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The impact of motor responses on serial-pattern learning

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Abstract Subjects are able to learn even very complex serial patterns in serial-reaction-time tasks. The investigation of the learning processes behind this phenomenon has yielded contradictory results. Some studies have come to the conclusion the subjects had learned the sequence of stimuli. Other studies have assumed that the sequence of responses had been learned or a combination of both stimuli and responses. The present experiments stress the impact of motor responses on serial-pattern learning. The subjects had to respond to serial targets that were presented within a matrix of distractors. The position of each target could be predicted from the identity and position of the previous target. If the subjects were to learn this pattern, they would be able to speed up the search for the target and give faster responses. The results indicated that the relation between the target identity and the position of the next target was acquired much better by those subjects who had to respond to each target with a special motor response. If the same response was required for the relevant targets, knowledge of the rule was somewhat fragmentary. To explain these results, mechanisms of motor learning and motor planning are discussed. It is assumed that learning of the rules occurs if the position changes appear to be effects of different motor responses.

Introduction

In the last few years numerous papers have appeared, addressing the problem of serial-pattern learning. Typically, the experiments have been perceptual-motor tasks. In these tasks subjects have to respond to a series of stimuli. The sequence of the stimuli is determined by rules. After some training, the performance of the subjects tends to improve, as lower response latencies or lower error rates indicate. If the rules are changed, or a random sequence is suddenly used, the performance deteriorates (e.g., Lewicki, Czyzewska, & Hoffman, 1987; Willingham, Nissen, & Bullemer, 1989; Cohen, Ivry, & Keele, 1990). These results prove that the subjects have learned the sequence, even if they are unaware of the rules.

The fact that the rules determining the sequence could be very complex was shown by Lewicki, Czyzewska, and Hoffman (1987). In their experiment, subjects had to respond to the location of a pre-specified target. The required response was to press a button corresponding to the quadrant of the screen that contained the target. In the first six trials of each block the target was easy to find, since it was the only stimulus that appeared on the screen. On the seventh trial the target was embedded in a matrix of 35 distractor stimuli. The sequence of four of the six previous target locations determined the target location in the seventh trial. Since every possible order was used, there were 24 rules of this kind. Each quadrant was determined by 6 rules. If the subjects were able to learn the rules, they could predict the next target location and thereby the next response. In fact the responses were observed to speed up during the training. After an extensive training of 12 hours a change in the rules produced a major negative-transfer effect. This indicates that the subjects had acquired some knowledge of the very complex rule pattern, but were not able to formulate the rules.

What is the basis of this learning process? What kind of knowledge is acquired by the subjects? In answer to these questions, two possibilities are discussed in the literature. The first possibility is that the subjects may have learned the stimulus sequence. This allows for the anticipation of the next stimulus and thus also for a preparation of the next response. The second possibility is that the subjects may have learned the sequence of the motor responses. According to this view, the next response is predicted directly on the basis of the sequence of the previous responses. Both alternatives have been examined in several experiments. The results are inconsistent.

Stadler (1989), for instance replicated the experiment performed by Lewicki, Czyzewska, and Hoffman (1987). After the original experiment, the subjects had to perform

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two additional transfer tasks. These were a position-transfer task and a response-transfer task. In the position-transfer task the position of the target within a quadrant differed from that in the training condition. Since the quadrants of the target presentation remained unchanged, the sequence of the responses was the same as during the training. In the response-transfer task the target locations remained exactly the same as during the training, but the subjects had to use other responses. Rule transfer took place only if the target positions were identical with the original task. This was the case in the response-transfer condition. The manipulation of the responses did not affect the rule transfer. Stadler (1989) concluded that rule learning relied on the perceptual aspects of the task, i. e., he assumed that the subjects had learned the sequence of stimuli.

A similar result was reported by Cohen et al. (1990). After the subjects had learned a sequence of stimulus–response pairs, the responses were changed. Instead of three different fingers, the subjects were required to use only one finger to press the response keys. The rules determining the sequence could be transferred to the new task. According to Cohen et al., this indicates that the knowledge of the sequential pattern was independent of the special motor system that had been used during the learning phase.

Howard, Mutter, and Howard (1992) also found evidence of perceptual learning. The authors used a variation of a serial-reaction-time task introduced by Nissen and Bullemer (1987). In the original task an asterisk could be presented in one of four possible positions. The subjects had, as quickly as possible, to press a response button corresponding to the location of the asterisk. The next asterisk then appeared. The locations of the asterisks followed a sequential pattern. In one of Howard et al.'s (1992) experiments, half of the subjects had to respond to each stimulus. The other subjects observed the stimulus sequence only during the first three experimental blocks (Howard et al., Experiment 2). In the fourth block all subjects responded to the asterisks' locations. There was no difference between the two subject groups. When a random sequence was used in the fifth block a similar increase in reaction times was observed for both groups. Howard et al. (1992) assumed that in the observation condition too the subjects had acquired the sequential pattern. The result suggests that knowledge of the serial order can develop as a result of simple perceptual experience.

A different suggestion came from the work of Willingham et al. (1989). They reported a transfer experiment that yielded no cues for purely perceptual learning (Willingham et al., Experiment 3). Willingham et al. (1989) tried to separate the learning of the stimulus sequence from the learning of the response sequence. There were two training conditions: a perceptual-sequence condition and a response-sequence condition. In the perceptual-sequence condition the stimuli appeared in locations that followed a sequential pattern. In contrast to the original task set by Nissen and Bullemer (1987), subjects did not have to respond to the stimulus locations, but to the colour of the stimuli. Since the sequence of colours was random, there was also a random sequence of responses. This condition was intended to provide the possibility of perceptual learning. The subjects were able learn where the next stimulus would appear. In contrast, in the response-sequence condition the stimulus positions varied randomly, whereas the stimulus colours followed a sequential pattern. The subjects were again required to respond to the stimulus colour. This condition provided the opportunity of learning the sequence of motor responses. After the training had been completed, the subjects were tested with a transfer task, in which all subjects had to respond to the location of uncoloured stimuli by pressing the corresponding key. The stimulus locations were exactly the same as in the training phase in the perceptual-sequence condition. The sequence of the responses was identical with the response-sequence condition. Two results are important here. First, it has to be assumed that the subjects did not learn the location sequence in the perceptual-sequence condition during the training task. It was only in the response-sequence condition that the reaction times decreased as a result of the training. Second, only minimal transfer was observed if the sequence of the motor responses was the same as before. The reaction times of subjects who first trained in the response-sequence condition were about 50 ms shorter than those of the subjects in the perceptual-sequence condition. The absence of any clear transfer effect for both conditions caused Willingham et al. (1989) to suggest that sequence learning would be neither solely perceptual nor solely motor. They assumed that the subjects would learn the sequence in the form of stimulus–response pairs or condition–action statements. According to this view, only those stimulus properties will be considered in the sequence learning that form a condition of a condition–action statement. Furthermore, a separate transfer of the stimulus sequence or of the response sequence appears to be impossible because both are integrated in the condition–action statements.

