence. Taken together, these figures show that it is possible to generate at least half of any of the sequences used in this study entirely by chance.

### 3.3. Discussion

In Experiment 2, implicit sequence learning occurred only in the conditions where two correlated sequences were present. This result supports the hypothesis that the existence of correlated streams of information is important for implicit sequence learning. It matches the results of Experiment 1 of the present study, as well as those of our previous study (Cock & Meier, 2007). It is also consistent with other works which have found task sequence learning using bivalent stimuli and task cues (Gotler et al., 2003; Heuer et al., 2001; Koch, 2001). Together, these results suggest that it is the presence of correlated streams of information and not the existence of a sequence of stimulus categories per se, that is at the core of implicit sequence learning.

With the possible exception of one participant, incidental rather than intentional learning took place and the resultant knowledge was generally implicit rather than explicit. Implicit sequence learning almost invariably gives rise to some explicit awareness of the presence, but not necessarily the structure, of a sequence – either as a result of conscious intention to learn or by spontaneous observation (e.g. Cleeremans, Destrebecqz, & Boyer, 1998; Frensch & Rüniger, 2003; Rüniger & Frensch, 2008; Shanks & St. John, 1994). However, in the *one sequence condition*, there was only chance level awareness of the existence of a stimulus location sequence and no sign of sequence learning except for one participant who seemed to have explicit rather than implicit knowledge. This result further supports the hypothesis that the stimulus location sequence was not learned in an incidental way because it was not correlated with any other sequenced stream of information.

Although Experiment 2 clearly demonstrated implicit sequence learning effects in the correlated sequences conditions, it could be argued that the disruption of participants’ RTs at block 7 occurred for a different reason. In fact, the task sequence and the stimulus location sequence were not only correlated but also had the same underlying structure (i.e. they were isomorphic). For example, for the task sequence “colour – shape – letter – shape – colour – letter” and the location sequence “left – middle – right – middle – left – right”, stimuli for the colour task were always presented at the left location, stimuli for the shape task always at the middle location, and stimuli for the letter task always at the right location. As a con-

sequence, participants might have learned that there was a correspondence between tasks and locations (similar to the classical SRTT). At block 7, the task sequence and the location sequence were switched, at the same time, to separately pseudo-randomized orders. This change in task and location consistency could, therefore, have affected the sequence learning disruption effect. In order to exclude the possibility that disruption in the *correlated sequences (locations and tasks)* of Experiment 2 was due to this inherent sequence feature, in Experiment 3, we re-ran this one condition without the isomorphic relation between task sequence and stimulus location sequence.

## 4. Experiment 3

The procedure for Experiment 3 was identical to the *correlated sequences (locations and tasks)* of Experiment 2, except that a different sequence of locations was used which had no isomorphic relationship to the sequence of tasks.

### 4.1. Method

#### 4.1.1. Participants

Twenty six undergraduate students (23 females and 3 males, mean age = 24 years, SD = 8, range = 19–47 years) from the University of Bern took part in return for course credit.

#### 4.1.2. Materials and apparatus

These were exactly as in Experiment 2, *correlated sequences (locations and tasks)* condition, except for the order of the stimulus locations. The stimulus location sequence was “middle – right – middle – left – right – left”, which resulted in a correlated, but not isomorphic, relationship with both of the task sequences that were used for counterbalancing (i.e. “letter – colour – shape – colour – letter – shape” and “colour – shape – letter – shape – colour – letter”). The L vs. R key-press response sequence was pseudo-random as in Experiment 2.

#### 4.1.3. Procedure and data analysis

These were as in Experiment 2.

### 4.2. Results

The RT results are also shown in Fig. 3, labelled *correlated sequences (locations and tasks) Experiment 3*. The mean *training score* (mean difference in RTs between blocks 3 and 6) was 89 ms (SE = 16). The mean *disruption score* (mean difference in RTs between block 7 and the average of blocks 6 and 8) was 20 ms (SE = 6), see also Supplementary Table 1.

