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ORIGINAL ARTICLE

Joachim Hoffmann · Claudia Martin · Annette Schilling

Unique transitions between stimuli and responses in SRT tasks: Evidence for the primacy of response predictions

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Abstract The present experiments aimed at separating the impact stimulus and response predictions have on serial learning and performance in SRT tasks. In Experiment 1, a unique transition between two of four responses in an otherwise random response sequence was triggered by ambiguous stimulus transitions, allowing local response predictions but no stimulus predictions. The data indicated explicit transition knowledge and strong performance benefits. In Experiments 2 and 3, unique transitions between two of four stimuli in otherwise random stimulus sequences allowed local stimulus predictions under conditions of ambiguous response transitions. The data indicated fragmentary explicit transition knowledge but no performance effects. Experiments 4a and 4b reveal that the inefficacy of the unique stimulus transitions in Experiments 2 and 3 was presumably due to the fact that the stimuli differed with respect to conjunctions of response relevant and response irrelevant features which participants did not have to attend. However, although in Experiments 4a and 4b unique transitions between response relevant stimuli were applied, substantial explicit transition knowledge but only marginal performance effects resulted. It is argued i) that in SRT tasks learning mechanisms are addressed that primarily strive for reliable predictions of forthcoming responses and ii) that for these mechanisms to work the predictors have to be attended. Response transitions are easily learned and used because both criteria are fulfilled. In contrast, pure stimulus transitions are learned only if the predictive stimuli are attended, and learned stimulus transitions become effective only to the extent that the predicted stimuli specify the required responses.

J. Hoffmann (✉) · C. Martin · A. Schilling
University of Würzburg, Würzburg, Germany
E-mail: hoffmann@psychologie.uni-wuerzburg.de

J. Hoffmann
Lehrstuhl Psychologie III, Röntgenring 11,
D-97070 Würzburg, Germany

In a standard SRT task, stimuli are successively presented on a computer screen and participants are required to respond as quickly as possible with assigned response keys. Each response triggers the presentation of the next stimulus which in turn triggers the next response and so forth. If participants respond to a structured series of stimuli, thus performing a structured sequence of keystrokes, reaction times (RTs) and error rates decrease faster than if responding to a random sequence. Moreover, if after some training the structured sequence switches to a random one, performance deteriorates again, indicating that the preceding improvement resulted in fact from an adaptation to the serial structure of stimuli and responses (cf. for recent overviews Stadler & Frensch, 1998).

SRT tasks mimic real life situations in which one has to respond to successive stimuli or events. Natural event sequences are almost never random but entail some regularity or structure. Sequential structures allow predictions, and predicting forthcoming events is advantageous because one can prepare for what will happen before it happens in fact. Thus, sensitivity to serial order can be considered one of the basic mechanisms by which humans (and organisms in general) adapt behavior to constraints in the succession of events. That is why the examination of serial learning has a prolonged research history (e.g. Ebbinghaus, 1902; Lashley, 1951; Miller, 1956) and why serial learning in SRT tasks deserves thorough investigation. Besides the issue of to what extent serial learning in SRT tasks is explicit or implicit, i.e. accompanied by awareness of the serial structure, the questions of what kind of serial redundancy serial learning bases and to what extent different kinds of redundancy contribute to the improvement of performance increasingly demand interest (e.g. Hoffmann & Koch, 1998; Hunt & Aslin, 2001; Willingham, Wells, Farrell, & Stemwedel, 2000).