Recently Nattkemper and Prinz (1993) reported an experiment in favour of response learning. In this experiment the subjects were required to respond to eight different letters with four different responses. Pairs of two letters had to be responded to with the same response. The sequence of the stimulus letters followed a sequential pattern. Sometimes the regular stimuli were replaced by irregular stimuli. If the irregular stimulus was a stimulus that had to be responded to with the same response as the regular stimulus, this manipulation did not violate the response sequence. In the other cases the response sequence was also impaired. The irregular stimuli led to reaction-time costs only if they required irregular motor responses. As Nattkemper and Prinz (1993) concluded, this result was evidence for the assumption that the subjects learn the sequence of responses rather than the sequence of stimuli.

Altogether, some of the experiments support the learning of the stimulus sequence, whereas others suggest that sequential patterns are learned as sequences of responses. The reason for the contradictory results of the various studies is not clear. A possible answer may be that the learning of the stimulus sequence was not clearly separated from the learning of the response sequence in all the studies. In most cases both were confounded with each other during the acquisition of the sequence, and only subsequently a separation was achieved by means of additional transfer tests. But the transfer task is a new task for the subjects, which has its own requirements. A failure of transfer of the stimulus sequence or of the response sequence does not necessarily mean that they were unimportant for the sequential-pattern learning in the training task. On the other hand, experiments that have tried to separate the two sides already in the acquisition of the sequences may not have been successful with respect to this goal. In the experiment done by Howard et al. (1992) it cannot be excluded that the subjects who observed the sequence in the first blocks showed some internal responses, e. g., the naming of the stimulus positions or a subliminal activation of motor responses (e. g., finger tapping). These internal responses may have been the basis of the pattern learning that was observed. Another problem is evident in the Willingham et al. (1989) study. The subjects who trained in the perceptual-sequence condition did not acquire the sequence of the stimulus locations. So the transfer task provides no information as to whether a transfer of the stimulus sequence was possible, provided it had been learned before. Furthermore, whether the perceptual-sequence conditions were appropriate for learning the stimulus locations has to be discussed. The subjects had to respond to the colour of the stimuli. The colour is a stimulus property that can be processed very quickly, and independently of the stimulus location. The subjects may have responded to the colour without discriminating the stimulus positions. So they were unable to acquire the sequential pattern of the positions. To avoid this problem, one could hide less salient stimuli in a more complex stimulus configuration (cf. Lewicki et al., 1987). In such a condition learning of the position sequence might also be possible.

In the following section of the paper I shall present an experiment that reduces the problem of serial-pattern learning to a more elementary one: how can subjects learn relations between succeeding stimuli? Does it simply require covariation learning (cf. Lewicki, 1986; Lewicki et al., 1987; Howard et al., 1992) or does the learning depend on the relation of these covariations to the motor responses required by the stimuli (cf. Willingham et al., 1989)?

Experiment 1

In a serial-reaction-time task the subjects had to respond to different target stimuli that were embedded in a matrix of distractors. The responses were dependent on the target identity. Each response triggered the next stimulus presentation. There was a systematic relationship between the target identity and the location of the next stimulus. The sequence of the targets was random. Thus, the sequence of responses, as well as the sequence of the target locations, was random. The only pattern the subjects could learn was the relation between the target identity and the location of the next target. For correct responses this relationship was irrelevant. But if the subjects acquired knowledge of the relations, they would be able to find the next target very fast and to speed up their responses. The critical variation consisted in the stimulus–response assignment. One group of subjects had to respond to different targets with different responses, whereas another group responded to different targets with the same response. The question was whether this variation would affect the learning of the relations between the succeeding targets.

Method

Subjects. Four groups of subjects, with 6 subjects in each group, took part in the experiment. All subjects were students of the Psychology Department at Humboldt University. Their participation fulfilled a requirement for the psychology course.

Apparatus and stimuli. The stimulus presentation and the recording of the responses were controlled by a personal computer. Responses were made by the pressing of five different buttons on the PC keyboard. The buttons a, s, ö, ä (German keyboard), and *space* were assigned to the left middle finger, the left index finger, the right index finger, the right middle finger, and the right thumb. During the experiment the fingers rested on the response buttons. As targets, the capital letters W, S, F, X, and V (standard characters of the PC) were used. The targets were presented at variable positions on a 5×5 matrix on the display screen. The matrix filled the screen of a 14″ monitor. The distance between the monitor and the subjects' eyes was about 80 cm. This corresponded to a visual angle of about 12° . The visual angle between neighbouring matrix positions amounted to about 3° . Besides the position of the target, the other positions of the matrix were occupied by dots in the first part of the experiment and later by the distractor letters E, Y, C, and M. These letters were selected because they are similar to the target letters: E to F; Y to X and V; C to S; M to W. If the targets were presented within the matrix of similar distractor letters, it would be quite difficult to find the targets. This should increase the possible effect of the rule learning on the speed of the target search.

Design and procedure. The experiment consisted of a serial-reaction-time task combined with a visual-search task. The subjects had to search for one of the five targets W, S, F, X, and V within the matrix of similar distractor letters. With the exception of target V, the responses to the targets triggered the next matrix with a new target letter. This procedure resulted in a stimulus–response sequence. Target V was always the last stimulus in a sequence. The response to this target stopped the sequence. After a short break the next sequence was started. The first target of each sequence appeared in the middle position of the matrix. The only instruction given to the subjects was that on their response to this target the next one would appear in one position above, below, left, or right. The subjects did not know that in two of the four groups of subjects the position of the next target was systematically related to the identity of the given target. If the given target was W, the next target appeared above the given position. If the target was S, the next target appeared below. Following an F, the position of the next target was on the left of the given position; following an X, it was on the right (cf. Figure 1).

The experiment was planned in a 2×2 design. The first factor was the number of responses (5 responses vs. 2 responses); the second factor was the existence of position rules (rule vs. random). The four groups of subjects were assigned to the four fields of the design. The first group, the Five-Responses Rule Group, had to respond to each target by pressing a particular key. W required a response with the left index finger, S a response with the right index finger, F required the left middle finger, and X the right middle finger. V had to be responded to with the right thumb. The position of the targets followed the rules described above. A second group of subjects, the Two-Responses Rule Group, had to perform only two different responses. W, S, F, and X had to be responded to with the right index finger. The target V again required a response with the right thumb. The positions of the target

