Journal of Cognitive Psychology

Implicit task sequence learning with auditory stimuli

Brigitte Weiermann [a] & Beat Meier [a]

[a] Department of Psychology & Center for Cognition, Learning and Memory, University of Bern, Switzerland

Available online: 15 Mar 2012

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Department of Psychology & Center for Cognition, Learning and Memory, University of Bern, Switzerland

We investigated implicit task sequence learning with auditory stimuli. In previous studies only visual stimuli have been used and thus learning may have been due to visuoperceptual learning. Further, we explored the generality of the correlated streams account which holds that correlated streams of information are necessary for implicit sequence learning to occur. We used three classification tasks with auditory stimuli. The presence or absence of a task sequence was orthogonally manipulated with that of a response sequence. Sequence-specific learning was found, but only in the condition with both a task and a response sequence. No learning was found in the conditions with a single task sequence and with a single response sequence. These results show that task–response sequence learning occurs with auditory stimuli and that visuoperceptual learning is not necessary. Moreover, they underscore the importance of correlated streams of information for implicit sequence learning.

Keywords: Correlated sequences; Incidental learning; Task switching.

Recently, the task sequence learning (TSL) paradigm has been introduced to investigate the ability to incidentally acquire and utilise knowledge about sequential regularities (e.g., Cock & Meier, 2007; Heuer, Schmidtke, & Kleinsorge, 2001; Koch, 2001; Meier & Cock, 2010; Weiermann, Cock, & Meier, 2010). In this paradigm, participants respond to different binary-choice tasks. Unbeknownst to them, the order of successive tasks is determined by a repeating sequence. The task sequence is present during several blocks of trials during which response times decrease. However, when the sequence is replaced by a random order of tasks, response times increase substantially. This increase is taken as indirect evidence of implicit task sequence learning. Theoretically, three different explanations have been put forward as to on what this learning effect may be based on. First, implicit task sequence learning may be attributed to automatic task-set activation, that is, an unspecific priming of task-sets (Koch, 2001). Second, implicit task sequence learning may be restricted to learning repeating perceptual stimulus features (such as stimulus location and colour; Heuer et al., 2001). Third, implicit task sequence learning may be dependent on the presence of correlated streams of information, irrespective of the type of information (e.g., stimulus features or motor responses; Meier & Cock, 2010). A conclusive comparison of these three theoretical accounts is beyond the scope of this study. Rather, the main purpose is to test the generality of the correlated streams account with *auditorily* presented stimulus material.

The correlated streams account does not specify the content of implicit sequence learning but rather defines the necessary conditions for

learning to occur. Thus, it should hold both for visual and auditory stimulus material. A stream of information is considered as a temporal flow of data which comprises separable events (e.g., stimuli, stimulus features, responses, or tasks). In a sequenced stream of information, the order of successive events is determined by a repeating sequence. Correlated streams of information involve two (or more) sequenced streams with mathematically compatible structures (cf., Meier & Cock, 2010; Weiermann et al., 2010). Thus, this account is compatible with the results from the classical serial reaction time task (SRTT; Nissen & Bullemer, 1987), in which a sequence of stimulus positions is typically correlated with a sequence of to-be-pressed response keys (see Meier & Cock, 2010, for an overview). In contrast, the task sequence learning paradigm allows for separating different sequences, for example a task sequence and a response sequence.

In the domain of *task sequence learning*, the correlated streams account has been specifically tested in three previous studies. Cock and Meier (2007) found sequence learning effects when a task sequence was correlated with a response sequence. In contrast, a single task sequence or a single response sequence was not learned. This result was replicated in a second study with different tasks and different streams of information (Meier & Cock, 2010). Again, sequence learning effects were found only when two correlated streams of information were present (a task sequence combined with either a response sequence or a sequence of stimulus locations; a response sequence combined with a sequence of stimulus locations), whereas no learning was observed in single sequence conditions. Using a different setup, Weiermann et al. (2010) found sequence learning effects only when a task sequence was correlated with a sequence of response mappings, but not with a single sequence of tasks or a single sequence of response mappings. Taken together, these studies provide evidence for the correlated streams account across a variety of different tasks and stimuli.

