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ORIGINAL ARTICLE

RT patterns and chunks in SRT tasks: a reply to Jiménez (2008)

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Abstract Previous research has shown that the formation of units or chunks contributes to sequence learning in serial reaction time (SRT) tasks (Koch & Hoffmann, Psychological Research 63:22–35, 2000). However, some of these results were assumed to be unrelated to sequence learning and to reflect preexistent response tendencies (Jiménez, Psychological Research 72:387–396, 2008). In the Experiment of this study, we aimed to evaluate this issue. One group of participants responded to a strongly structured sequence of digits by pressing one out of six response keys depending on digit identity. In a second experimental group, a weakly structured sequence was presented, which contained comparable transitions among the single items, but did not have series of ascending and descending triplets of successive digits. The results indicated that serial learning in general as well as response tendencies to certain fragments of the sequence were modulated by the manipulation of the strength of relational patterns. The data are consistent with the notion that relational patterns contribute to the formation of chunks as suggested in the original study.

Introduction

One of the preferred methods of investigating sequence learning is the serial reaction time (SRT) task (Nissen & Bullemer, 1987). In a typical SRT experiment, participants respond to successively presented stimuli as quickly as possible, usually by pressing response keys. Each response triggers the presentation of the next stimulus, to which subjects respond anew. Sequence learning is usually demonstrated by a decrease of performance when a fixed repeatedly practiced sequence is replaced with a random series of stimuli.

Several findings suggest that sequence learning in SRT tasks comprises the organization of the sequence into chunks (e.g., Cleeremans, Destrebecqz, & Boyer, 1998; Collard & Povel, 1982; Povel & Collard, 1982; Restle, 1970; Rosenbaum, Kenny, & Derr, 1983; Servan-Schreiber & Anderson, 1990). For instance, introducing consistent temporal and spatial inhomogeneities in the stimulus presentation proved to facilitate the parsing of the sequence and thus, to improve learning (Frensch, Buchner, & Lin, 1994; Stadler, 1993, 1995; Zießler, 1993). Other studies have suggested that systematic relational patterns within and between subsequences are also used for the formation of chunks accelerating the learning of the whole sequence (Hoffmann & Sebald, 1996; Koch & Hoffmann, 2000). Unlike statistical, temporal, and spatial structures, the concept of relational patterns is related to the systematicity of relations among successive stimuli or responses (Restle, 1970). For instance, the letter sequence ABCCAB can be parsed into two triplets of alphabetically ascending and descending runs (i.e., the letters within each run are systematically related by transposition). Moreover, the first run is inverted by the second one indicating a higher-order relation between the two triplets.

An example for the role of relational patterns within the SRT paradigm is provided by the study of Koch and Hoffmann (2000). In Experiment 1, participants

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responded to a sequence of 24 digits by pressing one out of six keys depending on the digit identity. Within a strongly structured sequence (123 321 456 654 123 234 345 456), relational patterns were introduced by ascending and descending triplets of successive digits and responses (i.e., "runs"). Moreover, the succession of the triplets was organized by systematic relational patterns as inversions (e.g., 123–321) and transpositions by either tree steps (e.g., 123–456) or one step to the right (e.g., 123–234). Such transitions between triplets were also implemented in a control sequence, which had exactly the same statistical structure (i.e., the frequency distributions of single stimuli, bigrams, trigrams etc., were identical with those of the strongly structured sequence). However, the triplets in this control sequence did not constitute ascending and descending runs either in the succession of digits, in the succession of responses, or in the succession of digits and responses. This variation was accomplished by an appropriate variation of the S-R mappings. The results indicated substantial sequence learning in those conditions, in which the succession of keystrokes contained runs. In contrast, learning was reduced when there were no runs in the succession of keystrokes. Moreover, analyzing the RT pattern with respect to the 24 serial positions of a response sequence containing runs, the authors observed that the RTs consistently increased at the beginning of each of the eight triplets (i.e., runs) and decreased within each triplet. These results were interpreted as evidence for the formation of "response chunks" in accordance with triplets, in which three adjacent keys were to be pressed either from left to right or from right to left (p. 26).