Statistical analyses were conducted separately for blocks 3–6 and 6–8. A one-way repeated measures ANOVA across blocks 3–6 (within subjects), revealed a significant main effect of block,  $F(3, 75) = 22.41$ ,  $MSE = 1709$ ,  $p < 0.01$ ,  $\eta^2 = .47$ . A separate one-way repeated measures ANOVA (within subjects) comparing RT performance on block 7 and the mean of surrounding blocks 6 and 8 revealed a significant main effect of block,  $F(1, 25) = 10.27$ ,  $MSE = 478$ ,  $p < .01$ ,  $\eta^2 = .29$ . An independent samples  $t$ -test, comparing *disruption scores* of the *correlated sequences (locations and tasks)* in Experiment 3 ( $n = 26$ , mean *disruption score* = 20 ms, SE = 6) with those of the *correlated sequences (locations and tasks)* in Experiment 2 ( $n = 24$ , mean *disruption score* = 51 ms, SE = 11) revealed no significant difference,  $t(48) = 1.5$ ,  $p > .10$ .

When interviewed afterwards, 11% of the participants (three out of 26) suspected that there was a task sequence and a separate stimulus location sequence, but they were unable to generate either correctly. Fifteen percent (a different four participants) sus-

pected that there was a task sequence but not a stimulus location sequence. Fifteen percent (yet another four participants) suspected the reverse. None of these 8 participants was able to generate either sequence correctly. In fact, none of the 26 participants reported the whole stimulus location sequence correctly. Just two participants, who were not amongst those referred to above, correctly generated the whole task sequence (*disruption scores* = –3 and 50 ms). Removing these two data sets from the analysis did not change the overall *disruption score* group mean.

#### 4.3. Discussion

Experiment 3 provided a clear result. Our hypothesis was confirmed that participants exposed to correlated sequences would show learning effects, in terms of significantly longer RTs, when the sequences were switched to pseudo-random. The possibility that disruption of performance was due to a confounding effect, namely a loss of previous consistency between stimulus locations and particular tasks, was ruled out in Experiment 3. Furthermore, the learning effect could not easily be attributed to explicit sequence knowledge.

### 5. General discussion

The present study was designed to test whether the existence of correlated sequences is necessary for implicit sequence learning. In Experiment 1, we showed that the presence of a sequence of conceptual tasks with verbal materials combined with the presence of a correlated sequence of required response key presses gave rise to implicit sequence learning. The mere presence of a single-sequence of tasks or required responses did not result in implicit sequence learning. This result extends previous findings in which implicit learning was found for a sequence of perceptual tasks with an emphasis on surface features combined with a correlated sequence of key-press responses (Cock & Meier, 2007). It suggests that the presence of correlated streams of information is at the core of implicit sequence learning rather than the learning of a response-related sequence of stimulus features or categories. It seems that, as long as at least two correlated streams are present, the sequences embedded in them can be of any kind. In Experiment 2, we introduced an on-screen stimulus location sequence which was separately combined with a correlated sequence of binary-choice tasks and a random L vs. R key-press response order, or with a correlated L vs. R key-press response sequence and a random binary-choice task order. We also ran a single-sequence condition, in which only the stimulus location order was sequenced, as well as a control condition in which all three streams were random. The results showed implicit sequence learning only in the conditions where two correlated sequences were present. In Experiment 3, we re-ran a condition of Experiment 2, with the exclusion of a potential confound between task sequence and correlated stimulus location sequence. The results replicated the finding from Experiment 2.

In all three experiments, implicit learning was found exclusively in conditions where correlated sequences were present. The overall observation was that the presence of a single stream of sequenced information did not result in sequence learning – no matter what kind of stimuli or responses was involved. This applied to the presence of a single-sequence of tasks and a single-sequence of required responses in Experiment 1 and the presence of a single-sequence of stimulus locations in Experiment 2. The fact that the single-sequence conditions failed to show implicit learning strengthens our argument that correlated streams are a prerequisite. One reason may be that with an accompanying random stream, performance cannot easily become proceduralized. From

dual task experiments on sequence learning it is well known that the presence of a secondary task is disadvantageous when the primary and the secondary tasks have a random relation (Cock, Berry, & Buchner, 2002; Riedel & Burton, 2006; Schmidtke & Heuer, 1997). The lack of predictability in an accompanying random stream may inhibit the participant's learning of any sequenced information by putting constraints on working memory and disrupting the formation of associative links between streams of information.