Furthermore, the results of other TSL studies are also in line with the correlated streams account. For example, in the studies by Koch et al. (Koch, 2001; Koch, Philipp, & Gade, 2006), an external instructional cue was presented as a separate event before the stimulus appeared on the screen. That is, one sequenced stream of information was present in the environment (the

perceptual sequence of instructional cues) and a second stream (the task sequence) originated by translating the cues into the to-be-performed tasks. This indicates that the correlation is not necessarily embedded within two physically present streams of information but that a sequenced stream of information can be mentally constructed. In the study by Heuer et al. (2001), distinct stimulus features served as instructional cues to indicate which task to perform and which task-to-response-mapping to apply on any given trial. Thus, a location sequence (stimulus location indicated which task to perform) was correlated with a colour sequence (stimulus colour indicated which mapping to apply) and, as a consequence, the task sequence was correlated with a mapping sequence. In fact, when the task sequence and the mapping sequence were isolated in this paradigm, no sequence learning of the single task sequence or the single mapping sequence occurred (Weiermann et al., 2010).

So far, all previous TSL studies have used visual stimuli. Although the TSL paradigm involves no stimulus sequence because stimuli are chosen randomly within a specific task, a visual regularity such as a sequence of visually presented instructional cues or a sequence of perceptually distinct stimuli (e.g., geometrical forms vs. coloured spots) or stimulus features has been present in previous studies. Thus, it remains unclear whether task sequence learning may be—at least in part—due to the presence of a visual regularity. As *task sequence learning* should involve learning abstract information (i.e., the order of tasks), it should not be dependent on visual surface features present in the stimulus material. Therefore, it is important to investigate whether implicit task sequence learning is restricted to visual stimulus material or can extend to another modality. Moreover, one might even predict that auditory sequence learning is stronger because auditory representations in short-term memory are more durable.

In fact, there is evidence for a modality difference in implicit statistical learning (e.g., Conway & Christiansen, 2005, 2009). Conway and Christiansen (2005) compared artificial grammar learning in the auditory, visual, and tactile modalities. The results showed learning in all modalities; however, most important for the present study, auditory learning was better than both visual and tactile learning. This finding was replicated and extended in a second study

with auditory and visual stimuli (Conway & Christiansen, 2009).

In the domain of the SRTT, there is also some evidence of sequence learning with auditory stimuli. In these studies, typically, simple tones of different pitches were used as stimuli and typically, sequence learning effects were found (e.g., Buchner, Steffens, Erdfelder, & Rothkegel, 1997; Buchner, Steffens, & Rothkegel, 1998; Schmidtke & Heuer, 1997; Zhuang et al., 1998; but see Perruchet, Bigand, & Benoit-Gonin, 1997, for an exception). Moreover studies with spoken words as stimuli provided further evidence for implicit sequence learning in the auditory modality (Dennis, Howard, & Howard, 2006; Riedel & Burton, 2006). However, despite similarities between the TSL paradigm and the SRTT, we do not know whether the same principles of learning hold for both situations. In TSL, participants have to switch between different tasks and learning seems to be related to a more abstract level of information compared to learning of perceptuo-motor sequences in the SRTT. Thus, it remains unclear whether sequence learning in TSL situations may be generalised from the visual to the auditory modality as easily as in SRTT studies.

In order to investigate implicit *task sequence learning* with auditory stimuli, we adapted the paradigm of Meier and Cock (2010, Exp. 1). Stimuli were spoken rather than written words which belonged to three classification tasks: an "animal" decision (bird vs. mammal), an "implement" decision (musical instrument vs. kitchen utensil), and a "plant" decision (tree vs. flower). Within each stimulus category (e.g., birds), the stimulus was chosen randomly among 16 different words, thus preventing the emergence of a repeating auditory stimulus pattern. As we used univalent stimuli, no additional instructional cues were necessary to indicate which task to perform. Four experimental conditions were tested. One condition with both a task sequence and a same-length response sequence (i.e., the correlated sequences condition), one condition with only a task sequence (but randomly ordered responses), one condition with only a response sequence (but randomly ordered tasks), and a control condition with both randomly ordered tasks and responses. This setup allowed for a direct comparison of auditory versus visual task sequence learning as investigated by Meier and Cock (Exp. 1).

According to the correlated streams account, implicit sequence learning would be expected to occur in the correlated sequences condition, but not in the single sequence conditions. The auditory stimulus presentation should not affect this result. According to the automatic task-set account (Koch, 2001), implicit sequence learning would be expected to occur as long as a repeating task sequence was present, that is, in the correlated sequences condition and in the single task sequence condition. According to the perceptual learning account (Heuer et al., 2001), no sequence learning would be expected to occur in any experimental condition, since no repeating pattern of stimuli or perceptual stimulus features is present.