This conclusion has been recently questioned by Jiménez (2008). According to the author, the improvement in sequence learning may merely be due to the fact that a relationally organized sequence of runs is more salient and thus provokes explicit sequence learning, which has been shown to be more effective than implicit learning. In addition, the increase of RTs at the beginning of each triplet and the decrease of RTs within the runs may rather be related to hand switches, immediate repetitions, and reversals at the beginning of the triplets, which are unrelated to learning. Jiménez (2008) reports a conceptual replication and extension of that condition of the Koch and Hoffmann's (2000) study, in which the runs were realized in stimuli and responses as well. The main results of this study were highly comparable to those obtained by Koch and Hoffmann (2000). Subjects learned the structure efficiently, and a similar RT pattern over the 24 sequence positions was observed as reported in the original study: An increase in RTs at the beginning of each triplet was followed by a decrease of RTs within the runs. However, this position effect was already present in the first training block and did not increase over the experimental session. In addition, a detailed analysis of the first block did not yield any evidence for the development of the triplet-related RT pattern. Instead, the RT patterns observed at the beginning of the first block, i.e., before any training, were comparable with those observed by Koch and Hoffmann (2000) after training and by Jiménez (2008) throughout the experiment. Since the triplet-related RT pattern was already obtained before training, the same author concluded: "Thus, the observation of slower RT at the beginning of a triplet could not be unequivocally taken as evidence of chunk learning" (p. 394). Instead, he argued that the hand switches, the repetitions, and the reversals (i.e., repetitions of the $n-2$ trial) at the beginning of the triplets decelerated the responses independently of any learning effects. Thus, Jiménez (2008) points to a confound of two variables (relational structure and characteristics of certain transitions) in the original experiment of Koch and Hoffmann (2000), both of which may be responsible for fast sequence learning and the appearing RT pattern. This study was designed to disentangle the impact of both variables.

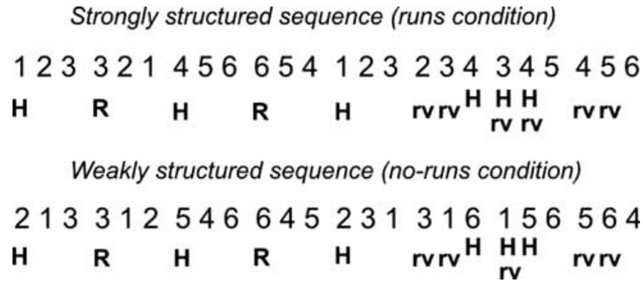

Fig. 1 Two digit sequences were used in this study. Both series contain highly comparable item transitions, such as hand switches (H), immediate repetitions (R), and reversals (rv), which were assumed to be unrelated to learning (Jiménez, 2008). The only one exception is related to the serial position 20, at which one reversal is missing as compared to the strongly structured sequence. Note, the triplets within the weakly structured sequence do not constitute ascending and descending runs

Based on the main argument of Jiménez, according to which the RT patterns obtained by Koch and Hoffmann (2000) are unrelated to learning and may merely reflect preexisting response tendencies, we modified the original sequence so that hand switches, repetitions, and reversals occurred at the same serial positions, i.e., at the beginning of triplets, while the relational patterns within the triplets, i.e., the runs, were eliminated (see Fig. 1). For comparison, another group of participants responded to the original sequence used by Koch and Hoffmann (2000) and

Jiménez (2008) as well, in which the triplets were organized as runs of digits and responses.[1]

If the mentioned transitions may exclusively account for the observed RT patterns, the triple-related RT patterns should remain unaffected by the implemented manipulation. Moreover, no learning-dependent changes of this RT pattern should be obtained. Finally, the amount of sequential learning should be of a comparable magnitude in both sequences.