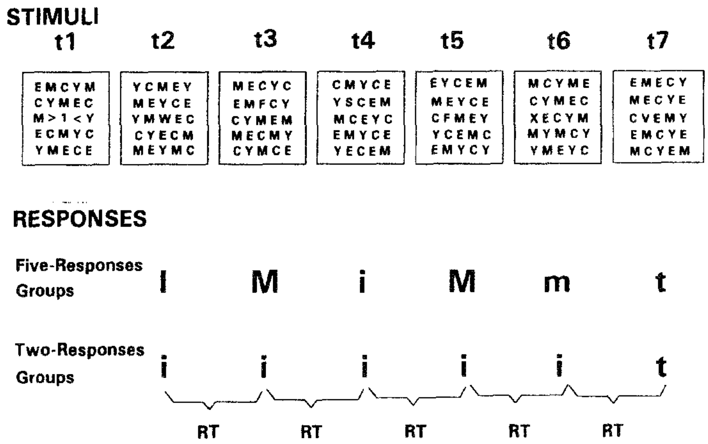


Fig. 1 Illustration of the experimental procedure. A sequence of 6 letters (W, F, S, F, X, V) is given as an example: in t1 the trial number is presented; the first stimulus letter W follows in t2; the appropriate response is the left index finger; one position above, in t3, the letter F is presented; in t4 the letter S follows one position to the left, etc. I: left index finger; M: left middle finger; i: right index finger; m: right middle finger, t: right thumb, RT: reaction time

presentation followed the same rules as those in the conditions of the Five-Responses Rule Group. To test the acquisition of the rules, the performance of these two rule groups was compared with two random groups. The stimulus–response assignments for the Five-Responses Random Group and the Two-Responses Random Group were identical with the rule groups. The only difference was that the position of the next target was random. Independently of the identity of the given target, the next target could appear with equal probability on one of the four neighbouring positions. The two random groups offered a baseline of the performance in the given task if no rules were available. In addition to this between-subjects test of the rule learning, a within-subjects test was stipulated for the two rule groups. At the end of an extensive training the rules were reversed. In this final control block, after the target W the next target appeared at one position not above, but below. Following F, the next target was presented not one position to the left, but to the right, etc. If the subjects had really used knowledge of the rules to find the next target, the reversing of the rules should cause longer response latencies because of the prolongation of the target search.

The experimental procedure was the same for all subject groups (Figure 1). The experiment was arranged in three sessions of 2 hours each. At the beginning of the first session the subjects were told which stimulus letter was assigned to which response. They were also informed that the relevant letter would be presented within 5×5 matrix of dots and later within a matrix of irrelevant letters. Their task was to find the relevant letter and execute the required response as quickly as possible and without errors. They were also told that the next target would appear one position above, below, to the right, or to the left, of the previous one. In the first session all subjects had to perform nine blocks. For all blocks the following procedure was used (Figure 1): at the beginning of each trial the number of the trial appeared in the middle position of the 5×5 matrix on the PC screen. The number of the trial informed the subjects about their progress in performing the task. The number was followed by the first target in the same position. The target had to be responded to as quickly as possible by pressure of the corresponding response button. The reaction time was measured by the computer. Each response triggered a new stimulus, which immediately appeared in one position apart from the previous one. The old stimulus was replaced by a dot or by a distractor letter. The new stimulus letter required the next response, which, in turn triggered a new stimulus letter. There was only one exception: the presentation of the letter V and the corresponding response with the right thumb closed the sequence. After a break of 2 s the next sequence was started with the next trial number. If the response was incorrect, a beep tone indicated the error. The sequence was stopped and the next one started 2 s later.

To make it impossible for the subjects of the Two-Responses Groups to respond without searching for the targets, the stimulus–response sequences differed in length between four and nine stimulus–response pairs. Thus, the subjects had to check each time whether V or one of the other targets was presented. There were 12 sequences with four stimulus–response pairs, 19 sequences with five pairs, 20 sequences with six pairs, 19 sequences with seven pairs, 4 sequences with eight pairs, and 1 sequence with nine pairs. The succession of the targets in the sequences was arranged pseudo-randomly by the experimenter. Within a block the targets W, S, F, and X were presented with almost the same frequency (90 and 91 respectively). This was equally true of all transitions between the different targets. No target could be used more than twice in consecutive presentations, or more than three times within one sequence. To meet these criteria, the different frequencies of the sequence lengths were allowed. Altogether the arrangement was designed to prevent subjects from anticipating the identity of the next target. A further constraint was put upon the border positions of the matrix. In these positions only those targets were allowed that held the next target within the matrix (with respect to the rules). A possible anticipation of the target identity due to these constraints should make no difference between the four experimental groups, because all groups were presented with the same sequence of targets.

Each block consisted of 75 stimulus–response sequences. Together, the 75 sequences corresponded to 437 stimulus–response pairs. On completion of each block, the computer calculated the mean reaction times for correct responses and the number of errors. Both values appeared on the screen and were used to stimulate the subjects to respond more quickly and more accurately in the next block, which started 2 minutes later.

In the first three blocks in the first session the targets were presented within a 5×5 dot matrix. These blocks were designed to familiarize the subjects with the experimental situation and help them to learn the assignment of the stimulus letters to the response buttons. In the following six blocks in the first session the dots were replaced by the distractors, which made it more difficult to find the relevant letter. A change in one position might indicate the position of the target. So all distractors in the letter matrix changed their position after each presentation.

The second session continued this procedure with 10-letter matrix blocks. Finally, in the third session, the subjects performed 10-letter matrix blocks again. In addition, the Five-Responses Rule Group and the Two-Responses Rule Group had to perform the final control block with reversed rules. On completing the final control block, the members of these two groups were asked whether they had noticed any difference between the last and the last block but one.

Results

Errors. Only correct responses were taken into account. The rate of errors was 1.19% in the Five-Responses Rule Group, 0.65% in the Two-Responses Rule Group, 1.35% in the Five-Responses Random Group, and 0.47% in the Two-Responses Random Group (related to the total number of

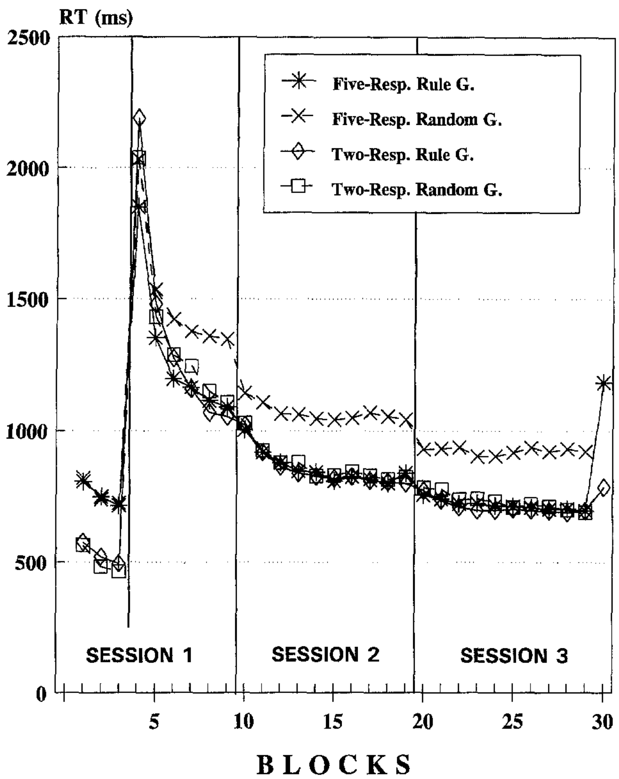


Fig. 2 Mean reaction times in Experiment 1

13,110 responses per subject). The greater number of errors in the Five-Responses Groups reflects the higher probability of false responses due to the greater number of possible responses.

Reaction times

The mean reaction times were calculated for each subject and block. The initial reaction times of all stimulus–response sequences were excluded from the computation of the subjects' mean value. Since every initial stimulus was presented in the central position of the matrix, the subjects in all groups had no uncertainty of the position in which this stimulus would appear. So the initial reaction times were irrelevant with respect to rule learning. Extreme values were cancelled from the data pool of each subject. Extreme values were those reaction times that exceeded the critical value ($p < .05$) of the Thompson–Rule (Müller, Neumann, & Storm, 1973). Figure 2 shows the results.