Three types of serial redundancy are usually confounded in a standard SRT task: redundancies in the transitions of stimuli (S-S), in the transitions of responses (R-R), and in the transitions between responses and following stimuli (R-S). For example, if S_1 is always followed by S_2, R_2 also always follows R_1, and R_1 is always followed by S_2. Thus if RTs to S_2 decrease, it remains open whether response acceleration is due to the learning of the S_1-S_2, R_1-R_2, or R_1-S_2 transitions. Numerous studies have been performed in order to disentangle the impact of these different transitions on serial learning. Some of these studies reported evidence for adaptation to redundancies in the stimulus sequence (e.g., Cohen et al., 1990; Frensch & Miner, 1995; Howard, Mutter, & Howard, 1992). Other studies were more consistent with the view that serial learning bases on the structure of the response sequence (e.g., Hoffmann & Sebald, 1996; Nattkemper & Prinz, 1993, 1997; Willingham, 1999). Finally, Ziessler & Nattkemper (2001) recently reported evidence also for the contribution of R-S relations to serial learning (cf. also Hazeltine, 2002; Hoffmann, Sebald, & Stöcker, 2001; Stöcker, Sebald, & Hoffmann, 2003; Ziessler, 1994, 1998).

It seems to be appropriate to conclude that both predictions of forthcoming stimuli (due to either redundant S-S or R-S relations) as well as predictions of forthcoming responses (due to redundant R-R relations) contribute to serial learning (cf. also Fendrich, Healy & Bourne, 1991; Goschke, 1998; Koch & Hoffmann, 2000; Mayr, 1996; Willingham et al., 1989). Faced with this evidence, the question emerges whether predictions of forthcoming stimuli and predictions of forthcoming responses base on the same learning mechanism and whether they influence performance to the same extent. In order to contribute to this issue, the present experiments examine the impact of stimulus and response predictability of equal strength on performance in a SRT task. In separate experiments unique transitions between either two responses or two stimuli were embedded in otherwise random stimulus and response sequences and we questioned whether unique S-S and unique R-R transitions similarly contribute to serial learning and performance.

Experiment 1

Unique transitions in SRT tasks are well learned even under attentional distraction (Cohen, Ivry, & Keele, 1990; Frensch, Buchner, & Lin, 1994). However, in these studies, unique transitions consisted of R-R and S-S transitions as well, so that it remains unsettled to what degree the improvement of performance is due to predictions of the next response or of the next stimulus. Furthermore, the unique transitions were part of fixed sequences of stimuli/responses which were cyclically repeated. Consequently, forthcoming stimuli and responses were not only predictable by the immediately preceding stimulus/response but also by more remote predecessors, which has been shown to affect serial learning as well (cf. Cleeremans & McClelland, 1991; Cleeremans, 1993; Jiménez, Méndez, & Cleeremans, 1996; Reed & Johnson, 1994; Stadler, 1992). Thus, it remains unspecified to what degree these higher order redundancies additionally contributed to learning. In order to avoid these confoundings we adopted a method by which each of the responses was required by several stimuli (cf. Nattkemper & Prinz, 1993, 1997; Ziessler & Nattkemper, 2001), so that a unique response transition could be triggered by ambiguous stimulus transitions. Furthermore, the unique response transition was embedded in an otherwise random sequence of responses, so that any impact of higher order redundancies was excluded.

Method

Task and apparatus Participants were required to respond to 16 ordinary playing cards by pressing one of four response keys as quickly as possible. The seven, eight, nine, and ten of hearts, clubs, diamonds, and spades were used as stimuli. The cards were presented individually in color on a green background at the center of a 15“ VGA monitor (40 mm x 30 mm) and were seen from a distance of about 60 cm. The four response keys were horizontally aligned on a separate response panel. The keys were to be pressed with the middle and index fingers of the left and the right hand. The cards with the values seven, eight, nine, and ten were assigned to the keys from left to right. Thus, the value of the cards was the relevant response feature, whereas their salient suit was response irrelevant.