Method

Participants

Twenty-eight undergraduate students of the University of Würzburg participated in partial fulfillment of course requirements. The sample comprised 25 females and 3 males, with ages ranging from 19 to 34 years (mean age 21.5, SD = 3.55). Fourteen subjects each were randomly assigned to one of two experimental conditions.

Task and apparatus

Participants were asked to respond to a digit between 1 and 6 by pressing a key on a standard QWERTZ keyboard as fast and accurately as possible. The digits were presented individually in blue on white at the center of a 15″ VGA monitor. The digits 1–6 were assigned to the keys "X," "C," "V," "N," "M," and ";" from left to right, respectively. Furthermore, the six response keys were assigned from left to right to the ring, middle, and index fingers of the left hand and to the index, middle, and ring fingers of the right hand, respectively.

Experimental procedure and design

The experiment started with two practice blocks. In either of them, a pseudo-random sequence of 24 digits was presented eight times. This pseudo-random series was identical to that used by Koch and Hoffmann (2000): 254534162361325621546143. The same pseudo-random sequence was used in block 6 that served as test block. In the intermediate blocks 3, 4, and 5, the relational structure of the stimulus and response sequence was varied between two subgroups of participants.

The first group of participants responded to the same sequence that was used by Koch and Hoffmann (2000) in the D+ K+ condition of Experiment 1, and by Jiménez (2008). In this sequence, the succession of digits and responses were organized in triplets of ascending and descending runs, which followed each other in regular way (the "runs-sequence" hereafter: 123 321 456 654 123 234 345 456). The second group of subjects responded to the following sequence: 213 312 546 645 231 316 156 564, which was organized in such a way that repetitions, hand switches, and reversals occurred at the beginning of triplets, whereas the runs within the triplets were eliminated (the "no-runs-sequence" hereafter, see also Fig. 1).

The latency between the onset of the stimulus presentation and the key press was defined as reaction time (RT). The response–stimulus interval (RSI) was set to 250 ms. When one of the participant's responses was incorrect, the German word for error appeared during the RSI. At the end of each block, subjects received information about the mean RT of the previous responses. The RT difference between block 5 and block 6 was used as a measure of sequence learning.

After completing the SRT task, participants were debriefed about the presence of the sequences and were asked to write down as many of the sequence elements as possible in correct order.

Results

The RTs from error trials were excluded from analyses (5.03%). Moreover, responses with a latency above 2,000 ms were considered as outliers and were discarded from further analyzes (0.24%). For the remaining trials, median RTs were computed for each subject and block of trials. The mean medians for each condition and block are shown in Fig. 2.

The initial level of performance achieved in the first two practice blocks was comparable for the runs and the no-runs-condition. However, the RTs over the next three training blocks of trials showed condition-specific courses (see Fig. 2). The average RTs in the runs-condition rather steeply decreased during the training blocks and in the fifth block were considerably shorter compared to the no-runs-condition. In contrast, training-related changes of the RTs in the no-runs-condition were only weakly pronounced. These condition-specific and learning-related changes in performance are substantiated by the results of an analysis of variance (ANOVA) with block as a within-subjects factor (5 levels)[2] and condition as a between-subjects factor (2 levels)

[1] This variation resembles the variations of Experiment 1 in the study of Koch and Hoffmann (2000) in which the runs within the triplets were eliminated by using different S-R mappings. However, by changing the S-R mappings, not only different S-R compatibilities were created but also the positions of hand switches and reversals were changed so that RT patterns over the triple positions were no longer comparable to each other.

[2] The last test block was not included in this analysis.

