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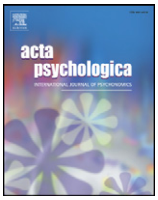

Only correlated sequences that are actively processed contribute to implicit sequence learning

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ABSTRACT

The purpose of the study was to investigate how implicit sequence learning is affected by the presence of secondary information that is correlated with the primary sequence but not necessarily relevant to performance. In a previous work, we have shown that correlation plays an important role but other prerequisites may also be involved. In Experiments 1 and 2, using a task sequence learning paradigm, we found that primary sequence learning was not affected by secondary information that was sequenced but irrelevant to performance, even though the two streams of information were correlated. In contrast, in Experiment 3, we found that sensitivity to the main sequence was greater with the provision of extra sequenced information that was relevant to performance in addition to being correlated. This suggests that sequence learning was enhanced through the integration of information. We conclude that information in secondary as well as primary sequences must be actively processed if it is to have a beneficial impact. By actively processed we mean information that is selectively attended and necessary for carrying out the tasks.

1. Introduction

Only some of our daily activities and experiences happen at random, many conform to routine sequences. Although our routines often grow out of habits that we set up ourselves, some of the sequences we follow are not of our own making. We learn about them through daily exposure. For example, on leaving for work, I usually meet my neighbor in the entrance hall before I pick up the newspaper. Then I walk to the train station. Mostly, I take the same route and cross the street at the same spot. I come across the same people in the same places at the same times and even the flow of traffic is largely predictable. None of this regularity is a deliberate construction, and yet, I come to learn the sequence without an intention to do so. In the laboratory, just as in the real world, implicit sequence learning is about sensitivity to environmental regularities and the order in which they occur. In recent years, a *task sequence learning* (TSL) paradigm has been used to investigate this sensitivity (e.g., Heuer, Schmidtke, & Kleinsorge, 2001; Koch, 2001). In the present study, we used a TSL paradigm to investigate whether implicit sequence learning is affected by the presence of another correlated sequence that is either relevant or not to performance.

The TSL design facilitates the inclusion of more than one sequence in a single serial reaction time task (SRTT). In fact, the TSL paradigm can be considered as an extension of the SRTT which was introduced to the literature by Nissen and Bullemer (1987). In the standard SRTT paradigm, which is known to give rise to robust sequence learning, there are two streams of information, namely, a visuo-spatial order of stimuli and motor-spatial order of key presses. Both these streams are sequenced and response-relevant. In the TSL paradigm, participants respond to a series of different intermixed tasks which are organized into blocks of stimulus–response trials. For example, they may be required to respond to stimulus size on the first trial, to stimulus form on the second trial, to stimulus color on the third trial, and so forth. Unbeknownst to participants, the order of the tasks is determined by a repeating sequence. However, within each task, the actual stimuli, such as different shapes or different letters, are presented at random. The stimuli belong to particular groups, or categories, as chosen by the experimenters. As in the standard SRTT, response times decrease with practice and increase again substantially when the sequence is replaced by a random order of tasks or an untrained sequence. This increase is taken as indirect evidence of learning of the task sequence, or at least sensitivity to some aspects of it. In the case of TSL, post-experimental assessment of awareness reveals that knowledge of the task sequence remains mostly implicit rather than explicit.

Task sequence learning has now been found across a variety of different tasks and stimuli (Cock & Meier, 2007; Gotler, Meiran, & Tzelgov, 2003; Heuer et al., 2001; Koch, 2001; Koch, Philipp, & Gade, 2006; Meier & Cock, 2010; Weiermann, Cock, & Meier, 2010). For example, in one of our previous studies we used a TSL paradigm involving three categorical classification tasks. We presented participants with a written stimulus word that belonged to one of three tasks (animals, implements,

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or plants). Within each task, participants were required to distinguish between two different stimulus categories (birds vs. mammals, musical instruments vs. kitchen utensils, and trees vs. flowers). They responded by pressing one of two specific keys (left vs. right), with the same keys used for all three tasks. Across participants, the presence or absence of a task sequence was orthogonally manipulated with that of a response sequence. Sequence learning was only found in the condition where a task sequence and a response sequence were both present. However, correlation between the tasks and the responses resulted in a third sequence consisting of stimulus categories. For example, a task order such as "plants–animals–implements–animals–plants–implements" combined with a same-length response order such as "left–right–left–left–right–right" lead to a stimulus category order of "tree–mammal–musical instrument–bird–flower–kitchen utensil". By stimulus categories we refer to the groupings of stimuli that are represented at a lower level than the tasks, that is, items with a common feature, such as red shapes or curved letters (Cock & Meier, 2007) or green or red digits presented above or below the fixation mark (Heuer et al., 2001; Weiermann et al., 2010) or different exemplars of birds and musical instruments (Meier & Cock, 2010). It has already been established that the presence of such a stimulus category sequence per se is not necessary for implicit TSL to occur as long as correlated streams of information exist (i.e., tasks and task cues in Gotler et al., 2003; Koch, 2001; Koch et al., 2006, and tasks and stimulus locations in Meier & Cock, 2010, Experiments 2 and 3). However, it is still possible that the existence of a secondary sequence, such as a stimulus category sequence, might have an impact on the primary sequence learning because it represents an additional correlated stream of information.

The purpose of the present study was to investigate whether sequence learning would be affected by the presence of a secondary sequence that was either irrelevant (Experiments 1 and 2) or relevant (Experiment 3) to performance. This question was motivated by our TSL-studies, however, it is strongly related to a more general question in implicit learning, namely whether the mere exposure to sequenced information affects learning. It has been shown in the SRTT literature that irrelevant sequences are not usually learned (Abrahamse, van der Lubbe, & Verwey, 2009; Jiménez & Méndez, 1999; Schmidtke & Heuer, 1997, among others). However, it is not always clear whether "irrelevant" refers to a lack of relation between streams of information that exist in the materials or task requirements, or a lack of necessity to attend to that information. In this study, by irrelevant, we mean that on any given trial stimuli in a secondary stream did not *need* to be processed in order to carry out the primary task. The secondary sequence had a different structure to the primary sequence but they were related by having the same number of elements (i.e., same length and hence correlated). We hypothesized that, in this way, seemingly "irrelevant" information might become "relevant" through the integration of information (see Berner & Hoffmann, 2009; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Mayr, 1996; Riedel & Burton, 2006; Schmidtke & Heuer, 1997; Shin & Ivry, 2002, for related discussions). By integration, we refer to the combined processing of all possible associations between the correlated streams (e.g., stimulus–stimulus, response–response, stimulus–response, response–stimulus, task–task, task–response, response–task, etc.). The repeated processing of these associations provides more structure to what is learned and consequently, the presence of an additional stream of information would enrich this structure and would enhance learning.

With a more highly structured learning environment arising from the presence of correlation, it is easy to see how a secondary stimulus sequence can become integrated with the primary sequence — and indirectly, with the responses as well. A unified structure gives greater statistical predictability through crosswise as well as lengthwise associations (Stadler, 1992; Stadler & Neely, 1997). In sequence learning, integration can even provide a useful simplification of information. For example, when two sequences with *ambiguous* transitions become integrated through correlation, the combined "supersequence" can have *unique* transitions. Suppose we have a binary-choice manual response sequence, such as left–right–left–left–right–right, and it is combined with a task sequence, such as colors–shapes–letters–shapes–colors–letters, then together they can result in a stimulus category sequence, such as red–angular–uppercase–curved–blue–lowercase–(red–angular–…. etc.). The advantage of using a task sequence learning paradigm is that correlation can be manipulated at different levels (e.g., tasks, stimulus categories, responses) and that decisions about stimuli can also be on different levels (i.e., "Is it a shape, a colored figure, or a letter?" and "Is this shape angular or curved? Is this figure red or blue? Is this letter upper case or lower case?"). In this way, stimuli can be presented in sequenced or random order at either or both levels, and we can test the extent of participants' sensitivity. Therefore, a novel aspect of this study is the investigation of whether incidental sequential knowledge can be acquired simultaneously at several different levels.