Design The experiment was run in eight blocks of 256 trials each. In all blocks each of the sixteen cards was presented 16 times so that each response was required 64 times. The succession of stimuli/responses was controlled by transition matrices (see appendix) which were randomly worked through by a computer program: In Block 1 and 7, all possible 16×16 transitions between cards were realized once so that all possible transitions of the four responses (response repetitions included) were required 16 times. In Blocks 2 to 6 and 8, one transition between two of the four responses was unique, i.e. after a certain key press a certain other key press was always required that was never preceded by another key press. Consequently, this unique transition was to be realized about three times as often as any other response transition (cf. the corresponding transition matrix in the appendix). For example, after Key 2, Key 3 was always required and Key 3 never followed any other key. However, the transitions between the stimuli that triggered the unique response transition were ambiguous, i.e. each of the four cards that triggered the first response of the unique transition could be followed by each of the four cards which triggered the second response of the transition.[1] Moreover, the selection of the responses between which unique transitions were realized was balanced between subjects in a way that each of the 4×3 possible pairs of different responses were 2 times concerned (i.e. response repetitions were excluded from being unique transitions). In sum, in Block 1 participants experienced a completely random sequence of cards and responses. In Blocks 2 to 6 a unique response transition was triggered by ambiguous stimulus transitions in an otherwise random sequence of stimuli and responses. In Block 7 the unique response transition was abolished, i.e. Block 1 was repeated. Finally, in Block 8 the unique response transition was reinserted.

Procedure Participants were informed of the card-key mapping and asked to respond as quickly and as correctly as possible. The card-key mapping was provided on a schema below the screen in order to facilitate learning of the mapping. Middle and index fingers of both hands had to rest on the respective response keys and

[1]In fact, the stimulus transitions which triggered the unique response transition were also varied between blocks. In Blocks 2 to 5 one of the transitions was unique, i.e. after a particular card another particular card always followed which was never preceded by another card. In block 6 this unique stimulus transition was abolished. This variation had no impact at all on RTs or on error rates. As the finding that one unique amongst a total of 16 by 16 possible stimulus transition is apparently not learned if confounded with a unique response transition surely does not allow concluding that unique stimulus transitions in general are not learned in SRT tasks, we skip this detail.

the experiment was started by pressing any key. Each card remained visible on the screen until the response was made. The latency between the onset of the stimulus card and the key press was measured as RT in ms. The response-stimulus interval (RSI) was set to 500 ms. During the RSI the stimulus cards were replaced by a neutral "placeholder" card which showed only a cross in the center. If participants pressed a wrong key, a short noise was presented during the RSI. No feedback was given when responses were correct. At the end of each block, participants were informed about mean RT and error rate of the last block. They started the next block by pressing a start key. At the end of the experiment explicit knowledge about the response transitions was assessed. Participants were asked to indicate which key they believe followed each of the four keys most frequently and the answers were recorded. In case participants were uncertain about the most frequently following response, they were encouraged to guess. The total time to complete the experiment was approximately 45 min.

Participants Participants were 24 undergraduate students of the University of Würzburg, of which 12 were female and 12 were male. The mean age was 23.67 years (SD = 2.95).

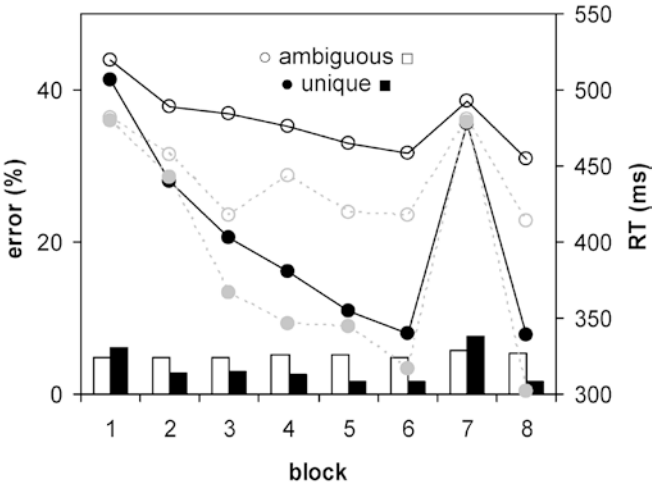

Fig. 1 Mean RTs (lines) and error rates (bars) of Experiment 1 plotted over blocks, separately for unique and ambiguous response transitions. Blocks 1 and 7 are random control blocks. The dotted grey lines present the mean RTs of one participant who failed to indicate the unique response transition in a postexperimental interview