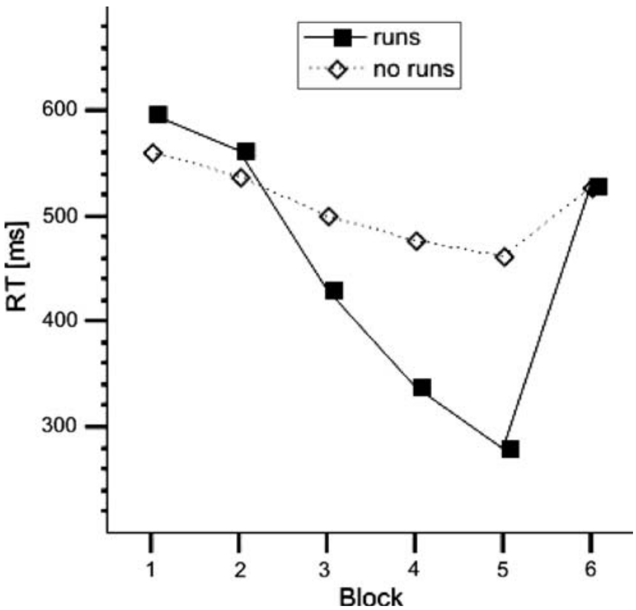

Fig. 2 The RTs as function of the experimental groups and of block of trials

indicating a highly significant Block × Condition interaction, $F(4, 104) = 21.25$, $P < .001$.

As a measure of structure-specific learning, we calculated the individual differences of RTs between block 5 and block 6. The mean differences were 252 ms ($SD = 141$ ms) and 65 ms ($SD = 21$ ms) for the runs- and the no-runs-conditions, respectively. These differences were significant, $t(13) = 6.67$, $P < .001$ and $t(13) = 11.87$, $P < .001$, and indicated structure-specific learning in both conditions. An analysis of variance (ANOVA) with the between-subjects factor condition performed on these difference values revealed a highly significant main effect condition, $F(1, 26) = 23.93$, $P < .001$. Sequence learning was substantially impaired when the ascending and descending runs within the triplets were eliminated.

Figure 3 (left) illustrates the mean RTs for each of the 24 serial positions of the sequence averaged over all the three training blocks. By and large, the data show a pattern similar to that found by Koch and Hoffmann (2000) as well as by Jiménez (2008) as the RTs rather regularly increase at the beginning of each triplet and decrease within each triplet. In particular, in the first half of the runs-sequence, the pattern reflects very systematically the triplet-structure. However, condition-specific differences are also present: Subjects who responded to the no-runs-sequence showed a less consistent pattern as compared with the runs-sequence. In order to quantify these differences, we computed the mean RTs separately for the keystrokes corresponding to the first, second, and third positions of all the eight triplets. The corresponding data are shown in Figure 3 (right).

An ANOVA with condition as between-subjects factor and position as within-subjects factor, which was performed with these scores, yielded a significant main effect position, $F(2, 52) = 55.05$, $P < .001$, a significant main effect condition, $F(1, 26) = 15.02$, $P < .001$, and, more importantly, a significant Condition x Position interaction, $F(2, 52) = 12.51$, $P < .001$. As can be seen in Fig. 3 (right), this interaction reveals that the triple-related serial position effect reported by Koch and Hoffmann (2000) and replicated by Jiménez (2008) was substantially attenuated in the no-runs-condition of this study.

We also analyzed a possible change in this serial position effect over all training blocks. Figure 4 shows the corresponding means for the two sequence types. In line with the results reported by Jiménez (2008), the position effect is already present in the first training block of the runs-condition, $F(2, 26) = 30.26$, $P < .001$, and do not seem to be affected by the course of training. However, as shown in Fig. 4, the data of the no-runs-sequence seem to indicate that the position effect increases over time of training.

We conducted a linear regression analysis to evaluate this observation. This analysis was performed for each subject and each triplet position with median RTs as dependent variable and block as independent variable.[3] The critical measure was the slope value extracted from the regression equations, which represents how steep the regression line is: The more negative this value, the stronger the decrease in RTs in the course of the three training blocks. Figure 5 shows mean unstandardized regression coefficients (B) indicating the slopes of the individual regression lines for each position within the triplet in both experimental groups. The negative slope exhibited the tendency to decrease from the first to the third triplet position in the runs condition suggesting a trend toward a decrease of the position effect. A similar finding, which may presumably be a result of a floor effect, has also been reported by Jiménez (2008). In contrast, the data of the no-runs condition revealed an opposite pattern, as the negative slope increased from the first to the third triplet position. We performed an ANOVA with triplet position and condition as factors and regression coefficients as dependent variable. The critical Condition × Position interaction just fell below significance, $F(2, 52) = 3.01$, $P = .058$.