Specifically, in Experiment 1, we tested whether a sequence of *stimulus categories* that was incorporated (i.e., correlated) into a sequence of *tasks*, but irrelevant to performance, would still affect sequence learning. As knowledge of the stimulus categories was not necessary, the only advantage it might bring to the main sequence learning was through a strengthening of structure. Rather than being a typical TSL paradigm, Experiment 1 can be considered as an example of semantic categorization combined with sequence learning (see Hartman, Knopman, & Nissen, 1989). There were three main categories (animals, plants and implements) each with two subcategories (birds and mammals for animals, trees and flowers for plants, and kitchen utensils and musical instruments for implements). In order to be consistent with our previous study (Meier & Cock, 2010), we use the term "task" for the higher-level categories (animals, plants, or implements) and "stimulus category" for the lower-level subcategories (e.g., birds, mammals) and, as participants had to make a category-choice decision on each trial rather than a simple stimulus–response reaction, Experiment 1 can be counted as an example of TSL. Importantly, as participants were required to make key press responses to *tasks* rather than *stimulus categories*, the stimulus category sequence could be manipulated separately.

In Experiment 2, we tested whether a *sequence of tasks* that was correlated with the sequence of *stimulus categories* but *irrelevant to performance* would affect sequence learning. Here, participants responded directly at the lower level of the stimulus categories. If the additional correlated, but irrelevant sequence (i.e., the *task* sequence in Experiment 2 and the stimulus category sequence in Experiment 1) were to affect performance, it would suggest that implicit sequence learning can indeed operate "as a byproduct of mere exposure" (Saffran, Johnson, Aslin, & Newport, 1999, p. 30). In contrast, however, if selective attention also plays a crucial role in implicit sequence learning, as it does in automatic statistical and covariation learning, then any information in a secondary stream, even when correlated with the primary stream, would not necessarily be used — at least not automatically (cf., Hoffmann & Sebald, 2005; Turk-Browne, Junge, & Scholl, 2005). Such a finding would suggest that information must be *processed actively* if it is to contribute to implicitly sequence learning, that is, it must be selectively attended and *task relevant* (see Abrahamse, Jimenez, Verwey, & Clegg, 2010; Cock & Meier, 2012; Heuer et al., 2001; Jiang & Chun, 2001; Jiménez & Méndez, 1999; Remillard, 2009; Rowland & Shanks, 2006, for related discussions).

In Experiment 3, we tested whether a correlated secondary sequence that was *relevant* to performance would affect primary sequence learning. Here, we reasoned that even though a secondary sequence might appear to be relevant from the experimenters' point of view, participants might not become sensitive to it. Specifically, the design was similar to that of Experiments 1 and 2 but we tested for sensitivity to a sequence of *stimulus locations* that was correlated with a *response-relevant sequence of stimulus categories*. Stimulus locations were relevant in the sense that they had to be attended by participants in order to identify and classify the stimuli (Cock & Meier, 2007; Deroost & Soetens, 2006; Meier & Cock, 2010; Riedel & Burton, 2006). An overview of the three experiments and the conditions is shown in Table 1.

2. Experiment 1

Experiment 1 was designed to investigate whether task sequence learning is affected by the presence of an additional but seemingly irrelevant stimulus category sequence. Two experimental conditions were tested (see Table 1). In the first condition, the higher level order of tasks was sequenced — and hence the order of responses was also sequenced—and an additional, lower level stimulus category sequence was also present. These two sequences were correlated. In a critical test block, all the sequences were changed to untrained orders. We refer to this condition as the *TCR* (*TCR change*) condition, as tasks (T), responses (R), and stimulus categories (C) are sequenced during training and all three sequences change in Block 7. If sequence learning occurs using this design, we would expect participants to slow down upon these changes. In the second condition, there was a higher level task sequence but *no* additional lower level stimulus category sequence. Here, the stimulus category, for example "trees" or "flowers" in the case of "plants", varied at random throughout the experiment, and in the critical test block, only the task sequence was changed to a different order. Thus, we refer to this condition as the *TR* (*TR change*) condition. If the presence of the correlated, lower level stimulus category sequence enhances response-sensitivity to the higher level task sequence, we would expect a weaker sequence learning effect (i.e., less RT disruption) in the second condition compared to the first. However, if participants do not benefit from the presence of the secondary sequence, we would expect the size of the learning effect to be much the same in the two conditions. In other words, on the one hand participants might benefit from the *mere presence* of the extra, correlated sequence, but on the other hand they might not — because the components of that sequence (stimulus categories) do not need to be processed in order to carry out the task.

2.1. Method

2.1.1. Participants

Fifty-six undergraduate students (47 female, mean age 21.4 years, $SD = 4.5$) from the University of Bern took part in return for course credit. They were pseudo-randomly assigned to one of two conditions (28 each): *TCR* (*TCR change*) and *TR* (*TR change*). Condition was manipulated between subjects, while block was manipulated within subjects, resulting in a mixed design.

2.1.2. Materials

Stimuli were written words belonging to three *higher level task categories* (animals, implements, or plants). They were selected such that each *task* comprised two lower level *stimulus categories*: *birds* or *mammals* in the case of animals, *musical instruments* or *kitchen utensils* in the case of implements, and *trees* or *flowers* in the case of plants. The stimulus categories had 16 exemplars each, thus, 96 different words were used in total. All stimuli were presented in German and shown in black 18-point Courier New font against a white background and at the center of a 15 in. computer monitor. The experiment was programmed in E-Prime (http://www.pstnet.com/e-prime).

Task order was sequenced according to one of two 6-element repeating cycles, counterbalanced across participants (i.e., "plants–animals–implements–animals–plants–implements", or "implements–plants–animals–plants–implements–animals"). As participants were required to distinguish between these tasks and respond at this level, the correct key press response order was correspondingly sequenced (i.e., "2–3–1–3–2–1", or "1–2–3–2–1–3", respectively). Additionally, in the *TCR* (*TCR change*) condition, embedded in the higher level task sequence was a repeating order of lower level stimulus categories, with four stimulus category sequences being used counterbalanced across participants, that is, two depending on each of the different task orders (i.e., "tree–mammal–musical instrument–bird–flower–kitchen utensil" vs. "flower–bird–kitchen utensil–mammal–tree–musical instrument" and "kitchen utensil–tree–mammal–flower–musical instrument–bird" vs. "musical instrument–flower–bird–tree–kitchen utensil–mammal"). In pseudo-random practice blocks, task and stimulus category orders were random with the following constraints: equal task frequency, equal stimulus category frequency, no task repetitions.

Table 1
Experimental conditions of Experiments 1 to 3. The order of tasks (T), the order of stimulus categories (C), the order of responses (R), or the order of stimulus locations (L) were sequenced (s) or random (r) in training blocks (blocks 3–6 and 8) and in the test block (block 7).