Separate three-way analyses of variance (ANOVAs), using the individual mean values as data, were performed to compare the four groups of subjects with respect to the 3 dot-matrix blocks, and the 26 letter-matrix blocks. The ANOVAs treated the effects of the number of responses and the existence of rules as between-subjects factors and the effect of blocks as a within-subjects factor. An additional two-way ANOVA tested the effect of the rule inversion in the final control block against the last-but-one block. The number of responses was treated as a between-subjects factor, the rule inversion as a within-subjects factor.

Dot-matrix blocks. The ANOVA yielded a significant effect of the number of responses, $F(1,20) = 46.46$, $p < .01$, $MS_e = 22660.13$, and of blocks, $F(2,40) = 47.48$, $p < .01$, $MS_e = 1157.53$. There was no difference between rule and random groups, $F(1,20) = 0.1$. The interactions were not significant (all F values < 1). On average the members of the Five-Responses Groups needed an additional time of 235 ms to respond to the targets. This additional time was not reduced by the training for each block and was independent of the rules that determined the next position.

Letter-matrix blocks. In contrast to that for the dot-matrix blocks, the ANOVA for the letter-matrix blocks indicated that the effect of the number of responses was not significant, $F(1,20) = 3.12$, $p > 0.05$. The existence of position rules, on the other hand, had a significant main effect, $F(1,20) = 5.47$, $p < .05$, $MS_e = 360807.53$. On average, the Five-Responses Rule Group responded 210 ms faster than the Five-Responses Random Group. The difference between the Two-Responses Rule Group and the Two-Responses Random Group amounted to 15 ms. However, this interaction was not significant, $F(1,20) = 4.08$, $p > 0.05$. Furthermore the training over the 26 letter-matrix blocks produced a significant main effect, $F(25,500) = 304.98$, $p < .01$. The only significant interaction was the one between the number of responses and the blocks, $F(25,500) = 3.58$, $p < .01$, $MS_e = 6480.87$. This interaction is caused by the fact that in the first letter-matrix blocks the Two-Responses Groups had longer reaction times than the Five-Responses Groups had. After some blocks this difference disappeared (F values for the other interactions < 1).

In order to consider only the highly trained level, a separate three-way ANOVA was computed for the data of the third session. The ANOVA yielded a significant effect of the number of responses, $F(1,20) = 6.85$, $p < .05$), of the existence of rules, $F(1,20) = 8.57$, $p < .01$, and of the interaction between both factors, $F(1,20) = 5.68$, $p < .05$, $MS_e = 89341.31$. The abolition of rules had a greater effect on the Five-Responses Groups than on the Two-Responses Groups. If one considers the last block only, it took the Five-Responses Random Group 224 ms longer to perform the task, whereas the reaction times of the Two-Responses Random Group were 6 ms shorter than those of the corresponding rule group. Again the effect of blocks was significant, $F(9,180) = 12.34$, $p < .01$, as was the interaction between the number of responses and blocks, $F(9,180) = 2.58$, $p < .01$. The interaction between all three factors was also significant, $F(9,180) = 2.11$, $p < .05$, $MS_e = 723.72$. These interactions reflect the fact that the members of the Five-Responses Random Group did not improve their performance in the third session, while the other groups showed a slight training effect. The interaction between the existence of the rules and the blocks was not significant $F(9,180) = 0.73$.

The effect of the final control block. The results of the final control block in both rule groups were compared with the previous letter-matrix block. The ANOVA indicated an

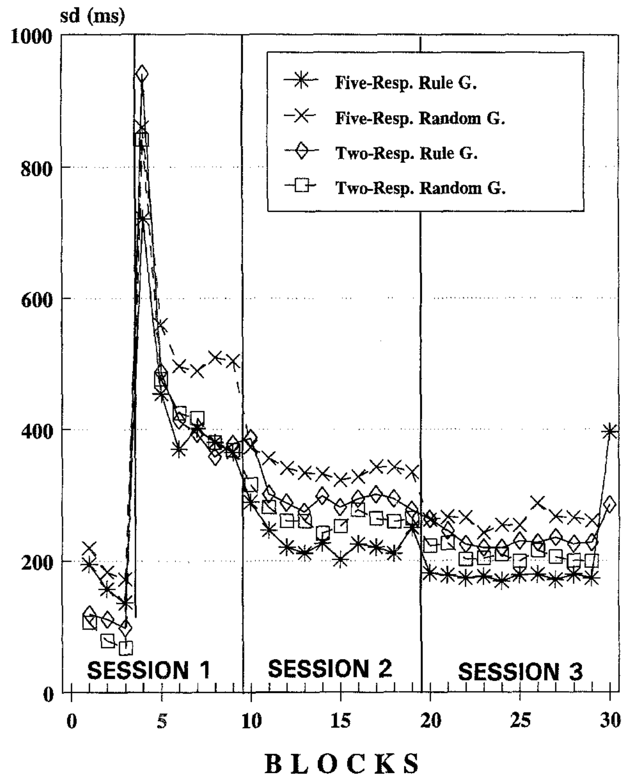


Fig. 3 Mean standard deviations in Experiment 1

effect of the number of responses, $F(1,10) = 26.46$, $p < .01$, $MS_e = 8943$, an effect of blocks, $F(1,10) = 68.35$, $p < .01$, and an interaction between groups and blocks, $F(1,10) = 31.93$, $p < .01$, $MS_e = 7305$. In both groups the reversal of the relations between the target identity and the position of the next stimulus caused a prolongation of reaction times. But the additional time was dependent on the stimulus–response assignment. Whereas in the Two-Responses Rule Group the reaction times increased by 91 ms, in the Five-Responses Rule Group reaction times were almost doubled, with an increase of 486 ms.

Standard deviations

Important information about the use of rule knowledge is given by the standard deviations. In the case of a search in accordance with the rules, within-subjects variability should be rather low, whereas a random search without any anticipation of the correct position should cause a higher variability. For each block and each subject the standard deviations of the reaction times for correct responses were computed. The initial reactions were again excluded from the computation. The individual values were used as data in analyses comparable to that performed to evaluate reaction times. Figure 3 illustrates the mean values of standard deviations for the four groups depending on the various blocks.

Dot-matrix blocks. On average, the reaction times in the Five-Responses Groups had a higher intra-individual variability than those in the Two-Responses Groups, $F(1,20) = 13.10$, $p < .01$, $MS_e = 8902.74$. The variability was reduced by the training over the three blocks, $F(2,40) = 25.87$, $p < .1$, $MS_e = 419.68$. There was no difference between rule and random groups, $F(1,20) = 0.01$. In no case was an interaction significant.