METHOD

Participants

Eighty volunteers (44 male, mean age 23.1 years, $SD = 3.3$) with German as the native language were recruited from the circle of acquaintances of the experimenters. They were randomly assigned to one of four conditions: *seq-seq* (tasks sequenced, responses sequenced), *seq-ran* (tasks sequenced, responses randomly ordered), *ran-seq* (tasks randomly ordered, responses sequenced), and *ran-ran* (control condition with both tasks and responses ordered randomly).

Material

Stimuli were German words, spoken by a female voice, and they belonged to three different tasks (implements, animals, or plants). Implements consisted of the stimulus categories *musical instruments* and *kitchen utensils*, animals of *birds* and *mammals*, and plants of *trees* and *flowers*. The stimulus categories had 16 exemplars each. Depending on tasks and trials, presentation of these exemplars varied at random. In the first block, stimuli were presented via the speakers of a laptop computer, which allowed the experimenter to control the response accuracy. In all following blocks, stimuli were presented via headphones. Left-hand (L) and right-hand (R) responses were given using two keys of the laptop keyboard.

In the *seq-seq* and the *seq-ran* conditions, task order was sequenced according to one of two 6-element sequences, counterbalanced within condition ("plants-animals-implements-animals-plants-implements" and "implements-plants-animals-plants-implements-animals"). In the *ran-seq*

condition, a pseudorandom task order was created, with no consecutive task repeats, only ambiguous task transitions, and equal task frequency. In the *seq-seq* and the *ran-seq* conditions, response order was sequenced according to one of two 6-element sequences, counterbalanced within condition ("L-R-L-L-R-R" and "R-L-R-R-L-L"). In the *seq-ran* condition, a pseudorandom response order was created, with equal frequency of L and R responses and maximally two response repetitions. In the *ran-ran* condition and in the pseudo-random blocks, the order of tasks and responses was random with the following constraints: equal task frequency, equal response frequency, equal stimulus category frequency, no task repetitions, and maximally two response repetitions.

Procedure

Participants were instructed to respond as quickly and as accurately as possible. They responded by pressing the "L" key with their left index finger and the "R" key with their right index finger. For the *implements* task, they pressed the "L" key for a *musical instrument* and the "R" key for a *kitchen utensil*. For the *plants* task, they pressed the "L" key for a *tree* and the "R" key for a *flower*. For the *animals* task, they pressed the "L" key for a *bird* and the "R" key for a *mammal*. The category–response mapping information was continuously presented on the screen.

Stimulus presentation time was dependent on word length and lasted about 800 ms ($M = 805$, $SE = 16$). Response time (RT) recording started with stimulus onset. The response–stimulus interval was 250 ms. Each block comprised 96 stimulus–response trials. Blocks were separated by breaks of 30 seconds. Two initial pseudorandom blocks were used to train participants on the category–response mapping. Then, four experimental blocks (Blocks 3–6) followed. Task and response order were dependent on sequence condition. In Block 7, the training sequence was replaced by the appropriate counterbalancing sequence. In Block 8, the original ordering was reinstated.

After the test session, 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 and then had to verbally reproduce any sequence information they could still remember or guess.

Data analysis

Mean error rate (averaged from Blocks 3 to 8) was less than 5% and comparable between conditions, and was not analysed further. For RT analyses, trials on which errors were made, trials that followed an error, and the first six trials of each block were excluded. Median RTs per block and participant were computed for the three tasks separately, and then averaged per block and participant.

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.

RESULTS

RT results are shown in Figure 1. RTs decreased initially in all blocks, reflecting a general practice effect. The mean training scores (i.e., the difference between performance at Block 3 and at Block 6) were 204 ms ($SE = 32$) in the *seq-seq* condition, 136 ms ($SE = 24$) in the *seq-ran* condition, 140 ms ($SE = 13$) in the *ran-seq* condition, and 117 ms ($SE = 23$) in the *ran-ran* condition. A two-factorial analysis of variance (ANOVA) with block (3–6) as a within-subject factor and sequence (*seq-seq*, *seq-ran*, *ran-seq*, *ran-ran*) as a between-subjects factor revealed a significant effect of block, $F(2.47, 187.35) = 83.46$, $p < .001$,