	Training blocks			Test block			Required response
Experiment 1							
	T	**C**	**R**	**T**	**C**	**R**	**T**
TCR (*TCR change*)	s	s	s	r	r	r	
TR (*TR change*)	s	r	s	r	r	r	
Experiment 2							
	T	**C**	**R**	**T**	**C**	**R**	**C**
TCR (*TCR change*)	s	s	s	r	r	r	
TCR (*CR change*)	s	s	s	s	r	r	
T (*T change*)	s	r	r	r	r	r	
Experiment 3							
	T	**R**	**L**	**T**	**R**	**L**	**C**
TRL (*TRL change*)	s	s	s	r	r	r	
TR (*TR change*)	s	s	r	r	r	r	

Note. In Experiment 3 the combination of tasks and responses resulted in an additional, secondary sequence of stimulus categories.

2.1.3. Procedure

Participants were tested individually. They were informed that different words of the semantic categories "musical instrument", "kitchen utensil", "tree", "flower", "bird", and "mammal" would appear on the screen one at a time and that their task was to decide whether the presented word was an implement, plant or animal. They were instructed to respond as quickly and as accurately as possible. They were told that if they made a mistake, they should simply continue. For the *implements* task, participants pressed a designated key with their right index finger. For the *plants* task, they pressed another designated key with their right middle finger. For the *animals* task, they pressed a third key with their right ring finger. Different keys were used, therefore, for each task. However, within each task, the same key was used for both stimulus categories (i.e., the same key was used for musical instruments and kitchen utensils, trees and flowers, birds and mammals, respectively). When the participant was ready, the experimenter pressed a key to initiate the blocks of trials. Depending on task and stimulus category, actual stimulus words were presented randomly but such that each exemplar occurred once per block. The stimulus remained on screen until the participant pressed a response key. The next stimulus appeared after a response–stimulus interval of 250 ms (see Fig. 1).

The experiment consisted of 8 blocks with 96 stimulus–response trials each. Blocks 1 and 2 were pseudo-random practice blocks used to train participants on the task type to response key mappings. In the *TCR* (*TCR change*) condition, for blocks 3–6 and 8, tasks (and hence responses) and stimulus categories were sequenced in unison. In block 7, both the task sequence (and hence the response sequence) *and* the stimulus category sequence were changed, in unison, to the alternative sequenced orders that were used for counterbalancing. In contrast, in the *TR* (*TR change*) condition, the tasks (and responses) were sequenced for blocks 3–6 and 8 but the kind of lower-level stimulus categories that were presented were not predictable. For example, if the task was "plants", the stimulus category could be either "flowers" or "trees" and these always varied at random. Hence, in this second condition, there was no stimulus category sequence. In block 7, the task sequence was changed to the alternative (counterbalanced) version and, on each trial, either of the two possible stimulus categories was still presented at random. Importantly, in both conditions, the stimulus categories were

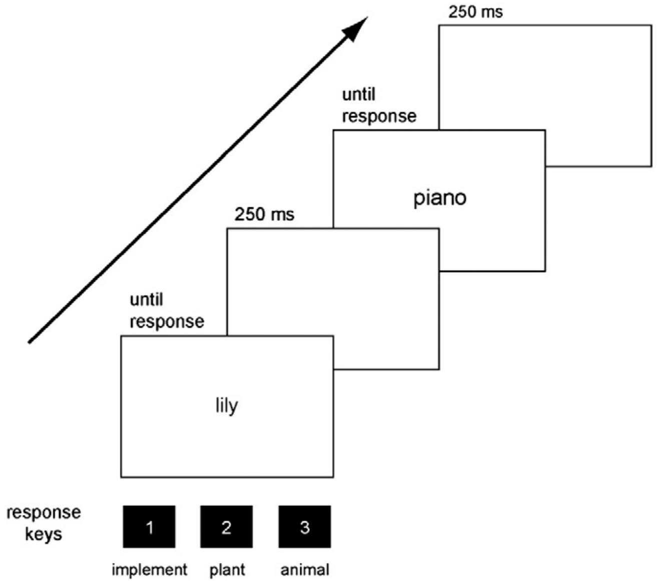

Fig. 1. Experimental set-up of Experiment 1.

response-irrelevant from the point of view of what the participant had to do. This was despite the fact that the primary sequence (higher level tasks) and the secondary sequence (lower level stimulus categories) were inevitably correlated. 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 various sequences. Participants were first asked about the possible presence of sequenced information. Next, as appropriate, they were asked to verbally reproduce whatever they could remember or guess of the task sequence and the stimulus category sequence they had received (sequence generation trials). They were not required to generate the key press response sequence because it was identical to the task sequence. For data analysis, responses were individually compared to the actual sequences that were presented.

2.1.4. Data analysis

Accuracy (averaged from blocks 1 to 8) was close to ceiling, with proportions of .97 (*SD* = .01) in both conditions and was not further analyzed. For response time (RT) analyses, trials on which errors were made, trials that followed an error, and the first 6 trials of each block were excluded. Median RTs per block and participant were computed for the three tasks separately. Then, the median RTs of the three tasks were averaged per block and participant. Disruption scores were calculated as the RT difference between performance at block 7 and mean performance at surrounding blocks 6 and 8.

For all statistical analyses, an alpha level of .05 was used. Greenhouse–Geisser corrections are reported where appropriate and effect sizes are expressed as partial η^2 values.

2.2. Results

2.2.1. Response times

The RT results of Experiment 1 are shown in Fig. 2. To assess the effect of sequence specific learning, disruption scores were calculated as the difference in RT at block 7 compared to the mean RT at blocks 6 and 8 combined. Mean *disruption scores* were 72 ms (*SE* = 17) for the *TCR* (*TCR change*) condition, and 56 ms (*SE* = 20) for the *TR* (*TR change*) condition. The disruption scores did not differ between conditions, $t(54) = 0.58$, $p = .562$. A 2 × 2 ANOVA, with block (7 vs. mean of 6 and 8 combined) as a within-subjects factor and sequencing condition [*TCR* (*TCR change*) vs. *TR* (*TR change*)] as a between-subjects factor revealed a significant main effect of block, $F(1, 54) = 23.61$, $p < .001$, $\eta^2 = .30$, but no effect of sequencing condition and no interaction, both Fs < 1.0, ps > .23. This indicates similar sequence-specific learning in both conditions.

2.2.2. Explicit knowledge

In the *TCR* (*TCR change*) condition, 24 participants reported that they had noticed a task sequence and 21 of them tried to reproduce it verbally. The mean number of correctly reported sequence elements was 4.4 (*SE* = 0.3); nine participants were able to report the whole task sequence correctly (6 elements). Only 3 participants reported that they had noticed the additional stimulus category sequence. One of them tried to reproduce it verbally but reported only 2 out of 6 elements correctly. In the *TR* (*TR change*) condition, 22 participants reported that they had noticed a task sequence, and 18 tried to reproduce it verbally. The mean number of correctly reported task sequence elements was 4.7 (*SE* = 0.4); twelve participants were able to report the whole task sequence correctly. The two conditions did not differ in explicit knowledge of the task sequence as indicated by an independent-samples t-test, $t(37) = .72$, $p = .48$.

Next, those participants who reported the whole task sequence correctly were excluded from analysis [9 in the *TCR* (*TCR change*) condition and 12 in the *TR* (*TR change*) condition]. The use of the full sequence as a cut-off for explicit knowledge is based on the empirical distribution of the number of items that were generated. Across experimental conditions, a total of 21 participants generated the complete six-element sequence, only 2 generated five elements, 6 generated four elements and 11 generated two or three elements of the task sequence; only one participant generated the whole category sequence, one generated 4 and one generated 3 elements.