Letter-matrix blocks. In the letter-matrix blocks the effect of the number of responses on the intra-individual variability disappeared, $F(1,20) = 0.03$. The existence of rules had no main effect, $F(2,20) = 2.19$, $p > .05$. But there was a significant interaction between the two factors, $F(2,20) = 5.54$, $p < .05$, $MS_e = 114639.9$. The intra-individual variability of reaction times was low in the Five-Responses Rule Group. The highest variability was found for the Five-Responses Random Group. Independently of the rule condition, the variabilities in the Two-Responses Groups were at a middle level. Furthermore, the ANOVA yielded a significant effect of the blocks, $F(25,500) = 156.59$, $p < .01$, and a significant interaction between the number of responses and the blocks, $F(25,500) = 2.04$, $p < .01$, $MS_e = 2775.23$). The training reduced standard deviations more markedly in the Two-Responses Groups than in the Five Responses Groups.

A separate test was performed for the third session. The results were similar to the analysis of all letter-matrix blocks. There was neither an effect of the number of responses, $F(1,20) = 0$, nor of the existence of rules, $F(1,20) = 2.17$, $p > .05$. The interaction between both factors was significant again, $F(1,20) = 6.54$, $p < .05$, $MS_e = 28261.14$. In the third session also the training reduced the variability of reaction times, $F(9,180) = 2.24$, $p < .05$, $MS_e = 551.99$. The training effect was independent of the other factors. The corresponding interactions did not reach the level of significance.

The effect of the final control block. The ANOVA comparing the last letter-matrix block with the final control block yielded no effect of the number of responses, $F(1,10) = .94$, $p > .1$, $MS_e = 4628$, but significant effects of blocks, $F(1,10) = 66.48$, $p < .01$, and of the interaction between the two factors, $F(1,10) = 23.17$, $p < .01$, $MS_e = 1774$. In the last letter-matrix block the mean standard deviation of the reaction times in the Five-Responses Rule Group was 56 ms lower than in the Two-Responses Rule Group. The reversal of the relations between the identity of the targets and the relative positions of the subsequent targets in the final control block increased the variability of reaction times very markedly in the Five-Responses Rule Group. On the other hand, there was only a slight increase in variability in the Two-Responses Rule Group. The standard deviations of the Five-Responses Rule Group were now 110 ms higher than those of the other group.

Postexperimental interview. None of the subjects of both rule groups noticed any difference between the last regular letter-matrix block and the final control block. The subjects had no idea of the rules determining the next target position. The members of the Five-Responses Rule Group especially were very surprised at their long reaction times in the final control block. They reported a feeling of low concentration, but had no explanation for their performance.

Discussion

What did the subjects learn over the three experimental sessions? First, they learned to combine the stimuli with the responses. This is one factor that contributed to the overall effect of blocks in all groups. Secondly, the subjects learned to distinguish the targets from the distractors. This was especially important for the subjects in the Two-Responses Groups at the beginning of the letter-matrix blocks. In the dot-matrix blocks they were able to perform the task by responding only to either V or to non-V. It can be assumed that the subjects in this condition did not differentiate between W, S, F, and X. The same strategy would result in relatively long search times in the first letter-matrix blocks, since the subjects had to scan all 25 matrix positions in their search for the target V. In order to make use of the information given in the instruction that the next target would appear in one position apart from the previous target position, the subjects had to discriminate the four non-V targets from very similar distractors. Only then could the search process be restricted to the 4 possible positions. The short reaction times at the end of the training procedure favour this learning process. The Five-Responses Groups had to discriminate the targets already in the dot-matrix blocks. The members of these groups therefore had presumably fewer problems in distinguishing them from the distractors. The interaction between the number of responses and the blocks may be due to this.

More important in the frame of this paper is a third point. Did the subjects learn how to make use of the covariation between the target identity and the relative position of the next target to control the search process? The results of the dot-matrix blocks give no hint as to the learning of rules. The performance of the rule groups was identical with that of the random groups. On the other hand, the dot-matrix blocks showed a clear difference between the Two-Responses Groups and the Five-Responses Groups. The subjects in the Five-Responses Groups had longer reaction times and a higher variability than the subjects in the other two groups. This pattern of results was to be expected. At the beginning of the experiment the subjects could have no knowledge of the rules that determined the next target position. If there had been any knowledge in the second or third block, its effect on the reaction times would have been quite low because the pop-out effect of the targets against the background of the dot matrix made it very easy to find the target. Thus, the differences observed reflect the number of responses only.

After a three-day training with the letter matrix, another pattern appeared. The Five-Responses Rule Group responded significantly faster and with a lower variability than the Five-Responses Random Group. This can be considered as evidence for the rule learning in the rule condition. Whereas the Five-Responses Random Group had to scan all possible positions to find the target, the Five-Responses Rule Group showed some bias for the correct target position, which speeded up the search process and decreased the variability. On the other hand, there was no difference between the Two-Responses Rule Group and the Two-Responses Random Group with respect to reaction times and their variability. This result indicates that the Two-Responses Rule Group did not acquire knowledge of rules. It has to be assumed that the Two-Responses Rule Group, as well as the Two-Responses Random Group, scanned the possible target positions randomly. The advantage of the rule knowledge for the search process of the Five-Responses Rule Group made it possible for the members of this group to respond as fast as the subjects in the Two-Responses Groups. The most convincing fact is that in the third session, despite the higher number of responses, the intra-individual variability of reaction times in the Five-Responses Rule Group was lower than the variability in both Two-Responses Groups.

Additional evidence for this interpretation is provided by the final control block in both rule conditions. The reversal of the relations between the target identity and the position of the subsequent target resulted in a major increase in reaction times and their variability for the Five-Responses Rule Group. This is the group in which the comparison with the random group also indicated that rule acquisition had taken place. Reaction times almost doubled, indicating a systematic bias of the search process in the wrong direction. In this condition the search took longer than in the condition of the Five-Responses Random Group, for which random scanning of the possible positions had to be assumed.

Nevertheless, in the conditions of the Two-Responses Rule Group also, reaction times and their variability increased from the last regular letter-matrix block to the final control block. In other words, these subjects also showed a bias to the originally correct position. Therefore we have to assume that the Two-Responses Rule Group acquired some knowledge of rules, but compared with that in the Five-Responses Rule Group, the effect was rather small. It remains open here why this slight rule-learning effect was not found in the comparison between the Two-Responses Rule Group and the Two-Responses Random Group. On analogy with the Five-Responses Groups, the difference between the Two-Responses Groups should amount to about 45 ms. This effect would be half the increase between the last regular block and the final control block. Perhaps the slight rule-learning effect may have been covered by the between-subjects variability in the between-subjects test. It was only the more sensitive within-subjects comparison between the last regular block and the inversed block that made the rule learning visible.

However, whereas for the Five-Responses Rule Group there was clear evidence of rule acquisition, it has to be assumed that rule acquisition in the Two-Responses Rule Group was somewhat fragmentary. Altogether the results indicate that rule learning took place mainly in the Five-Responses Rule Group. On the basis of the covariation between the target identity and the relative position of the subsequent target, it was possible, in principle, for both the Five-Responses Rule Group and the Two-Responses Rule Group to anticipate the next target position. In fact the corresponding rules were acquired much better by the group that had to perform different responses to the targets.