Results

Accuracy data Altogether, an error rate of 4.4% was registered. For further analyses, all response repetitions (19.1%) were discarded. An analysis of variance (ANOVA) over the mean error rates of the remaining trials with transition (unique vs. ambiguous) and block (2–6) as repeated measures, indicated a main effect of transition ($F(1, 23) = 35.10$, $p < .001$), a main effect of block ($F(4, 92) = 2.81$, $p < .05$), but no interaction ($F(4, 92) < 1$. Error rates were smaller for unique transitions and decreased with practice. A corresponding ANOVA over the error rates of Block 7 versus Blocks 6 and 8 which were collapsed together revealed no main effect of transition ($F(1, 23) = 1.51$, $p > .05$), a main effect of block ($F(1, 23) = 28.58$, $p < .001$), and a significant interaction ($F(1, 23) = 13.44$, $p = .001$). Error rates increased in general in the random Block 7, but they increased substantially more for the transitions that were unique in Blocks 6 and 8.

RT data All errors (4.4%), all of the remaining RTs which exceeded 2.5 standard deviations from individual means (1.9%), all response repetitions (19.1%), and the first trial of each block were discarded from RT analysis. The means for the valid RTs were calculated for each participant and block, separately for the one response which could be reliably predicted from the preceding response (unique transition) and the three other unpredictable responses (ambiguous transitions). Figure 1 shows the mean RTs and error rates plotted over blocks.

An ANOVA over the mean RTs with transition (unique vs. ambiguous) and block (2–6) as repeated measures indicated a main effect of transition ($F(1, 23) = 54.72$, $p < .001$), a main effect of block ($F(4, 69) = 37.62$, $p < .001$), and a significant interaction ($F(4, 69) = 19.14$, $p < .001$). RTs decrease with practice in general, but RTs after unique transitions decrease much faster than RTs after ambiguous transitions. A corresponding ANOVA over the mean RTs of Block 7 versus the mean RTs of Blocks 6 and 8 which were collapsed together revealed a main effect of transition ($F(1, 23) = 41.23$, $p < .001$), a main effect of block ($F(1, 23) = 91.86$, $p < .001$), and a significant interaction ($F(1, 23) = 53.67$, $p < .001$). RTs increase in general in the random Block 7, but they increase substantially more for the transitions which were unique in Blocks 6 and 8.

Explorative data The unique key transition was correctly indicated by 23 of 24 participants, i.e. by 96%, which significantly differs from chance (25%, Binomial, $p < .001$). One participant did not know the unique transition and guessed wrong.

Discussion

The results show that participants quickly adapt to the unique response transition. Participants initiate increasingly faster and less error prone that one of the four responses which consistently followed a certain other response. Moreover, after abolishing the unique transition in Block 7, RTs and error rates increase to approximately the level of all other ambiguous response transitions. The explorative data additionally show that all subjects except one seemed to be aware of the unique response transition.[2] In sum, the results confirm the known finding that unique response transitions in SRT tasks are quickly learned and substantially affect speed and accuracy of the responses (Cohen, et al., 1990; Frensch, et al., 1994). The present experiment extends the given evidence as it shows effective learning of unique response transitions under conditions which the

[2] Although the performance data of the only participant who failed to indicate the unique response transition are in no case meaningful, it might be nevertheless interesting to notice that she showed the same data pattern over blocks as the "aware" participants (cf. Figure 1).

unique response transition was neither confounded with a unique stimulus transition nor with higher order sequential redundancies. Humans obviously possess a learning mechanism well suited to exploiting the local predictability of forthcoming responses (cf. also Hunt & Aslin, 2001).