For the remaining non-explicit participants, mean disruption score was 47 ms (*SE* = 13) for the *TCR* (*TCR change*) condition, and 28 ms (*SE* = 18) for the *TR* (*TR change*) condition, and the two conditions were not significantly different from each other, $t(33) = 0.88$, $p = .39$. The pooled mean disruption score was 38 ms (*SE* = 11), which was significantly different from zero, $t(34) = 3.51$, p(one-tailed) < .01. Thus, sequence learning was present in participants with little or less explicit knowledge and it did not differ between conditions.

2.3. Discussion

In Experiment 1, we compared two conditions, which featured a task sequence in conjunction with a correlated response sequence. Critically, one condition had an additional stimulus category sequence that was irrelevant to performance, but the other did not. Both conditions provided evidence of primary sequence learning and this was not entirely attributable to explicit knowledge. More importantly, the two conditions did not differ significantly in the degree of learning,

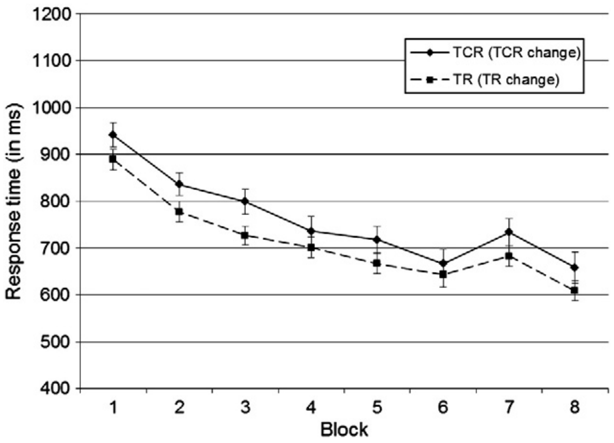

Fig. 2. RT results of Experiment 1. Error bars represent standard errors.

indicating that sequence-specific sensitivity occurred irrespective of the presence of the secondary stimulus category sequence. In other words, learning seems to have been driven by the primary task sequence in conjunction with the response sequence, with the secondary stimulus category sequence playing little or no role. In fact, participants did not appear to be sensitive to the stimulus category sequence at all. It would appear that information in this stream was either not processed, or at least not used, because it was not response-relevant in the sense that it was not needed in order to carry out the tasks. We conclude that sensitivity to a secondary sequence, even when it is correlated with the primary sequence, does not develop automatically through "mere exposure".

Experiment 2 was designed to further investigate this assumption. We used a similar design and materials to Experiment 1, but participants were required to respond to the stimulus categories themselves rather than the tasks (cf., Meier & Cock, 2010, Experiment 1). That is, within each task (animals, implements or plants), they were required to discriminate between the two stimulus categories (bird vs. mammal, musical instrument vs. kitchen utensil, and tree vs. flower). As a consequence, the sequence of stimulus categories was now the primary response-relevant sequence. In contrast, the higher-level task sequence was now irrelevant to responses, although, of course, the two sequences were still related through the lengthwise correlation between the levels. Furthermore, instead of requiring a key-press response, participants were asked to respond verbally, that is, by speaking aloud. For example, if the word "sparrow" appeared on the screen, participants were required to respond by naming the stimulus category "bird". In this way, both levels of semantic categories might be activated and processed (i.e., through spreading activation, the participant should also know that the exemplar is an "animal" if s/he makes the response that it is a "bird"). We chose to use verbal rather than manual responses because the latter would have necessitated using 6 keys, two being designated for each task. This would have meant that the task sequence was accompanied by a finger-type sequence, such as index fingers for animals (R for birds, L for mammals), middle fingers for objects (R for utensils, L for implements), ring fingers for plants (R for trees, L for flowers). As we wanted the task sequence to "stand alone", introducing correlated sequences of this kind had to be avoided and verbal responses provided the solution.

3. Experiment 2

The purpose of Experiment 2 was to generalize the findings of Experiment 1 at the level of stimulus categories instead of tasks. Thus, the lower level stimulus category sequence was now the primary sequence and response-relevant, whereas the higher level task sequence was secondary and response-irrelevant. Three experimental conditions were tested, all of which involved a response-irrelevant task sequence (see Table 1) and the two sequences, where they were present, were correlated as in Experiment 1. In the *TCR* (*TCR change*) condition, tasks were presented in a sequenced order, and a response-relevant stimulus category sequence also existed. To test for sequence learning, both sequences were changed to alternative (untrained) sequencing in block 7. We would predict that, upon changing the sequences in this way, performance would be significantly disrupted, providing indirect evidence of sequence learning. The *TCR* (*CR change*) condition was similar, except that only the stimulus category sequence was changed to an alternative (untrained) sequence in block 7 and the response-irrelevant task sequence was maintained. Here, we would predict that, upon changing the response-relevant stimulus category sequence, performance would be disrupted. However, if participants had become sensitive to the task sequence as well, they might benefit from the continuation of the task sequence in block 7. That is, they should not slow as much when only the stimulus category sequence is changed compared to when both the stimulus category sequence and the task sequence are changed. Finally, in the *T* (*T change*) condition, tasks were presented in a sequenced order but the order of stimulus categories (and, hence, the order of verbal responses) was pseudorandom throughout the experiment. In block 7, the task sequence was changed to an alternative (untrained) sequence. We would expect to find disruption of performance if the participants are sensitive to the response-irrelevant task sequence. However, if participants are not sensitive to it under these circumstances, no change in performance should occur (cf., Cock & Meier, 2007; Meier & Cock, 2010).

3.1. Method

3.1.1. Participants

Sixty undergraduate students (45 female, mean age 22.0 years, $SD = 4.1$) from the University of Bern took part in return for course credit. They were randomly assigned to one of three conditions: *TCR* (*TCR change*), *TCR* (*CR change*), and *T* (*T change*). Condition was manipulated between subjects, while block was manipulated within subjects, resulting in a mixed design.

3.1.2. Materials

Stimulus material and presentation was the same as in Experiment 1. However, instead of giving a key-press response participants were required to respond verbally. They were asked to say out aloud the name of the stimulus category to which the stimulus word belonged. Thus, the order of verbal responses was also sequenced according to whichever of the (counterbalanced) four stimulus category sequences was present. The response time (i.e., time from stimulus onset until speech onset) was automatically recorded with a speech-controlled voice key. The response–stimulus interval was set to 250 ms.

3.1.3. Procedure

Procedure was identical to Experiment 1 except for the following changes. Participants were informed that different words from three task categories (animals, implements, and plants) would appear on the screen one at a time. For the *animals* task, they were required to differentiate between birds and mammals. For the *implements* task, they were required to differentiate between musical instruments and kitchen utensils. For the *plants* task, they were required to differentiate between trees and flowers. They responded verbally by saying the appropriate stimulus category aloud (e.g., the German word for "bird").

Two initial practice blocks, each comprising 96 random order trials, were used to adjust the microphone and to train participants on the response requirements. In the *TCR* (*TCR change*) condition, for blocks 3–6 and 8, tasks and stimulus categories (and hence verbal responses) were sequenced in unison (i.e. correlated) using sequences from Experiment 1. In block 7, both the task sequence *and* the stimulus category sequence were changed, in unison, to the alternative sequenced orders that were used for counterbalancing. The *TCR* (*CR change*) condition was identical to the *TCR* (*TCR change*) condition except that in block 7 only, the stimulus category sequence was changed to a counterbalancing sequence whereas the task sequence was maintained. In the *T* (*T change*) condition, for blocks 3–6 and 8, only tasks were sequenced whereas stimulus categories (and hence verbal responses) were ordered randomly. In block 7, the task sequence was changed to the alternative sequenced order used for counterbalancing (stimulus categories were still presented randomly).