What may the role of the responses be with respect to rule learning? There are two alternatives. First a direct impact of the motor responses on the rule learning can be assumed. The idea is that processes of motor control are involved in the rule acquisition. Before discussing this alternative in detail, we have to exclude a second alternative, which assumes only an indirect impact of the different responses on rule learning. According to this alternative, the rules are acquired by purely perceptual learning of the covariations between the target identity and the position of the next target. A learning mechanism of this kind would result in rule learning only if the targets were actually distinguished from one another. This may have been the problem for the Two-Responses Rule Group. Since the subjects had to respond to the stimuli W, S, F, and X with the same response, the discrimination of the stimuli could have been lost (Shiffrin & Schneider, 1977). Those effects have also been discussed in the literature in terms of the so-called "predifferentiation" or "pretraining" effect (Cantor, 1965; Norcross, 1958; de Rivera, 1959; Gibson & Gibson, 1955): In transfer experiments the performance of subjects in a choice-reaction task depended on the experience with the stimuli collected in a pre-training task. If the subjects had to discriminate all the stimuli in the pretraining, their performance was better in the choice-reaction task and vice versa. In other words, the discrimination of the stimuli depended on the behaviour required. In the present experiment it might be assumed that the subjects of the Two Responses Rule Group did not discriminate between W, S, F, and X. The identification of these targets as non-V was sufficient to perform the task. Because of the reduced target discrimination, a learning mechanism that connects the succeeding stimuli enabled the subjects of the Two-Responses Rule Group to learn only that the stimulus V was followed by the end of the sequence and the stimulus non-V by a new stimulus in one of four possible positions. Conversely, for the Five-Responses Rule Group the task required the discrimination of all targets. Thus, it was possible to learn that the target position was dependent on the identity of the previous target.

A preliminary objection to this alternative explanation has already been discussed above. The similarity between the distractors and the targets should force the subjects in the Two-Responses Groups to discriminate between the targets. For instance, in order to identify target F, it had to be discriminated from distractor E. The identification of target W required discrimination from distractor M. Nor did the targets have any features in common, which made them more similar to each other than to the distractors. Thus, it seems unlikely that the subjects did not discriminate between the targets.

The second experiment was designed to test the second alternative more directly.

Experiment 2

The purpose of Experiment 2 was to make the subjects discriminate all targets under the same conditions as those in the Two-Responses Rule Group. If the low effect of rule learning in the Two-Responses Rule Group was due to a lack of discrimination between the targets, better rule learning should be expected now. But if the processes of motor control were important for the learning process, the forced target discrimination is not likely to help the subjects in the Two-Responses Rule Group to acquire additional rule knowledge.

Method

Subjects. Six subjects were recruited from the Department of Psychology at Humboldt University. All subjects fulfilled a requirement in the psychology course by their participation.

Apparatus and stimuli. These were the same as in Experiment 1.

Procedure. Experiment 2 repeated the task of the Two-Responses Rule Group from Experiment 1 and combined it with an additional task. In the Two-Responses Rule Group the subjects responded to targets W, S, F, and X by pressing the relevant key with the right index finger, and to target V with the right thumb. This had to be done as quickly as possible in the Experiment 2 also. On completion of each stimulus–response sequence by pressure of the right thumb, the subjects were also asked to name the target that had been presented before the V target. This subject group was therefore called the Target-Naming Group. To indicate the name of the target, the subjects had to press the W, S, F, or X keys on the left side of the PC keyboard with the fingers of the left hand. They were instructed that it was important to give the right answer independently of the response time. Since the sequences varied in length, this procedure made the subjects identify the targets and store their identity up to the presentation of the next target. It should be noted here that it was possible to ignore the exact identity of the first two targets in each sequence. Since the minimal sequence length was 4 targets, the first two targets never had to be recalled. But at almost all target presentations (the mean sequence length was 5.8 targets) the next target could have been V, which required it to be named as the last-but-one target. Thus, it seems unlikely that the subjects changed their strategy between the second and the third target.

Results

The subjects solved the target-naming task very well. The average rate of errors was 2.20%. There was also a low rate of errors in the reaction task (0.54%). In the further analyses only correct responses were considered. Separate ANOVAs were performed to investigate the effect of the additional target naming. The ANOVAs compared the results of the Two-Responses Rule Group (Experiment 1) with the results of the Target-Naming Group of Experiment 2.

Reaction times

In Figure 4 the reaction times for the Target-Naming Group are presented, together with the reaction times of the Two-Responses Rule Group from Experiment 1.

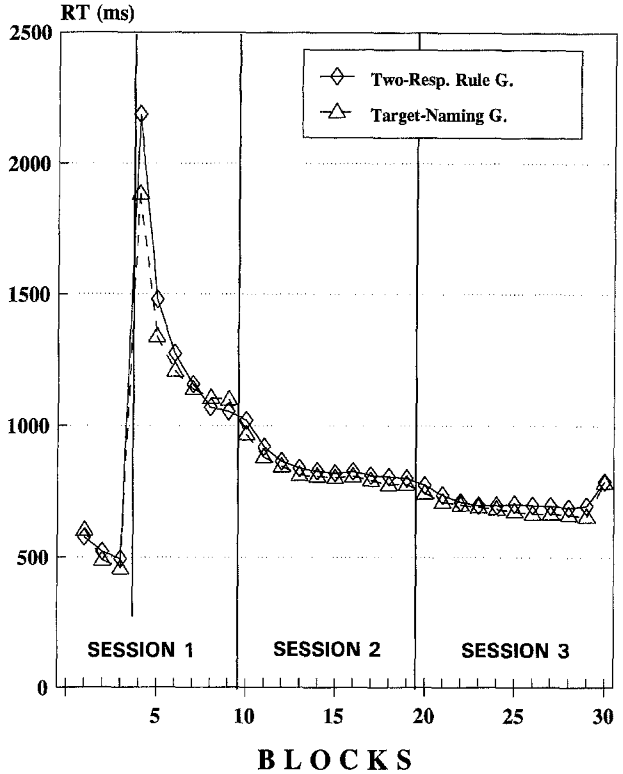


Fig. 4 Mean reaction times in Experiment 2 compared with the Two-Responses Rule Group in Experiment 1

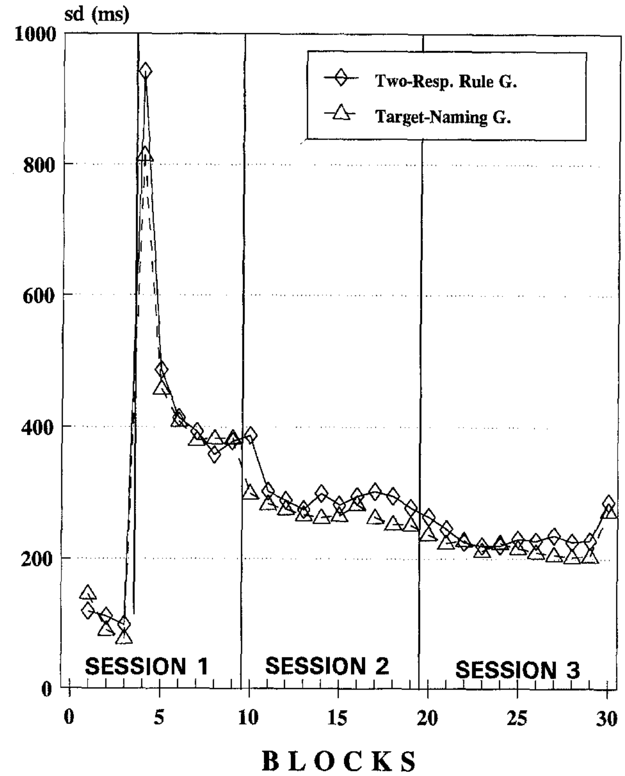


Fig. 5 Mean standard deviations in Experiment 2 compared to those of the Two-Responses Rule Group in Experiment 1