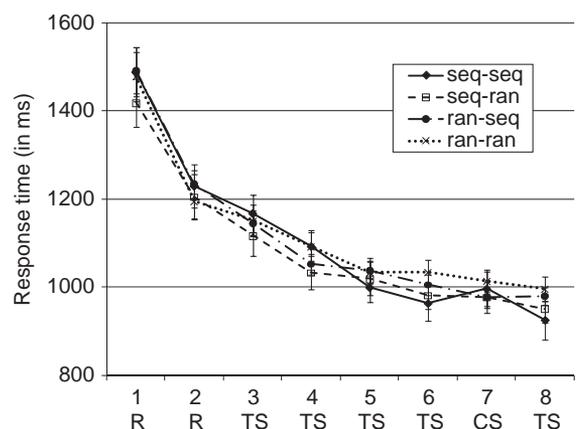
Figure 1. Response time as a function of blocks (R: random; TS: training sequence; CS: counterbalancing sequence), separately for sequence conditions (*seq-seq*: tasks and responses sequenced; *seq-ran*: tasks sequenced, responses randomly ordered; *ran-seq*: tasks randomly ordered, responses sequenced; *ran-ran*: tasks and responses randomly ordered). Error bars represent standard errors.

$\eta^2 = .52$, and a significant Block × Sequence interaction, $F(7.40, 187.35) = 2.43$, $p = .019$, $\eta^2 = .09$. However, the effect of sequence was not significant, $F(3, 76) = 0.28$, $p = .840$, $\eta^2 = .01$.

Disruption scores (i.e., the difference between performance at Block 7 and mean performance at Blocks 6 and 8) were calculated to assess sequence-specific learning. Mean disruption scores were 52 ms ($SE = 20$) in the seq-seq condition, 11 ms ($SE = 10$) in the seq-ran condition, −15 ms ($SE = 55$) in the ran-seq condition, and −1 ms ($SE = 11$) in the ran-ran condition. A two-factorial ANOVA with block (7 vs. 6 and 8 averaged) as a within-subject factor and sequence (seq-seq, seq-ran, ran-seq, ran-ran) as a between-subjects factor gave a significant Block × Sequence interaction, $F(3, 76) = 4.48$, $p = .006$, $\eta^2 = .15$. Neither the effect of sequence, $F(3, 76) = 0.47$, $p = .704$, $\eta^2 = .02$, nor the effect of block was significant, $F(1, 76) = 2.95$, $p = .090$, $\eta^2 = .04$. In a separate one-sample t-test, the disruption score of the seq-seq condition was different from zero, $t(19) = 2.65$, p(one-tailed) $= .008$, $\eta^2 = .27$. However, no differences were found for the seq-ran, ran-seq, and ran-ran conditions (all $ps > .20$).[1] Thus, sequence learning occurred only in the seq-seq condition.[2]

Next, we tested the impact of explicit knowledge on sequence learning. Only the seq-seq condition was included, because only in this condition sequence learning occurred. Overall, the mean number of correctly reproduced sequence elements was 0.20 ($SE = 0.09$) for the sequence of tasks and 0.70 ($SE = 0.11$) for the sequence of responses. No participant was able to generate the whole task sequence, but four reported the whole response sequence. When these four participants were excluded, the mean disruption score was 30 ms ($SE = 13$), which was still significantly different from zero, $t(15) = 2.22$, $p = .021$, $\eta^2 = .25$.

Modality effect

In a previous study, we used the same TSL paradigm but presented stimuli visually rather than auditorily (Meier & Cock, 2010, Exp. 1). Mean disruption scores were 127 ms ($SE = 41$) for the seq-seq, 6 ms ($SE = 7$) for the seq-ran, 17 ms ($SE = 14$) for the ran-seq, and −1 ms ($SE = 13$) for the ran-ran condition.[3] We compared the disruption scores between the two experiments with a two-factorial ANOVA with modality (auditory vs. visual) and sequence (seq-seq, seq-ran, ran-seq, ran-ran) as between-subjects factors. This analysis showed a significant effect of sequence, $F(3, 152) = 10.623$, $p < .001$, $\eta^2 = .17$. Post hoc Tukey HSD tests revealed that the disruption score of the seq-seq condition was significantly higher than any other condition (all $ps < .001$), whereas the seq-ran, ran-seq, and ran-ran conditions did not differ from each other (all $ps > .95$). This suggests sequence learning in the seq-seq condition only. The effect of modality and, more importantly, the Modality × Sequence interaction were not significant, with $F(1, 152) = 3.59$, $p = .060$, $\eta^2 = .02$, and $F(3, 152) = 1.93$, $p = .127$, $\eta^2 = .04$, respectively. These results indicate that sequence learning was not affected by modality. Numerically, the disruption score of the visual seq-seq condition was larger than that of the auditory seq-seq condition. However, a direct comparison revealed no significant difference, $t(38) = 1.64$, $p = .109$.