Experiment 2

Numerous studies have already provided evidence for serial learning of redundancies in stimulus transitions independent of response sequence learning (Frensch & Miner, 1995; Goschke, 1998; Howard, Mutter, & Howard, 1992; Koch & Hoffmann, 2000; Mayr, 1996; Stadler, 1989). Thus, besides response predictions, stimulus predictions also seem to contribute to serial learning in SRT tasks. However, it remains to be clarified whether redundancies in pure stimulus transitions are learned and used to the same extent as redundancies in pure response transitions. In Experiment 2, a unique transition between two of four stimuli was inserted in an otherwise random stimulus sequence in the same way as in Experiment 1 with a unique transition between two of four responses. The frequencies of stimuli and responses as well as the response transitions were kept constant throughout all blocks, so that the effects of the variation of stimulus transitions could be assessed under conditions of controlled response transitions. We were interested to see whether a unique stimulus transition embedded in an otherwise random sequence of four stimuli would result in comparable learning and performance effects as the unique response transition which was likewise embedded in an otherwise random sequence of four responses in Experiment 1.

Method

Task and apparatus Task and apparatus were the same as in Experiment 1, except that the response panel with four keys was replaced by one with two horizontally aligned keys, which were to be pressed with the left and the right index fingers. Furthermore, only four ordinary playing cards, the jack and the king of hearts and spades, served as stimuli. The jacks were assigned to the left key and the kings to the right. Thus, the value of the cards was again the relevant response feature whereas the salient suit of the cards (red hearts versus black spades) was response irrelevant.

Design The experiment was run in seven blocks of 256 individual trials each. In all blocks each of the four cards was presented 64 times so that each of the two key presses was required 128 times. Transitions between keys were kept constant. In each block there were 43 repetitions of each key press and 170 alternations between the two key presses (170 + 86 = 256). Transitions of the cards were varied between blocks. In Blocks 1 and 6 the transitions between all four cards (repetitions included) were as evenly distributed as possible within the constraints of the fixed number of response repetitions and alternations (see the corresponding transition matrix in the Appendix). In the remaining blocks (2–5, and 7) there was a unique transition between two of the four cards. For example, after the jack of hearts the king of spades was always presented and the king of spades never followed any other card (cf. the corresponding transition matrix in the Appendix). Otherwise, the succession of stimuli and responses was random. Moreover, the cards between which the unique transition was realized were balanced between participants within the constraint that the unique transition always triggers a response alternation.

Procedure The procedure was the same as in Experiment 1. After performing the SRT task, participants were shown the four cards and were asked to indicate which card they believed followed each of the four most frequently. The answers were recorded. In case participants were uncertain about the most frequently following card, they were encouraged to guess. The total time to complete the experiment was approximately 35 minutes.

Participants Participants were 24 undergraduate students of the University of Würzburg, 16 female and 8 male. The mean age was 29.4 years ($SD = 6.47$).

Results

Accuracy data Altogether, 5.4% of errors were registered. For each participant and block, error rates were separately calculated for response repetitions (always triggered by ambiguous stimulus transitions) and for the response alternations which were either triggered by the unique or by an ambiguous stimulus transition. In order to assess first the impact of the response transitions independently of stimulus transitions, the error rates of response repetitions were compared with the error rates of those response alternations which were also triggered by ambiguous stimulus transitions. A corresponding ANOVA with transition (repetition vs. alternation) and block (1–7) indicated a main effect of transition ($F(1,23) = 23.47$, $p < .001$), a main effect of block ($F(6,138) = 3.54$, $p < .05$), and a significant interaction ($F(6,138) = 4.40$, $p < .001$). Response repetitions were on average more error prone than response alternations (9.13% vs. 3.34%) and the difference increased over blocks.