The same structured interview was used as in Experiment 1, however, participants who acknowledged the possible presence of sequenced information were enjoined to generate this information unconditionally.

3.1.4. Data analysis

This was the same as in Experiment 1, except that the data from the first two practice blocks (1 and 2) were omitted from analyses as they were used for adjusting the microphone and for getting accustomed to the verbal response mode. Trials on which the participant had to repeat a response because the microphone did not pick up the first input were considered as error trials and excluded from analyses. Accuracy (averaged from blocks 3 to 8) was .95 ($SD = .04$) for the *TCR* (*TCR change*) condition, .96 ($SD = .02$) for the *TCR* (*CR change*) condition, and .94 ($SD = .03$) for the *T* (*T change*) condition. The three groups did not differ from each other as indicated by a one-way ANOVA, $F(2, 57) = 1.01$, $p = .371$.

3.2. Results

3.2.1. Response times

The RT results of Experiment 2 are shown in Fig. 3. To assess the effect of sequence specific learning, disruption scores were computed as in Experiment 1. Mean disruption scores were 66 ms ($SE = 19$) for the *TCR* (*TCR change*) condition, 52 ms ($SE = 26$) for the *TCR* (*CR change*) condition, and −4 ms ($SE = 12$) for the *T* (*T change*) condition. A 2×3 ANOVA, with block (7 vs. mean of 6 and 8 combined) as a within-subjects factor and sequencing condition [*TCR* (*TCR change*), *TCR* (*CR change*), and *T* (*T change*)] as a between-subjects factor revealed a significant effect of block, $F(1, 57) = 10.59$, $p = .002$, $\eta^2 = .16$, a significant block × sequencing condition interaction, $F(2, 57) = 3.39$, $p = .041$, $\eta^2 = .11$, but no significant effect of sequencing condition, $F < 1.3$, $p = .288$. Post-hoc tests on the disruption scores revealed that the *T* (*T change*) was significantly different from the *TCR* (*TCR change*) condition, $p = .017$, and marginally significant from *TCR* (*CR change*), $p = .051$, while the *TCR* (*TCR change*) and the *TCR* (*CR change*) were not different, $p > .64$. To follow up, the disruption scores in each condition were compared to zero in separate one-sample *t*-tests. The disruption scores of the *TCR* (*TCR change*) condition and the *TCR* (*CR change*) condition were significantly different from zero, with $t(19) = 3.40$, $p(\text{one-tailed}) = .002$, and $t(19) = 1.99$, $p(\text{one-tailed}) = .031$. In contrast, the disruption score of the *T* (*T change*) condition was not different from zero, $t(19) = .35$, $p(\text{one-tailed}) = .366$. This provides evidence for sequence-specific learning in the *TCR* (*TCR change*) and in the *TCR* (*CR change*) conditions, but not in the *T* (*T change*) condition.

3.2.2. Explicit knowledge

In the *TCR* (*TCR change*) condition, 9 participants reported that they had noticed a task sequence, and 6 of them tried to reproduce it verbally. The mean number of correctly reported sequence elements was 4.3 ($SE = 0.6$). Thirteen participants reported that they had noticed a stimulus category sequence, and 11 tried to reproduce it verbally. The mean number of correctly reported sequence elements was 3.3 ($SE = 0.7$). In total, 5 participants were able to report at least one of the two sequences correctly (6 elements). In the *TCR* (*CR change*) condition, 7 participants reported that they had noticed a task sequence, and seven of them tried to reproduce it verbally. The mean number of correctly reported sequence elements was 4.9 ($SE = 0.5$). Thirteen participants reported that they had noticed a stimulus category sequence, and 11 tried to reproduce it verbally. The mean number of correctly reported sequence elements was 3.8 ($SE = 0.7$). In total, 6 participants were able to report at least one of the sequences correctly. In the *T* (*T change*) condition, 2 participants reported that they had noticed a task sequence and tried to reproduce it verbally. The mean number of correctly reported sequence elements was 2.0 ($SE = 1.0$). Neither reported the whole sequence. The three conditions did not differ in explicit knowledge of the task sequence as indicated by a one-way ANOVA, $F(2, 12) = 3.16$, $p = .079$. The *TCR* (*TCR change*) condition and the *TCR* (*CR change*) condition did not differ with regard to explicit knowledge of the stimulus category sequence as indicated by a *t*-test, $t(20) = 0.56$, $p = .581$.

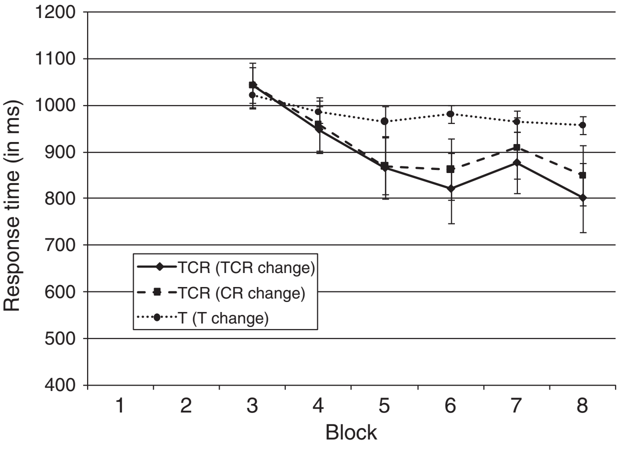

Fig. 3. RT results of Experiment 2. Error bars represent standard errors. Random blocks 1 and 2 were used for calibration only.

Next, those participants who reported at least one sequence correctly were excluded from analysis [5 participants in the *TCR* (*TCR change*) condition, and 6 participants in the *TCR* (*CR change*) condition]. Across experimental conditions, a total of 6 participants generated the whole task sequence, none generated five elements, 3 generated four elements, 5 generated five elements and one generated 2 elements. In addition, a total of 9 participants generated the whole category sequence, none generated five elements, one generated four elements, and five generated two or three elements. This is consistent with a previous study, in which we used a very similar set-up. That analysis showed a similar bimodal distribution, with 5 reproduced items as the separator of the two peaks (Weiermann & Meier, 2012a).

For the remaining non-explicit participants, mean disruption score was 50 ms ($SE = 17$) in the *TCR* (*TCR change*) condition, and 57 ms ($SE = 32$) in the *TCR* (*CR change*) condition, and the two conditions were not significantly different from each other, $t(27) = 0.19$, $p = .849$. Moreover, each of these scores was significantly different from zero, both $ps < .01$. Thus, sequence learning was present in participants with little or no explicit knowledge and did not differ between the *TCR* (*TCR change*) and the *TCR* (*CR change*) conditions.

3.3. Discussion

In Experiment 2, responses were made at the level of stimulus categories (birds, mammals, trees, flowers, instruments, or utensils) while the level of tasks (animals, implements, or plants) was irrelevant to performance. The purpose was to investigate whether participants would become sensitive to the presence of the task sequence. Two conditions featured a response-relevant category sequence in conjunction with a correlated but response-irrelevant task sequence. In block 7, either both the task sequence and the category sequence were changed, or only the category sequence was changed whereas the task sequence was maintained. A third condition featured only a response-irrelevant task sequence but randomly ordered stimulus categories and, hence, randomly ordered responses. Here, in block 7, the task sequence was changed to an alternative (untrained) sequence.