However, from dual task experiments on sequence learning it is also known that the presence of a secondary task is advantageous when it has a systematic relation to the primary sequence. Similarly, an “irrelevant response effect” occurs when an additional, redundant stream of tones is presented in sequence learning experiments. Hoffmann, Sebald, and Stoecker (2001) and Stoecker, Sebald, and Hoffmann (2003) found that if tones were introduced in a classical SRTT and these tones were mapped onto the SRTT responses contingently, serial learning was improved. This improvement occurred despite the fact that the tones were irrelevant to the task at hand (i.e. pressing the keys according to the screen location of the stimulus). Both the advantageous effects of a compatible secondary task and the irrelevant response effects are easily accounted for by the correlated sequences explanation. They indicate that two correlated streams are necessary for learning and that adding yet another can further facilitate performance.

The “irrelevant response effect” suggests that even a seemingly unattended stream of information can affect sequence learning. The results from Experiments 2 and 3 of the present study (*correlated sequences, locations and tasks and correlated sequences, locations and responses*) offer a similar conclusion. Participants showed sequence learning even though one of the correlated streams comprised a stimulus location sequence which did not need overt responses. In other words, participants could perform the binary-choice tasks without paying deliberate attention to the ordering of the stimulus locations. These findings seem to contrast with the results and conclusions from Jimenez and Mendez (1999) who suggested that deliberate selective attention to the predictive dimension was necessary. We would point out that, in the critical conditions our present study, processing the stimulus locations was mandatory for performing the decision tasks. It is possible, therefore, that for sequence learning to occur, participants must attend to the separate components of each stream as part of the experimental requirements. However, that does not mean that participants must pay deliberate attention to the sequenced ordering of a stream of information, or that they need to be aware of it.

The present study also adds to the issue of whether sequence learning is possible in the absence of a sequence of responses (cf. Ziessler & Nattkemper, 2001). The results from Experiment 2 of the present study (*correlated sequences, locations and tasks condition*) indicate that this can be the case. When the sequences of locations and tasks were correlated learning occurred in the absence of an overt response. However, we would like to point out that this conclusion depends on the precise definition of what a response is. We would argue that even in experiments in which no overt response is required to perform a task (listen to a sequence of words, e.g. Hartman, Kopelman, & Nissen, 1989; or observing a sequence of stimuli, e.g. Willingham, 1999) a cognitive response, in the sense of an acknowledgement of information that is present, must be made in order to process the stimuli. Using a more lenient definition of a “response”, our finding of sequence learning in the *correlated sequences, locations and tasks condition* could simply be interpreted as further evidence that implicit sequence learning can occur without an overt motor response.

Although sequence learning did not occur in single-sequence conditions in the present study, we cannot exclude that under dif-

ferent conditions learning of this kind might be found, for example, as a result of more extensive training, or with a different kind of sequence structure (i.e. with longer runs of repetitions and/or alternations). Moreover, it is possible that different kinds of materials and different procedures might also give rise to single-sequence learning. For instance, Saffran, Johnson, Aslin, and Newport (1999) exposed their participants to a stream of continuous and highly structured sounds, in the absence of any other obviously correlated stream of information. Later the participants were required to make forced choice recognition decisions between old and new sequence fragments. The results showed that they were able to classify these fragments reliably above chance level. Fiser and Aslin (2002) also investigated whether sensitivity to the probabilities of temporally ordered visual stimuli can develop automatically. They exposed their participants to a continuous stream of shapes. Later the participants were required to make forced choice recognition decisions about sequence fragments. The results showed that sequences of shapes, presented during a familiarization phase, were reliably distinguished afterwards from sequences that were never, or very rarely, seen during familiarization. Basically, the results of these studies show that, after explicit exposure to a single stream of information, observers can become sensitive to probabilities of single elements, to the joint probabilities of successive pairs, and even to conditional probabilities of successive pairs, when tested with forced recognition (Fiser & Aslin, 2002; Saffran et al., 1999). Furthermore, the single stream studies reported so far seem to be more about the learning of statistical properties per se than the representation of complex and comprehensively structured sequences as are typically used in SRTT studies.

Hunt and Aslin (2001) combined the learning of statistical probabilities with a novel version of the SRTT. The set-up involved pairs of lights and matching pairs of keys arranged in a semicircular array and participants were exposed to several probabilistic sequence triplets. Obviously, using this kind of set-up, two streams of correlated information were present, namely, the visuo-spatial transitions to and between lighted pairs of buttons that corresponded to the elements of the sequences on which participants were being trained, and the corresponding motor-spatial task of moving their hand back and forth to these buttons from a central “home” point on the keyboard. Participants were trained for an hour a day over several consecutive days and RTs were recorded. The results showed that learning occurred at several different levels, including a global level conforming to the predictability of single elements and a local level characterized by clusters of elements. Moreover, this study also supports the importance of correlated streams of information in implicit sequence learning.