Participants' performance in the post-experimental recall was scored by determining the number of recalled triplets, which were part of the respective sequence. The participants of the runs condition produced a mean number of 5.64 triplets ($SD = 2.17$). In contrast, only 1.64 of eight

[3] We would like to thank Bernhard Hommel suggesting this kind of analysis.

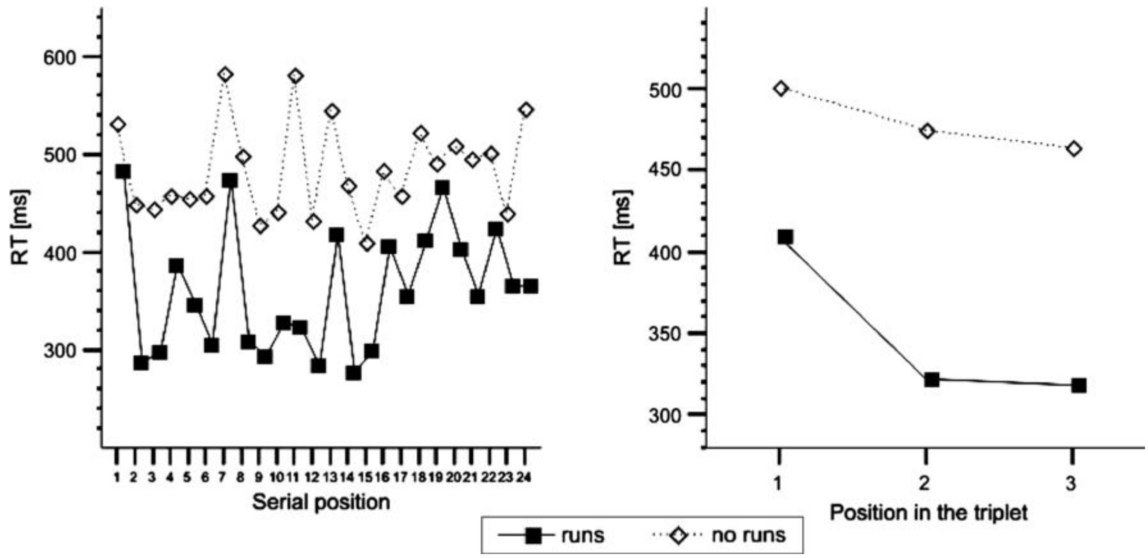

Fig. 3 *Left* Average RTs in the two experimental conditions as a function of serial position within the 24-item sequence. *Right* RTs as a function of the condition and the position within the triplet