In the latter condition, with only the single task sequence present together with randomly ordered stimulus categories, participants showed no increase in response times when the trained sequence was changed. This suggests that they did not learn the task sequence. The lack of learning of the single task sequence is in line with our previous studies showing that correlated streams of information are necessary for implicit task sequence learning to occur (cf., Meier & Cock, 2010; Weiermann et al., 2010). For example, sequence learning occurred only when the task sequence was correlated with a motor response sequence, a sequence of stimulus locations or a sequence of response mappings (Cock & Meier, 2007; Meier & Cock, 2010; Weiermann et al., 2010).

The more critical question, however, is whether the sequence learning effect would be similar in the *TCR* (*TCR change*) and the *TCR* (*CR change*) conditions. If participants have learned something of the response-irrelevant task sequence (merely through exposure, for example), the continuation thereof should be beneficial to performance even though other regular information is changed. As a consequence, participants should not slow down as much when only the stimulus category sequence is changed as when both the stimulus category sequence *and* the task sequence are changed. In contrast, if participants are not sensitive to the presence of the response-irrelevant task sequence, then performance disruption should be similar in both conditions. That is, the presence of the task sequence would not provide any advantage. The results were in line with the latter assumption. Both these conditions showed evidence of sequence learning, but the sequence specific learning scores did not differ between conditions. Furthermore, sequence learning was not restricted to participants with explicit knowledge. These results are in line with findings from Experiment 1, suggesting that participants do not benefit, in this instance of implicit sequence learning at least, from the presence of response-irrelevant information even though it is correlated with response-relevant information. In other words, correlation may be important but it is not the only prerequisite for sequence learning.

In Experiment 3, we aimed to investigate whether secondary, sequenced information that is correlated with the primary stream and *relevant to* performance would affect learning. In one of our previous studies, we included an on-screen stimulus location sequence in a TSL paradigm (Meier & Cock, 2010, Experiment 2). In that experiment, participants were instructed to respond to stimulus identity rather than to stimulus location, but the location had to be attended to in order to identify the stimulus. Thus, stimulus location was highly relevant even though it was not the stream of information to which participants made overt motor responses (see Mayr, 1996). By means of eye movements, the locations had to be processed. They could not be ignored or become irrelevant or redundant. For this reason, we included a stimulus location in Experiment 3.

4. Experiment 3

In Experiment 3, we used a TSL paradigm with three perceptual tasks (cf., Cock & Meier, 2007; Meier & Cock, 2010): a letter task on different letters (lower vs. uppercase), a shape task on geometric shapes (rounded vs. angular), and a color task on fuzzy figures (red vs. blue). Stimuli were presented at three different locations on the screen (left, middle, and right). Participants responded to *stimulus categories* (i.e. lowercase, uppercase, rounded, angular, red or blue) by pressing one of two designated response keys, with the same two keys used for all three binary-choice tasks. In the *TRL* (*TRL change*) condition, tasks and responses were presented in correlated, sequenced orders (see Materials section below). Additionally, the order of locations at which the stimuli appeared on screen was also sequenced and correlated with other streams. To test for sequence learning, all the sequences were changed to alternative (untrained) sequences in block 7. In contrast, in the *TR* (*TR change*) condition, tasks and responses were presented in correlated, sequenced orders, but the order of locations was pseudo-random throughout. In block 7, the task sequence and the response sequence were changed to alternative (untrained) sequences (see Table 1). We would predict that, upon changing the task sequence and the response sequence, performance would be disrupted in both conditions. However, if the presence of the location sequence was of benefit to the main sequence learning (tasks, responses and stimulus categories combined), the amount of disruption should be larger in the *TRL* (*TRL change*) condition than in the *TR* (*TR change*) condition.

4.1. Method

4.1.1. Participants

Fifty-six participants (40 female, mean age 22.2 years, $SD = 2.8$) took part in return for course credit or money. They were assigned equally to one of two conditions: *TRL* (*TRL change*) and *TR* (*TR change*). Condition was manipulated between subjects, while block was manipulated within subjects, resulting in a mixed design.

4.1.2. Materials

Stimuli were approximately 4×3 cm in size, and presented against a white background (cf., Cock & Meier, 2007; Meier & Cock, 2010). Stimuli were presented on the left, middle or right of the screen. The middle on-screen stimulus location was centered vertically and horizontally. Left and right side locations were positioned approximately three degrees of visual angle left and right of the middle location. For the letter task (lower vs. uppercase), 6 different letters were used, for the shape task (rounded vs. angular), 6 different geometric shapes were used, and for the color task (red vs. blue), 6 different fuzzy figures were used. Participants responded by pressing the left (L) or right (R) key of an external response box with their left and right index fingers, respectively. Task order was sequenced according to one of two 6-element repeating cycles, counterbalanced across participants (i.e., “letter–color–shape–color–letter–shape”, or “color–shape–letter–shape–color–letter”). Additionally, response order was sequenced according to one of two 6-element repeating cycles, counterbalanced across participants (i.e., “L–R–L–L–R–R” or “R–L–R–R–L–L”). The correlation between the task and the response sequence resulted in the presence of a stimulus category sequence (e.g., “lowercase–blue–rounded–red–uppercase–angular”). Additionally, in the *TRL* (*TRL change*) condition, the order of stimulus locations was sequenced according to a 6-element repeating cycle (i.e., “left–middle–right–middle–left–right”). In the *TR* (*TR change*) condition, the order of stimulus locations was pseudo-random with no location repetition trials and with equal frequency of each location. In both conditions, in pseudo-random practice blocks, the order of tasks, responses and locations were random with the following constraints: equal task frequency, equal location frequency, no task repetitions, no location repetitions, and maximally two response repetitions.

4.1.3. Procedure

Participants were tested individually. They were informed that the experiment comprised three different tasks. For the letter task, they were instructed to press the L key with their left index finger for lowercase letters and the R key with their right index finger for uppercase letters. For the shape task, they were instructed to press the L key for rounded shapes and the R key for angular shapes. For the color task, they were instructed to press the L key for red fuzzy figures and the R key for blue fuzzy figures. Depending on task and response, actual stimulus exemplars were presented randomly. The stimulus remained on screen until the participant pressed a response key. The next stimulus appeared after a response–stimulus interval of 250 ms.

The experiment consisted of 8 blocks. Blocks 1 and 2 were pseudo-random practice blocks (one comprising 48 trials and one comprising 96 trials) used to train participants on the stimulus category to response key mappings. In the *TRL* (*TRL change*) condition, for blocks 3–6 and 8, tasks, responses and stimulus locations were sequenced in unison. In block 7, all sequences were changed, in unison, to pseudo-random order. In contrast, in the *TR* (*TR change*) condition, for blocks 3–6 and 8, tasks and responses were sequenced, in unison, but stimulus locations were ordered at random throughout the experiment. In block 7, both the task sequence and the response sequence were changed to pseudo-random order. There was a brief pause between blocks. No feedback on performance was provided.

After the test session, a structured interview similar to the interview used in Experiment 1 was carried out to assess explicit knowledge of the various sequences. Participants were first asked about the possible presence of sequenced information. Next, all participants were asked to verbally reproduce six elements of the location sequence, the response sequence, and the task sequence (sequence generation trials). They were encouraged to guess when not sure. For data analysis, responses were individually compared to the actual sequences that were presented.

4.1.4. Data analysis

This was the same as in Experiment 1. Accuracy (averaged from blocks 1 to 8) was close to ceiling, with .97 ($SD = .02$) for the *TRL* (*TRL change*) condition, and .98 ($SD = .01$) for the *TR* (*TR change*) condition.