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[1]The disruption score of the seq-ran condition was not significantly different from zero, the effect size (d_z) was 0.26. The required sample size to reach significance (with alpha level set to .05, one-tailed) would be 165 participants (G*Power Version 3.1.2; Faul, Erdfelder, Lang, & Buchner, 2007). Thus, the lack of finding a learning effect is not due to a power problem.

[2]We ran additional analyses to test whether sequence learning in the seq-seq condition affected n–2 task repetition costs. In task switching studies, it has been shown that n–2 task repetitions (e.g., ABA) are associated with a performance cost relative to nonrepetitions (e.g., CBA; see Koch, Gade, Schuch, & Philipp, 2010, for a recent review; Mayr & Keele, 2000). We compared n–2 task repetition costs of Block 7 (transfer sequence) to mean n–2 task repetition costs of Blocks 6 and 8 (training sequence). A two-factorial ANOVA with block (7 vs. 6 and 8 averaged) and n–2 task repetition (n–2 task repetition vs. nonrepetition) as within-subject factors revealed a significant effect of block (mean RTs were slower in Block 7 than in Blocks 6 and 8 averaged; 1008 ms vs. 956 ms), $F(1, 19) = 7.77$, $p = .012$, $\eta^2 = .29$, but no effect of n–2 repetition, with $p = .072$ (mean RTs of n–2 task repetition trials did not significantly differ from n–2 nonrepetition trials; 995 ms vs. 969 ms). Importantly, the Block × n–2 repetition interaction was not significant, with $p = .304$. Thus, task inhibition did not decrease as a function of sequence learning. This result is in line with findings from Koch et al. (2006), who found reduced task inhibition in a TSL paradigm only in intentional-learning participants with explicit knowledge but not in incidental-learning participants. We thank Iring Koch for suggesting this analysis.

[3]For the between-experiments comparison, we used a different data filter than in the original study by Meier and Cock (2010). Therefore, the disruption scores of the "visual" experiment differ slightly from the previously published data.

DISCUSSION

The purpose of this study was to investigate whether task sequence learning occurs with auditory stimuli. We used classification tasks and auditory stimuli in order to prevent the emergence of a repeating perceptual pattern. First, the results showed implicit sequence learning with auditory stimuli. This finding is in line with previous SRT studies with auditory stimuli (e.g., Buchner et al., 1997, 1998; Dennis et al., 2006; Riedel & Burton, 2006; Schmidtke & Heuer, 1997). In addition, a comparison between the auditory and a visual version of this experiment revealed that sequence learning effects were similar across modalities. This finding is in contrast to evidence from implicit statistical learning suggesting an advantage of auditory learning compared to visual learning (Conway & Christiansen, 2005, 2009). If at all, the present results reveal rather the reverse, that is, a numerical benefit for visual compared to auditory stimuli in implicit task sequence learning.

Second, irrespective of modality, the results showed implicit sequence learning only in the correlated sequences condition, that is, when both a task and a response sequence were present. In contrast, no learning occurred in the single sequence conditions and in the control condition. These results are in line with the correlated streams explanation and show that this account can be generalised across modalities (cf., Meier & Cock, 2010; Weiermann et al., 2010).

However, rather than correlated sequences, an alternative explanation of the present results might be that sequence learning was simply due to the emergence of a sequence of stimulus categories (e.g., "tree-mammal-musical instru-ment-bird-flower-kitchen utensil"). The present data alone cannot dismiss this interpretation. However, an earlier study with a similar setup specifically tested this alternative explanation (Meier & Cock, 2010, Exps. 2 and 3). There, sequence learning occurred in correlated se-quences conditions even when a task sequence was combined with a sequence of stimulus loca-tions or when a response sequence was combined with a stimulus location sequence. Neither of these conditions involved a sequence of stimulus categories. Thus, it is unlikely that the emergence of a stimulus category sequence is sufficient to explain the present results. Moreover, in other studies in which bivalent stimuli were used and

instructional task cues were correlated with tasks, sequence learning was also found in the absence of a category sequence (e.g., Heuer et al., 2001; Koch, 2001; Weiermann et al., 2010, Exp. 1). These results indicate that the presence of a sequence of stimulus categories is not the main cause for the learning effects and they suggest that the presence of correlated sequences is a more general explanation.