Dot-matrix blocks. In the dot-matrix blocks the additional target naming on completion of each sequence had no main effect on reaction times, $F(1,10) = .12$, $MS_e = 14\,914$. There was an effect of blocks, $F(2,20) = 39.24$, $p < .01$, and of the interaction between the groups and blocks, $F(2,20) = 3.55$, $p < .05$, $MS_e = 1082$. The members of the Target-Naming Group reduced their reaction times over the three dot-matrix blocks by 147 ms, whereas for the Two-Responses Rule Group a reduction of only 82 ms was observed.

Letter matrix blocks. Reaction times over the 26 letter-matrix blocks were almost identical for both groups. There was only a main effect of blocks, $F(25,250) = 84.99$, $p < .01$, $MS_e = 12\,880$, indicating the effect of the training on the reduction of reaction times. Neither the effect of groups, $F(1,10) = .36$, $MS_e = 295\,646$, nor the interaction between the two factors $F(25,250) = .94$, was significant.

The effect of the final control block. The effect of the reversal of the relations between the identity of the targets and the relative position of the subsequent target was tested against the last letter-matrix block for both groups. The ANOVA yielded a main effect of blocks, $F(1,10) = 49.22$, $p < .01$, $MS_e = 1499$, but no effect of groups, $F(1,10) = .24$, $MS_e = 11\,957$. For both groups the change in the relations caused an increase in reaction times. For the Two-Responses Rule Group of Experiment 1 the increase amounted to 91 ms, and for the Target-Naming Group of Experiment 2 127 ms were obtained. But this interaction did not reach significance $F(1,10) = 1.30$, $p > .05$.

Standard deviations

The mean standard deviations of reaction times are summarized in Figure 5.

Dot-matrix blocks. The intra-individual variability of reaction times was identical in both groups, $F(1,10) = 0.1$, $p > .1$, $MS_e = 2197$. Practice reduced the variability $F(2,20) = 23.33$, $p < .01$, $MS_e = 281$. There was a more marked reduction for the Target-Naming Group compared to the Two-Responses Rule Group, $F(2,20) = 8.15$, $p < .01$.

Letter-matrix blocks. The additional target-naming task had no effect on the variability of reaction times. The difference between both groups was not significant, $F(1,10) = .59$, $MS_e = 69\,881$. Both groups showed a similar reduction in reaction-time variability as an effect of training over the 26 letter-matrix blocks, $F(25,250) = 58.59$, $p < .01$ for the block factor and $F(25,250) = .71$, $MS_e = 3747$ for the Group × Block interaction.

The effect of the final control block. The inversion of the relations between the succeeding stimuli had the same effect on both the Two-Responses Rule Group and the Target-Naming Group. For both groups the variability of reaction times increased from the last experimental block to the final control block, $F(1,10) = 38.38$, $p < .01$, $MS_e = 625$. There was no main effect of groups, $F(1,10) = 0.5$, $MS_e = 4036$ and no Group × Block interaction, $F(1,10) = 0.32$.

Post-experimental interview. None of the subjects had any idea about the rules determining the position of the subsequent target.

Discussion

The results of Experiment 2 make it very unlikely that the lack of rule learning in the conditions of the Two-Responses Rule Group can be explained by a loss of target discrimination. The conditions of Experiment 2 demanded an exact target identification and required the subjects to store the target identity until the next target was presented. This should provide the best opportunity for learning the systematic relations between the target identity and the position of the subsequent target. However, the subjects in Experiment 2 did not differ in their performance from the subjects in the Two-Responses Rule Group (Experiment 1). The explicit demand in Experiment 2 – to discriminate all targets from one another – did not produce a higher degree of rule learning. Nevertheless, the increase in both the reaction times and their variability in the final control block again indicated that there was some bias forwards the position of the subsequent target. This effect was only slightly strengthened in the target-naming task. So it can be assumed that the relations between the succeeding stimuli also had an impact on rule learning, but compared to the impact of different responses, the effect was quite small.

An objection to this interpretation might be that the naming task did not really made the subjects discriminate the targets during the serial-reaction-time task. The assumption is that the targets were only stored in a buffer until the next target appeared. If the target was V, the buffer was read out to solve the naming task. Only then did target discrimination take place. The naming task therefore cannot have had any influence on rule learning. What could this sort of buffer be like? A first possibility is to assume a visual buffer that stores the visual configuration of the letter matrix. However, since with each new target in all matrix positions other distractors were presented, the buffer would be erased before the naming task had to be performed. Another possibility would be to store only the visual characteristic of the target itself in the buffer. This would presuppose its localization in the matrix, which is impossible without discrimination from the similar distractors. It has therefore to be assumed that the targets are processed so as to include their differentiation. The same holds true for phonological or articulatory buffer stores. The naming task can be solved only if the code in the buffer preserves the identity of the targets. This requires processing of the targets during the serial-reaction-time task that differentiates between them.

General discussion

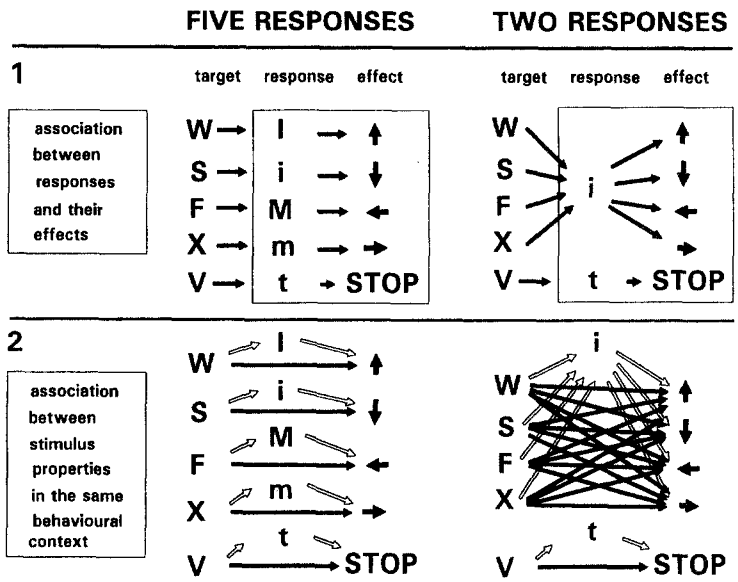
Altogether the results of the two experiments are not in line with assumptions of a mechanistic learning of covariations between successive stimuli. They demonstrate that in the given conditions motor responses play an important role in rule learning. The existence of systematic relationships between successive targets was not sufficient to induce the learning process. But if different motor responses were required by the targets, the subjects learned the rules very well and used them to facilitate their search for the next target.