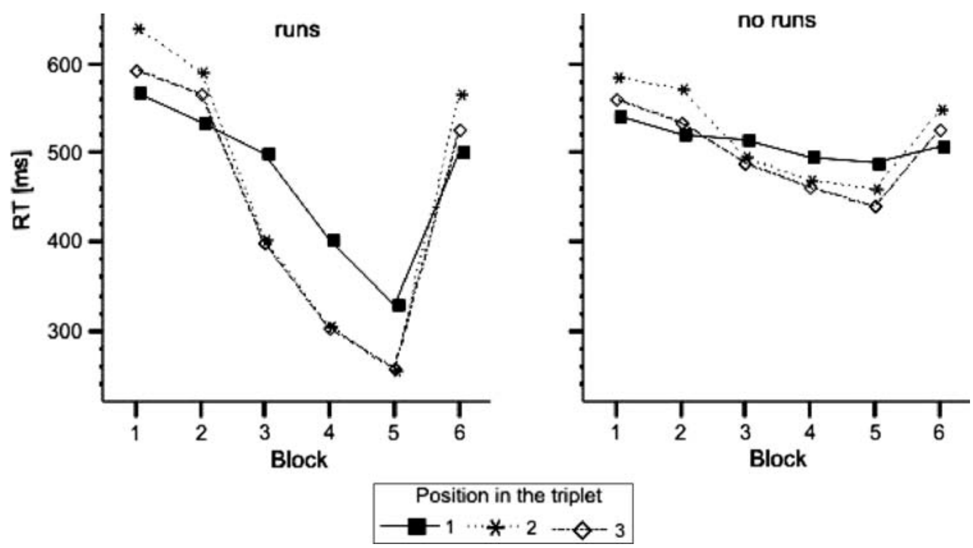

Fig. 4 Average RTs for the runs and no runs conditions as a function of the position within the triplet and the blocks of trials

triplets were recalled on average in the no-runs condition ($SD = 1.22$). This difference was significant, $t(26) = 6.02$, $P < .001$, and suggests that the participants of the runs condition possessed considerably more explicit knowledge about the sequence structure than the participants of the no-runs condition.

Discussion

Koch and Hoffmann (2000) reported a quite consistent increase in RTs at the beginning of triplets, which constituted ascending and descending runs, and a subsequent decrease of RTs within the runs. This result was taken as evidence for the formation of sequence units or chunks. However, the same RT pattern was shown to be already present before any systematic training and to be widely unaffected by the course of training (Jiménez, 2008). As nicely illustrated by Jiménez (2008), this fact may theoretically be explained by hand switches, repetitions, and reversals, which frequently occurred at the beginning of the triplets. More importantly, these transformations were assumed to slow down the performance independently of any learning mechanisms (Jiménez, 2008).

We tested this idea in this experiment by analyzing a sequence, in which the same transitions were implemented at the beginning of each triplet but the runs within the triplets were eliminated. Assuming that the existence of systematically related runs will support sequence learning by the formation of chunks, we expected that the

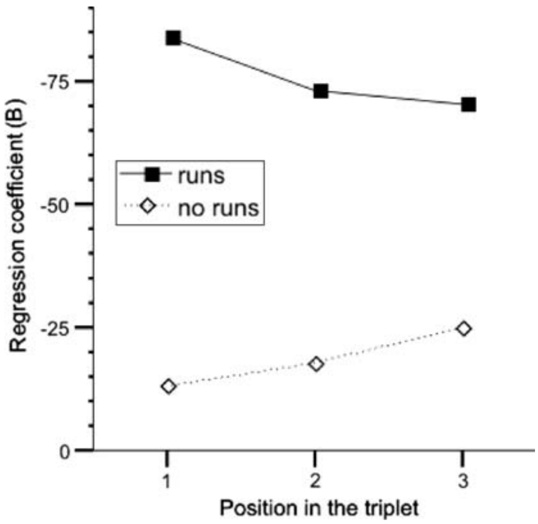

Fig. 5 Mean unstandardized regression coefficients (B) of the two experimental conditions as a function of the position within the triplet

"distraction" of runs will result in a decrease in learning performance and in an attenuation of the triplet-related serial position effect. In contrast, if the impact of the mentioned transitions on RTs is unrelated to learning, and chunk formation does not take place, then both measures should be unaffected as compared with the sequence of ordered runs. The results were in line with the former prediction as well as with other similar findings (e.g., Hoffmann & Sebald, 1996; Koch & Hoffmann, 2000): Subjects learned the no-runs-sequence less efficiently and showed a less pronounced serial position effect in comparison to the runs-sequence. Moreover, the RT pattern relating to the serial positions did not increase over the course of training in the runs-condition. However, some indices for the development of this position effect were observed in participants, who trained the no-runs-sequence: The RT differences across the three positions of the triplets tended to increase from the first to the third training block. Hence, the results support the notion that the amount of sequential learning and the observed local RT patterns in the runs-condition are at least partly the result of chunk formation by using the systematicity in the order of runs.