Second, in order to assess the impact of stimulus transitions independent of response transitions, the error rates of response alternations which were triggered by the unique stimulus transitions were compared with the error rates of response alternations which were triggered by ambiguous stimulus transitions. A corresponding ANOVA with transition (unique vs. ambiguous) and block (2–5) as repeated measures indicated no main effect of transition ($F(1, 23) < 1$, no main effect of block ($F(3, 69) = 1.85$, $p > .05$) and no interaction ($F(3, 69) = 1.48$, $p > .05$). Another ANOVA over the error rates of Block 6 versus Blocks 5 and 7 which were collapsed together also neither revealed main effects of transition ($F(1, 23) = 1.60$, $p > .05$) and block ($F(1, 23) < 1$, nor an interaction ($F(1, 23) = 1.98$, $p > .05$).

RT data All errors (5.4%), all of the remaining RTs which exceeded 2.5 standard deviations from individual means (2.2%), and the first trial of each block were discarded from RT analysis. The mean for the valid RTs was calculated for each participant and block, separately for response repetitions and for response alternations which were either triggered by the unique stimulus transition or by ambiguous transitions. Figure 2 shows the mean RTs and error rates for response alternations triggered either by unique or ambiguous stimulus transitions plotted over blocks.

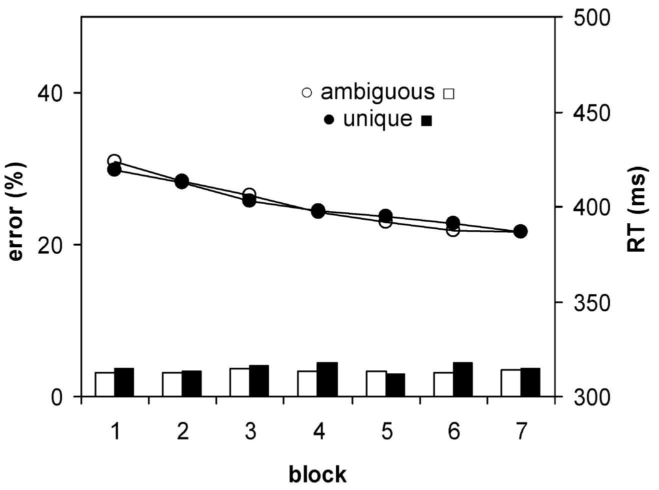

Fig. 2 Mean RTs (lines) and error rates (bars) of alternating responses in Experiment 2 plotted over blocks, separately for unique and ambiguous stimulus transitions. Blocks 1 and 6 are random control blocks

In order to assess first the impact of the response transitions independently of stimulus transitions, the RTs of response repetitions were compared with the RTs of those response alternations which were also triggered by ambiguous stimulus transitions. An ANOVA with transition (repetition vs. alternation) and block (1–7) indicated a main effect of transition ($F(1,23) = 4.61$, $p < .05$), a main effect of block ($F(6,138) = 5.48$, $p < .001$), and a significant interaction ($F(6,138) = 7.51$, $p < .001$). Response repetitions were on average slower than response alternations (413 ms. vs. 401 ms) and the difference increased over blocks.

Second, in order to assess the impact of stimulus transitions independently of response transitions, the RTs of response alternations which were triggered by the unique stimulus transitions were compared with the RTs of response alternations which were triggered by ambiguous stimulus transitions. An ANOVA with transition (unique vs. ambiguous) and block (2–5) as repeated measures indicated no main effect of transition ($F < 1$), a main effect of block ($F(3, 69) = 10.10$, $p < .001$), and no interaction ($F(3, 69) < 1$). RTs do not differ for unique and ambiguous stimulus transitions and both equally decrease with practice. Another ANOVA over the mean RTs of Block 6 versus Blocks 5 and 7, which were collapsed together, indicated no main effect of transition, no main effect of block, and no interaction (All F's < 1). The change from an embedded unique stimulus transition in Blocks 5 and 7 to ambiguous transitions between all stimuli in the random Block 6 had no effect at all on mean RTs of the alternating responses.