4.2. Results

4.2.1. Response times

The RT results of Experiment 3 are shown in Fig. 4. To assess the effect of sequence specific learning, disruption scores were calculated as the difference in RT at block 7 compared to the mean RT at blocks 6 and 8 combined. Mean disruption scores were 99 ms ($SE = 12$) in the *TRL* (*TRL change*) condition and 57 ms ($SE = 15$) in the *TR* (*TR change*) condition. The disruption scores differed between conditions, $t(54) = 2.15$, $p < .05$. One-sample *t*-tests revealed significant learning in both conditions, with $t(27) = 8.34$, $p < .001$ for the *TRL* (*TRL change*) condition and $t(27) = 3.80$, $p < .005$ in the *TR* (*TR change*) condition. A 2 × 2 ANOVA, with block (7 vs. mean of 6 and 8 combined) as a within-subjects factor and sequencing condition [*TRL* (*TRL change*) vs. *TR* (*TR change*)] as a between-subjects factor confirmed a significant effect of block $F(1, 54) = 56.25$, $p < .001$, $\eta^2 = .55$, and a significant block × condition interaction, $F(1,\ 54 = 4.63$, $p < .05$, $\eta^2 = .08$. Thus, sequence learning occurred in both conditions, however, the amount of learning differed.

4.2.2. Explicit knowledge

In the *TRL* (*TRL change*) condition, 19 out of 28 participants reported that they had noticed a task sequence. Among all participants, the mean number of correctly reported sequence elements was 3.68 out of 6 ($SE = 0.3$). Twenty-four participants reported that they had noticed a response sequence. The mean number of correctly reported sequence elements was 5.0 out of 6 ($SE = 0.2$). Twenty participants reported that they had noticed a stimulus location sequence. The mean number of correctly reported sequence elements was 3.96 out of 6 ($SE = 0.2$). In total, 13 out of 28 participants were able to report at least one of the three sequences correctly (6 elements). In the *TR* (*TR change*) condition, 10 out of 28 participants reported that they had noticed a task sequence. Among all participants, the mean number of correctly reported sequence elements was 3.64 out of 6 ($SE = 0.3$). Fifteen participants reported that they had noticed a response sequence. The mean number of correctly reported sequence elements was 4.93 out of 6 ($SE = 0.2$). In total, 10 out of 28 participants were able to report at least one of the two sequences correctly (6 elements). Additionally, thirteen participants reported that they had noticed a stimulus location sequence. For each participant in the *TR* (*TR change*) condition, the reported stimulus location sequence was compared to the stimulus location sequence used in the *TRL* (*TRL change*) condition in order to determine a baseline performance level of guessing. The mean number of correctly reported sequence elements was 3.93 ($SE = 0.2$). The two conditions did not differ in explicit knowledge of the task sequence, or in explicit knowledge of the response sequence, with $t(54) = 0.10$, $p = .92$, and $t(54) = 0.32$, $p = .75$, respectively. Furthermore, the *TRL* (*TRL change*) condition did not perform any better than the chance level performance of the *TR* (*TR change*) condition in generating the stimulus location sequence, $t(54) = 0.12$, $p = .91$.

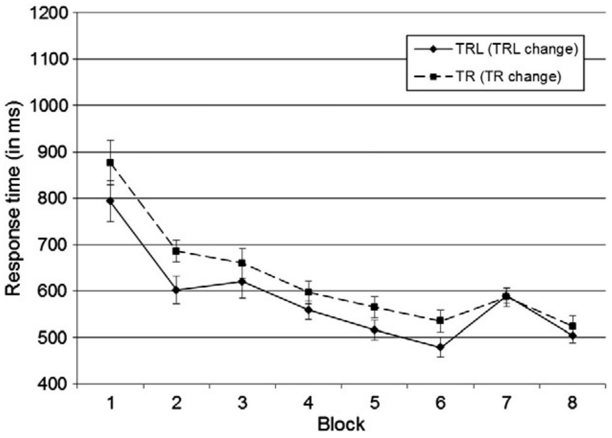

Fig. 4. RT results of Experiment 3. Error bars represent standard errors.

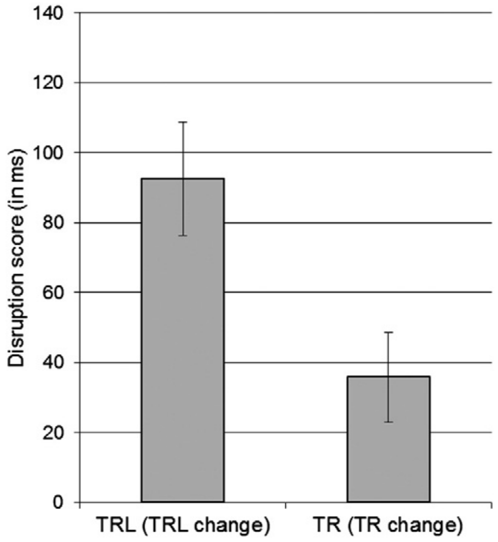

Fig. 5. Experiment 3: disruption scores of participants with no explicit sequence knowledge. Error bars represent standard errors.

Next, those participants who reported at least one sequence correctly were excluded from analysis [8 in the *TRL* (*TRL change*) condition and 6 in the *TR* (*TR change*) condition]. Across experimental conditions, eight participants generated the whole task sequence, seven generated 5 elements, ten generated four elements, and thirty-one generated two or three elements. In addition, eighteen participants generated the whole response sequence, eighteen generated 5 elements, and twenty generated four elements. Moreover, six participants generated the whole location sequence, twelve generated 5 elements, fourteen generated four elements, and twenty-four generated two or three elements. This is consistent with another previous study that used a very similar set-up as Experiment 3, in which we systematically analyzed “sequence knowledge” of participants in conditions with random sequences and compared their guesses with the experimental sequences (Meier & Cock, 2010). A total of 40% percent of the participants who did not receive any task sequence still generated at least 4 elements of the task sequence, 100% still produced at least 4 elements of the response sequence and 43% produced at least 4 elements of the location sequence. Together, this indicates that a large amount of “explicit knowledge” can be generated simply by chance.

Mean disruption scores of the remaining participants are shown in Fig. 5. Importantly, the disruption score of these “non-explicit” participants in the *TRL* (*TRL condition*) was significantly higher than the *TR* (*TR change*) condition, as indicated by an independent-samples *t*-test, $t(31) = 2.78$, $p < .01$. The disruption scores of both the *TRL* (*TRL change*) and the *TR* (*TR change*) condition remained significantly different from zero, with $t(14) = 5.72$, $p < .001$, and $t(17) = 2.71$, $p < .05$, respectively. This indicates that, for participants with little or no explicit sequence knowledge, the sequence-specific learning effect was greater in the *TRL* (*TRL change*) condition compared to the *TR* (*TR change*) condition.

4.3. Discussion

In Experiment 3, both conditions featured a task sequence in conjunction with a correlated response sequence. One condition had a secondary sequence of stimulus locations (correlated with the primary sequencing), the other did not. This additional sequence was relevant to performance as the location of the stimulus had to be attended to in order to respond to the stimulus. Both conditions provided evidence of sequence learning. However, more importantly, they differed in the degree of learning. Even when participants with explicit knowledge were excluded from the analysis, the results showed an additional benefit of the secondary sequence that was both correlated and performance relevant.