In a further development of the SRTT, Goschke and Bolte (2007) used easy-to-name line-drawings of simple objects from four different semantic categories. In three experiments the semantic categories were presented in a repeated order while the specific stimulus for each trial was selected randomly. Participants had to name the specific stimulus on each trial as fast as possible. The results showed that naming latencies decreased across the sequenced blocks, however, when the order of the semantic categories was switched to random, latencies increased – an indication of sequence learning. Although these results would seem to show single-sequence learning, it is possible that participants subvocally verbalized the categories. In fact, this strategy was experimentally instructed in Experiment 1, and the pattern of this experiment was not different to the subsequent experiments where these instructions were not given. It certainly seems possible that at least some of the participants verbalized the categories, perhaps even unintentionally and without awareness. This other stream would complement the sequence of visually presented categories by providing a supportive sequence of sub-vocally verbalized categories with the two being perfectly correlated. Using such a strat-

egy would be a powerful way of creating two correlated streams from a single stream condition. It could apply to a variety of tasks and in many different contexts. Such a strategy may not only be at the core of implicit sequence learning, but it may be highly beneficial for explicit sequence learning. For example, a participant might be able to create a subjective stream of information that comprises anticipated, verbalizable (or imaginable) sequence components. This subjective stream can be “tested” against the objective stream that comprises the single-sequence of events to which the participant is exposed.

While the mechanisms for implicit and explicit sequence learning may turn out to be somewhat similar in the end, the focus of the present study is clearly on implicit learning. There is still the possibility, of course, that explicit rather than implicit knowledge was acquired in our present set of experiments. However, how to measure explicit knowledge remains an unsettled issue (cf. Shanks & St. John, 1994). In the present study we used a short structured interview immediately after the experiment and this gave no obvious indication that sequence learning was explicit. Roughly 10% of participants in each experimental condition where learning was found also had some relevant awareness of sequences in the materials. When they were excluded from analysis, learning effects were still very significant. Therefore we are inclined to believe that explicit knowledge was not the source of sequence learning in the present study. Furthermore, the results from the structured interview revealed that even in those conditions where no sequence was present, participants could still generate at least half of each experimental sequence purely by guessing. Consequently, sequence reproduction might not be the most reliable way of assessing genuine explicit knowledge. Seemingly relevant explicit knowledge might be inflated by uninformed guesswork.

In summary, our results provide evidence that implicit learning is not restricted to the acquisition of simple associations between specific perceptual stimuli, or indeed between specific stimuli and specific responses, but that a fairly complex sequential structure underlying a sequence of perceptual stimuli can be learned implicitly as well. In addition, we demonstrate that sequence learning can occur even when no overt motor response to the particular sequence components is required. However, the learning effects we have found were restricted to conditions in which two correlated sequences were present and hence, we conclude that the presence of correlated streams of information is an important pre-requisite for implicit sequence learning.

## Acknowledgements

We thank Alodie Rey-Mermet, Sibylle Matter, and Nicolas Rothen for assistance with data collection and management, and Brigitte Weiermann for valuable comments on an earlier version of the manuscript. This research was supported in part by a grant from the Swiss National Science Foundation (Grant 120580) to B. Meier.

## Appendix A. Supplementary data

A supplementary table of combined results associated with this article can be found, in the online version, at [doi:10.1016/j.actpsy.2009.08.001](https://doi.org/10.1016/j.actpsy.2009.08.001).

## References

- Cleeremans, A., Destrebecqz, A., & Boyer, M. (1998). Implicit learning: News from the front. *Trends in Cognitive Sciences*, 2, 406–416.
- Cock, J., Berry, D. C., & Buchner, A. (2002). Negative priming and sequence learning. *European Journal of Cognitive Psychology*, 14, 27–48.
- Cock, J., & Meier, B. (2007). Incidental task sequence learning: Perceptual rather than conceptual? *Psychological Research*, 71, 140–151.