Similarly, it might be argued that an alternative explanation for the lack of learning in the single response sequence condition is that nominally same responses are not represented as the "same" responses in terms of their meaning (cf., Schuch & Koch, 2004). For example, a left-hand response indicates "bird" in the animals task but "tree" in the plants task. The continuous presentation of the category-to-response mapping on screen might even have enhanced the tendency to access the responses via their meaning. Hence, the regular response sequence of the single response sequence condition (e.g., "L-R-L-L-R-R") would have been irregular in terms of the response meanings. In contrast, in the correlated sequences condition, the response sequence was regular in terms of responses and in terms of response meanings (i.e., stimulus categories). Again, the present data alone cannot dismiss this interpretation. However, even if one considers the *response* sequence as irregular in the single response sequence condition, there still is a rather simple regular *motor* sequence of left- and right-hand keypresses. As already noted, when this motor sequence was correlated with a sequence of stimulus locations, sequence learning occurred even though the meaning of the responses was "irregular" (Meier & Cock, 2010, Exp. 2). These results indicate that it is rather the correlation of two streams of information that is a prerequisite for implicit learning to occur than that it is necessary that the meanings of the responses are regular.

Although our results showed no learning in single-sequence conditions, we cannot exclude that learning of single-stream sequences can be found under different conditions. For example, Goschke and Bolte (2007) investigated implicit learning of a stimulus category sequence using easy-to-name line-drawings of simple objects from four different semantic categories. The semantic categories were presented in a se-quenced order and the specific stimulus for each trial was selected randomly. Participants were instructed to name the specific stimulus on each

trial as fast as possible. The results showed evidence of learning the stimulus category sequence. However, it is possible that participants sub-vocally verbalised the categories. This strategy was experimentally instructed in Experiment 1, and the pattern of this experiment did not differ from the subsequent experiments where these instructions were not given. Thus, it seems possible that at least some of the participants verbalised the categories and, as a consequence, sequence of subvocally verbalised categories would correlate perfectly with the sequence of visually presented categories.

In another line of research, Remillard has provided evidence for pure perceptual-based implicit sequence learning (e.g., Remillard, 2003, 2009; see also Deroost & Soetens, 2006). Using probabilistic sequences rather than repeating complex sequences as in standard sequence learning studies, Remillard showed that participants are able to learn high- versus low-frequency transitions. However, the experimental method of these studies differs considerably from the SRTT or the TSL paradigm, for example, with regard to the sequential information learned (transition probabilities vs. repeating sequences) and with regard to the training duration (several sessions vs. a single session). Thus, possibly, sequence learning and learning of sequential probabilities are based on different processes.

It is noteworthy that in the SRTT, the standard paradigm for the investigation of sequence learning, correlated streams are typically present (i.e., the stimulus sequence and the response sequence). This concurrence of a stimulus sequence and a response sequence has evoked an ongoing debate on what exactly is learned in the SRTT (see Abrahamse, Jiménez, Verwey, & Clegg, 2010, for a recent review). According to the correlated streams account, sequence learning in the standard SRTT is presumably neither purely perceptual-based (S-S learning; e.g., Clegg, 2005; Howard, Mutter, & Howard, 1992) nor purely motor-based (R-R learning; e.g., Nattkemper & Prinz, 1997; Willingham, Wells, Farrell, & Stemwedel, 2000), but rather involves learning the correlation between the stimulus sequence and the response sequence. This explanation is also compatible with evidence of learning the sequence of rules associating stimuli and responses (S-R learning; e.g., Schwarb & Schumacher, 2010; Willingham, Nissen, & Bullemer, 1989) and with evidence of response-effect learning in the SRTT (Ziessler & Nattkemper, 2001) that are also based

on the presence of two correlated streams of information.

The correlated streams account may be a general explanation for implicit sequence learning in many different situations, but a detailed discussion of all these situations is beyond the scope of this study. Here, we were motivated by a more modest goal—to demonstrate that implicit task–response sequence learning can occur with auditory stimuli and that the correlated streams account holds for this particular experimental setup.

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