This conclusion seems to be at odds with the observation reported by Jiménez (2008) that the triplet-related RT pattern was already evident early in the experiment and before systematic learning effects could be expected. A similar result was also obtained in the runs-condition of this study. However, this fact does not necessarily speak against the contribution of chunk formation to sequence learning if one assumes that the runs are used from the outset to structure the sequence. Jiménez (2008) discusses a similar notion, but argues that "… this account does not seem to be very plausible, given the well known limits of human working memory (p. 395)." However, the formation of chunks is known to be the most appropriate method to overcome the limits of human working memory (Miller, 1956; Ericsson & Chase, 1982). For instance, a phone number such as 16322361 can be stored in an instant if it is parsed into the right chunks: ((16)(32)(2361))—partitioned in these chunks, the sequence can easily be stored by the number 16 and two rules: first, double 16 and then repeat the resulting string in reversed order (cf. also Restle, 1970). In the same way, it is quite probable that participants try to store the runs-sequence from the beginning on by relating the salient and easily detectable runs into a systematic order. As a result, the triplet-related RT pattern appears from the beginning. In contrast, in the no-runs-sequence, in which the runs were eliminated, no runs are detectable. Nevertheless, the sequence of finger movements appears to become at least loosely parsed into triplets by salient transitions such as repetitions, hand switches, and reversals which are requested every third step. Such operations may indeed build integral parts of "rule systems" or "structure trees" underlying the learning of regular patterns (e.g., Restle, 1970). However, as the triplets are less salient compared to runs, the acquisition of a regular structure becomes more difficult, as compared with the runs condition. Accordingly, the triplet-related RT patterns are clearly attenuated in the beginning and become only slightly strengthened in the course of learning. This idea seems also to be supported by the free recall data. Participants responding to the runs-sequence were able to correctly reproduce 5.6 of eight triplets on average. In contrast, a mean number of only 1.6 triplets was correctly recalled in the no-runs condition. Thus, the responding to the strongly structured sequence was accompanied by the acquisition of a considerable amount of explicit knowledge. In contrast, learning in the no-runs condition was mainly implicit.

According to this, one may argue that if relational structure of a sequence is very obvious, then chunk learning may occur at the very beginning of training and may help participants to explicitly parse the whole sequence into segments. Moreover, such explicit processes appear to operate on a rather global level in the course of training by accelerating the learning in general, rather than to affect local response patterns (i.e., responses within the chunks). On the other hand, if the relational patterns are less salient, then the initial learning may be more fragmentary and thus, may surpass the explicit memory limitations. However, in the course of training, learners may gradually build up a more general representation of the sequence by using salient markers, such as certain types of transitions to reduce the amount of information. This may possibly explain a rather slow emergence of explicit knowledge in the no-runs condition of the given experiment. It should be noted that the tendency toward position-specific learning rates in the no-runs condition may also be explained by statistical learning: Mean conditional probabilities of order 1 are larger for the second and third element of the triplets (.44 and .39, respectively), as compared to those for the first element (.27). Accordingly, learning dependent changes may progress faster for the second and third element of the triplet, than for the first element. However, the distribution of corresponding probabilities over the triplet positions of the runs-sequence, in which an opposite trend relating position-specific learning was observed, is comparable to that of the no-runs -sequence (.31, .55, and .53 for the first, second, and third positions, respectively). Thus, a purely statistical account appears to be insufficient to explain the results.

Altogether the results of this study reveal that the triplet-related RT patterns in the runs-sequence are not solely due to the specificity of certain response transitions at the beginning of the triplets. Rather, it has been shown that the existence of runs substantially contribute to the emergence of the triplet-related RT patterns and the fast sequence learning as well. Thus, the results confirm the use of relational structures between elements of a sequence for the formation of chunks in SRT tasks and the contribution of such chunk formation to sequential learning.

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