Thus, the presence of the location sequence in Experiment 3 appeared to enhance the main sequence learning. The greater disruption of response times in this condition compared to the other implies that implicit knowledge of the location sequence was integrated into the main sequence learning and the latter was thereby strengthened. Beneficial effects of multi-dimensional implicit sequence learning have already been demonstrated and are thus consistent with the literature (cf., Keele et al., 2003; Meier & Cock, 2010; Schmidtke & Heuer, 1997; Schwarb & Schumacher, 2010).

5. General discussion

In the present study, we investigated if, and how, implicit sequence learning is affected by the presence of a correlated sequence that is either irrelevant or relevant to performance. In Experiments 1 and 2, we tested whether participants would be sensitive to a correlated sequence that was response-irrelevant. If correlated, but irrelevant secondary information were found to have an effect on performance, it would suggest that such information can be picked up automatically in this and similar settings. By “automatic” we mean a passive kind of processing that does not need to involve selective attention or response relevance. Alternatively, the impact might be restricted to information that is relevant to performance and that must be attended (i.e., actively processed). Therefore, in Experiment 3, we tested if, and how, a correlated sequence that was *properly relevant* would affect implicit sequence learning.

Specifically, in Experiment 1, participants responded at the level of tasks by indicating whether the presented stimulus belonged to animals, implements or plants by pressing one of three corresponding keys. The order of tasks and, therefore, the order of motor responses followed a predetermined sequence. We tested whether participants were sensitive to additional response-irrelevant but sequenced information by adding a stimulus category sequence (e.g., “tree–mammal–musical instrument–bird–flower–kitchen utensil”) to the task sequence. Although this sequence was correlated with the primary sequence of tasks, and theoretically “available” to the sequence learning mechanism, the stimulus categories were irrelevant to performance from the participant's point of view. In other words, they were not obviously useful — participants did not need to attend or remember information at this level in order to make their responses. On the other hand, as it was correlated, the secondary sequence might have added more structure to the learning environment and thereby facilitated primary sequence learning. The results showed that implicit sequence learning was unaffected by the secondary category sequence of categories, which suggests that, even when it is correlated with the main task and response streams, the simple presence of additional information is not sufficient to affect sequence learning.

The results of Experiment 2 further support this assumption. Here, participants responded at the level of stimulus categories (and *not* at the level of tasks) by verbally discriminating between birds and mammals, musical instruments and kitchen utensils, and trees and flowers. The order of stimulus categories and, hence, the order of verbal responses was sequenced. We tested whether participants were sensitive to the additional correlated but response-irrelevant higher-order sequence of tasks. Again, the results showed that performance was not affected by the presence of this additional sequence. Furthermore, in line with previous studies, it would appear that a *single*, response-irrelevant task sequence, that is, with randomly ordered stimulus categories and randomly ordered responses to the stimulus categories, was not learned (cf., Cock & Meier, 2007; Meier & Cock, 2010; Weiermann & Meier, 2012b; Weiermann et al., 2010).

In contrast to Experiments 1 and 2, Experiment 3 was designed to investigate the impact of correlated sequenced information that was *relevant* to performance. We introduced stimulus locations that had to be attended to in order to process the stimuli. The results showed that the presence of this secondary sequence augmented sensitivity to the primary sequence, suggesting that it was beneficial to sequence learning.

Taken together, these results suggest that secondary information can be beneficial to implicit sequence learning but only when it is useful for performance from the participant's point of view. This does not mean that the participants know about the additional information and that it is sequenced. Rather, it is something that helps them carry out the task more easily and more efficiently — in line with, or sometimes even regardless of, the experimenters' intentions.

Furthermore, the implication is that implicit sequence learning relies on a process that does not integrate *all* the external inputs in a nonselective manner (cf., Jiang & Chun, 2001; Jiménez & Méndez, 1999; Logan, Taylor, & Etherton, 1996). In fact, in a recent review, Abrahamse et al. (2010) suggested that sequence learning was constrained by task set. Selective attention would therefore be a direct consequence of a particular task set that determines the specific processing priorities (see also Lavie, 2010).

The finding of a lack of benefit from additional information that is sequenced but response-irrelevant is consistent with a recent task sequence learning study (Meier & Cock, 2012). There, we investigated whether the presence of a correlated stream of task cues affects performance when stimuli are univalent. Using the task sequence paradigm introduced by Koch (2001), our results showed that the mere presence of task cues was not sufficient to give rise to task sequence learning for tasks with univalent stimuli. In contrast, task sequence learning occurred for tasks with bivalent stimuli, as, in this condition, the sequence of task cues had to be actively processed in order to comply with instructions.

The lack of benefit of additional information that is sequenced but irrelevant to responses is also consistent with findings in the SRTT-literature on implicit sequence learning. For example, in an adapted version of the SRTT, Riedel and Burton (2006) examined whether implicit learning of an auditory sequence was possible with or without responses. Four different actors spoke the same four color words that were presented such that speaker identity followed one sequence and the words spoken followed another. Participants were asked to respond with a key press to one of these dimensions (i.e., either identity or word), and ignore the other. Results showed learning for either type of stimulus order, but *only* when it was responded to. No learning of either type of auditory sequence was found by listening alone. Riedel and Burton concluded that relevant responses must be made to a sequence if it is to be learned. Our results are also in line with a study in which the potential benefit of an additional tactile sequence was tested in an SRTT (Abrahamse et al., 2009). Abrahamse et al. failed to find enhancement of sequence learning and suggested that a lack of integration of sequenced streams was responsible for this result.

On the other hand, several studies have shown that, under certain conditions, participants can become sensitive to – seemingly – irrelevant additional sequenced information in SRTT-experiments. For example, Schmidtke and Heuer (1997) reported experiments in which they combined a tone sequence with a sequence of visual response stimuli. For one group of participants, the two sequences were correlated, leading to a consistent audio-visual “supersequence”. For another group, the two sequences were uncorrelated. The results clearly indicated better serial learning with correlated than with uncorrelated sequences. However, the correlated tones sequence *only* improved serial learning when participants were required to respond to the tones (by pressing a foot pedal to tones of high or low pitch) but *not* when the tones were merely presented without requiring any response (Schmidtke & Heuer, 1997).

Similarly, Rah, Reber, and Hsiao (2000) required participants to respond to stimuli while counting tones that were presented in each response-to-stimulus interval. They showed that contingent relations between presented tones and subsequent stimuli were learned, as indicated by the fact that performance was disrupted when these relations were changed. Stoecker, Sebald, and Hoffmann (2003) also found that introducing tones into an SRTT-type experiment improved sequence learning, but only when the tones were contingently mapped to the responses (see also Hoffmann, Sebald, & Stoecker, 2001; Kunde, Koch, & Hoffmann, 2004). They suggested that the beneficial effect of the contingent tones was the result of additional sensory effects that were integrated with the sensory action effect representations.

To summarize, the results of the present study help clarify what is already known about the effects of a secondary sequence on primary incidental sequence learning. For example, although we found that sensitivity to a primary sequence can be enhanced by correlated secondary information that is relevant to performance (Experiment 3), we also found that a correlated but response-irrelevant secondary sequence was not automatically integrated into the main sequence learning (Experiments 1 and 2). Rather, the present results suggest that secondary information must be actively processed, in the sense of selectively attended, if it is to have an impact. In brief, the results point to what could be the three essential components of information processing in SRTT-type experiments: 1. correlation between streams of information, 2. relevance of information to performance, and 3. involvement of selective attention. Whereas some studies have pitted one against the other as explanations for the effects, we propose that they are closely related and that all three are necessary for incidental sequence learning. The overall conclusion is that while a correlated secondary sequence can contribute to primary sequence learning through the integration of information, its mere presence is not enough. It must also be relevant to performance and actively processed.

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