One more question to be asked is: how can processes of motor control be involved in rule learning? Several explanations are possible. A first explanation, which I want to discuss here, assumes a learning mechanism that associates responses along with their effects. Bolles (1972) pointed out that the relationship of responses and their effects is important for learning processes to take place. According to his view, learning occurs if a response always has the same effect. Only in this condition can the effect of the response execution be anticipated (Shanks, 1985; cf. Hoffmann, 1992). In the present experiment the relative position of a given target may appear to the subjects as an effect of the response to the previous target. A learning mechanism that associates responses with their effects can predict rule learning only in the conditions of the Five-Responses Rule Group. It was only in these conditions that the subjects had to respond to each target with a special response, and in this way each response had a special effect. Conversely, in the Two-Responses Rule Group the targets W, F, S, and X required the same response. Thus, all four position changes could appear only as effects of the same response. This made it more difficult for the subjects to acquire the rules. Figure 6 (1) illustrates this explanation.

A second explanation includes the targets in addition to the responses and their effects (Figure 6 (2)). The assumption is that a stimulus will be associated with a successive stimulus if both have a common behavioural context (Holyoak, Koh, & Nisbett, 1989). In other words, if both stimuli are related to the same motor response (as initial conditions or as effects), they will be connected with each other. In the case of the Five-Responses Rule Group all targets and the corresponding position changes were connected with a special response. This enabled the subjects to associate the target identity and the next position. In the conditions of the Two-Responses Group the same learning mechanism could not operate. Because targets W, S, F, and X required the same response, the learning mechanism would associate all these targets with all position changes. From this point of view, a given target obtained its predictive quality for the next target position only if it constituted the initial condition of a response, and the subsequent target position appeared as the effect of this response.

Both explanations assume a causal role of motor responses for rule learning in the present visual-search task. The data of the experiments are not sufficient to make a decision between these alternatives. The at best fragmentary rule learning observed in the Two-Responses Rule Group remains an unsolved problem for both alternatives. An additional assumption in the context of the second explanation might help to take this fact into account. The

Fig. 6. Illustration of two different explanations for the results. The upper part of the figure shows what will be learned by a mechanism that associates responses with their effects (1). In the lower part of the figure associations between the successive stimuli are established if they belong to the same behavioural context (2). I: left index finger; M: left middle finger; i: right index finger; m: right middle finger; t: right thumb, RT: reaction time. The arrows in the effect column indicate the direction of the position change



learning process may be thought of as having three components: the first associates the targets along with the responses, the second associates the responses with their effects (i.e., the next position), and the third associates the targets with the next position. Thus, the learning process connects the targets and the subsequent positions via two routes, i.e., directly and indirectly through the responses. If these two ways are assumed to interfere with each other, the fragmentary rule learning in the conditions of the Two-Responses Rule Group can also be explained. In the case of the Five-Responses Rule Group, both ways connected the different targets with the corresponding position changes that facilitated the rule learning. Conversely, in the case of the Two-Responses Rule Group it was only the direct associations that preserved the rules between target identity and the position of the next target. The second route via the responses did not allow for rule learning, so the rule learning was impaired.

What is the functional value of such learning mechanisms? I can present here only some speculations as to the role of the mechanisms assumed for the control of behaviour.

A general assumption of both learning mechanisms was that motor responses are associated with their effects. To control behaviour successfully, one has to know the possible effects of actions or reactions. Only then is it possible to select the behaviour appropriate for the accomplishment of the intended goal (an arbitrarily chosen goal in an action, or the general goal of avoiding a danger in a reaction). And in turn, the first information as to whether an action or a reaction has been successful is given by its effect. If the effect is in accordance with the goal (the expected effect), the behaviour has been appropriate. In other words, the effects of motor behaviour are important for both the selection of the behaviour and the verification of its appropriateness. From this point of view, it makes sense to assume a learning mechanism that connects actions or reactions with their effects independently of consciousness. Whenever we do anything, we learn what it is going to change in the environment. For the learning process, the contingency between the motor behaviour and the change effected in the environment seems to be sufficient. Causality does not matter, i.e., all changes in the environment that proceed with some regularity if a particular form of behaviour is executed will be learned as effects of this behaviour. This is a well-known phenomenon. Take, for instance, the gambler who from former random experience thinks that he can control the roulette ball by his own behaviour.

Since the real effect of a particular form of behaviour depends on the given environmental conditions, it makes sense to include the initial conditions in the learning process in addition to the effects of that behaviour. Only if the initial conditions and the chosen form of behaviour correspond, can the intended goal be achieved. A learning process that associates the initial conditions with possible effects would make it possible to assess the likely actions or reactions in advance.

Such speculations are supported by discussion in the literature. For instance, the schema theory of motor learning of Schmidt (1975) assumes that all executions of a motor program are stored together with the initial conditions, the parameter specifications of the general program, the sensory consequences of the execution, and the outcome or the effect with respect to the goal. These are the data for the schema abstraction. The abstraction process is directed to the acquisition of rules that on the one hand relate the outcomes to the parameters of the movement (the recall schema), and the outcomes to the sensory consequences of the movement (the recognition schema) on the other.

Prinz (1992) stressed the role of the effects for the control of actions. In his view, actions are cognitively represented by codes of their environmental effects. He assumes that the control of actions is realized by the activation of their effects in memory. Experiments carried out by Hommel (1992) demonstrate that the anticipation of the effect may be a part of motor planning. In his experiments the subjects had to respond to different stimulus letters with key-pressing responses. As an effect of the responses, another letter appeared regularly. After a training procedure, the generation of the responses was facilitated, when the letters the correct effect were presented together with the stimulus letters.

Hoffmann (1992, 1993 a, b) proposed a model of anticipatory control of behaviour. According to this model, an intended action is accompanied by the anticipation of its effects. The anticipation relies on former experience of the action in the given initial conditions. The anticipated effects will be compared with the actual effects of the action. If the anticipated effects are identical with the actual effects, the association between the initial conditions are the anticipated effects is assumed to be strengthened. As a result of this learning process, it would be possible to anticipate the effects that could be obtained from the implementation of the intended behaviour on the basis of the given environmental conditions.

In conclusion, it seems appropriate to say that the serial-pattern learning in the present experiments could be a product of processes that are involved in motor learning and motor control (cf. Hoffmann, 1993 a). It could therefore be concluded that a certain degree of rule learning was found, as far as motor learning and motor planning were required in the serial-reaction-time task. Motor learning and motor planning were more important in the conditions of the Five-Responses Rule Group than in the conditions of the Two-Responses Rule Group.

So far, the explanations seem to be plausible. But it remains an open question as to whether rule learning is linked to motor responses only. An alternative view would be that each behaviour, including internal behaviour, could initiate rule learning. That means, whenever a task requires different processing of targets, rules in the target sequence would be acquired. This would question the role of the effects of responses assumed for the learning process, since only motor behaviour can have an environmental effect. The results of Experiment 2 are the first evidence that we have against this alternative. The internal naming of responses to the targets was not sufficient to induce rule learning. However, in order to answer this question more convincingly, additional experiments, including some other kinds of internal behaviour, are necessary.

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