- Cohen, A., Ivry, R. I., & Keele, S. W. (1990). Attention and structure in sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 17–30.
- Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, 122, 371–396.
- Fiser, J., & Aslin, R. N. (2002). Statistical learning of higher-order temporal structure from visual shape-sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28, 458–467.
- Frensch, P. A., & Rüniger, D. (2003). Implicit learning. *Current Directions in Psychological Science*, 12, 13–18.
- Göbel, S., Walsh, V., & Rushworth, M. F. S. (2001). The mental number line and the human angular gyrus. *Neuroimage*, 14, 1278–1289.
- Goschke, T., & Bolte, A. (2007). Implicit learning of semantic category sequences: Response-independent acquisition of abstract sequential regularities. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 33, 394–406.
- Goschke, T., Friederici, A. D., Kotz, S. A., & van Kampen, A. (2001). Procedural learning in Broca's aphasia: Dissociation between the implicit acquisition of spatio-motor and phoneme sequences. *Journal of Cognitive Neuroscience*, 13, 370–388.
- Gotler, A., Meiran, N., & Tzelgov, J. (2003). Nonintentional task set activation: Evidence from implicit task sequence learning. *Psychonomic Bulletin and Review*, 10, 890–896.
- Hartman, M., Kopelman, D. S., & Nissen, M. J. (1989). Implicit learning of new verbal associations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15, 1070–1082.
- Heuer, H., Schmidtke, V., & Kleinsorge, T. (2001). Implicit learning of sequences of tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 27, 967–983.
- Hoffmann, J., Sebald, A., & Stoecker, C. (2001). Irrelevant response effects improve serial learning in serial reaction time tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 27, 470–482.
- Hunt, R. H., & Aslin, R. N. (2001). Statistical learning in a serial reaction time task: Access to separable statistical cues by individual learners. *Journal of Experimental Psychology: General*, 130, 658–680.
- Jimenez, L., & Mendez, C. (1999). Which attention is needed for implicit sequence learning? *Journal of Experimental Psychology: Learning, Memory and Cognition*, 25, 236–259.
- Koch, I. (2001). Automatic and intentional activation of task sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 27, 1474–1486.
- 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.
- Meier, B., Woodward, T. S., Rey-Mermet, A., & Graf, P. (in press). The bivalency effect in task switching: General and enduring. *Canadian Journal of Experimental Psychology*.
- Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, 19, 1–32.
- Riedel, B., & Burton, A. M. (2006). Auditory sequence learning: Differential sensitivity to task relevant and task irrelevant sequences. *Psychological Research*, 70, 337–344.
- Rüniger, D., & Frensch, P. A. (2008). How incidental sequence learning creates reportable knowledge: The role of unexpected events. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 34, 1011–1026.
- Ruthruff, E., Remington, R. W., & Johnston, J. C. (2001). Switching between simple cognitive tasks: The interaction of top-down and bottom-up factors. *Journal of Experimental Psychology, Human Perception and Performance*, 27, 1404–1419.
- Saffran, J. R., Johnson, E. K., Aslin, R. N., & Newport, E. L. (1999). Statistical learning of tone sequences by human infants and adults. *Cognition*, 70, 27–52.
- Schmidtke, V., & Heuer, H. (1997). Task integration as a factor in secondary-task effects on sequence learning. *Psychological Research*, 60, 53–71.
- Shanks, D. R., & Channon, S. (2002). Effects of a secondary task on “implicit” sequence learning: Learning or performance? *Psychological Research*, 66, 99–109.
- Shanks, D. R., & St. John, M. F. (1994). Characteristics of dissociable human learning systems. *Behavioral and Brain Sciences*, 17, 367–447.
- Shin, J. C., & Ivry, R. B. (2002). Concurrent learning of temporal and spatial sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28, 445–457.
- Stoecker, C., Sebald, A., & Hoffmann, J. (2003). The influence of response-effect compatibility in a serial reaction time task. *The Quarterly Journal of Experimental Psychology*, 56, 685–703.
- Willingham, D. B. (1999). Implicit motor sequence learning is not purely perceptual. *Memory and Cognition*, 27, 561–572.
- Woodward, T., Meier, B., Tipper, C., & Graf, P. (2003). Bivalency is costly: Bivalent stimuli elicit cautious responding. *Experimental Psychology*, 50, 233–238.
- Ziessler, M., & Nattkemper, D. (2001). Learning of event sequences is based on response-effect learning: Further evidence from a serial reaction task. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 27, 595–613.