Explorative data The unique stimulus transition was correctly indicated by 8 of 24 participants, i.e. by 33.3 percent, which does not differ significantly from chance (25%, Binomial, p = .234). In order to assess a possibly influence of the correctness of the indicated unique transition on its behavioral effects, we recalculated the corresponding ANOVAs over the data of alternating responses with correctness as an additional post hoc variable between participants. The ANOVAS over the RT and error data of Blocks 2–5 revealed no influence at all of correctness (all p's $> .1$). Likewise the ANOVA over Block 6 versus Blocks 5 and 7 revealed no impact of correctness on RT data (all F's < 1). In the corresponding ANOVA over error rates only the triple interaction between correctness, transition, and block was significant ($F(1, 22) = 6.87$, $p < .05$, all other p's $> .05$). Participants who correctly indicated the unique transition showed a decrease of error rate for the unique transition in the random Block 6, whereas participants who failed to indicate the unique transition showed an increase of error rate for the unique transition in the random Block 6.

Discussion

Although Experiment 2 was mainly conducted in order to assess the impact of a unique stimulus transition, the different frequencies of response repetitions and response alternations additionally allowed an examination of response transition learning. The data clearly indicated behavioral adaptation to the redundancies in response transitions: In comparison to the response alternations which were also triggered by ambiguous stimulus transitions, the seldom response repetitions became increasingly slower and more error prone which suggests that participants increasingly expected alternations to occur.

In contrast to this adaptation to the different frequencies of response transitions, the data surprisingly shows that a unique transition between two stimuli, embedded in an otherwise random sequence of four stimuli and not confounded with a unique response transition, in no way influences performance in the present SRT task. Moreover, the majority of participants seem to not have noticed the unique card transition, although there was no attentional distraction. Note that in Blocks 2 to 5 and 7 the unique card transition was approximately three times more frequent than each of the other transitions and that on average each fourth transition was the unique one (64 of 256 per block). Nevertheless, our data clearly show no effect of this substantial redundancy in the stimulus sequence, largely irrespective of whether or not the unique card transition was correctly indicated. It has been argued that unique transitions address a basic learning mechanism that associates consecutive stimuli even under attentional distraction (Cohen, et al., 1990). In contrast, the present results suggest that learning of unique transitions between stimuli per se, i.e. if they are neither confounded with response transitions, stimulus frequencies, or higher order transitions, is not mandatory, even if stimuli are fully attended.

One possible reason for this unexpected result might be that the differences between the stimuli within the response categories (i.e. between jacks and kings) are not adequately noticed. Although the stimuli were purposefully selected so that the differences within the categories (black spades versus red hearts) are intuitively more salient than the differences between the response categories (jacks versus kings) it might be that the suit of the cards was not reliably encoded so that the unique transitions between cards of the two response categories could not become effective. In order to check this possibility we replaced the four cards of Experiment 2 by still more distinct stimuli in Experiment 3.

Experiment 3

In Experiment 3 the four playing cards of Experiment 2 were replaced by "playing cards" of the same size which showed either the digit 1 or the digit 2 in grey on either a bright yellow or a deep red background. Cards with the digit 1 were assigned to the left response key and cards with the digit 2 were assigned to the right.

Method

Task and apparatus Task and apparatus were the same as in Experiment 2.

Design The experiment was run in five blocks of 128 individual trials each. In all blocks each of the four cards was presented 32 times so that each of the two responses was required 64 times.[3] Moreover, transitions between responses were kept constant. In each block there were 21 repetitions of each response and 86 alternations between the two responses (42 + 86 = 128). Transitions between cards were varied between blocks. In Block 4 the transitions between all four cards (repetitions included) were distributed as evenly as possible within the constraints of the fixed number of response repetitions and alternations (cf. the corresponding transition matrix in the Appendix). In the remaining blocks (1–3, and 5) a unique transition between two of the four cards was realized. For example, after the "yellow 1" the "red 2" was always presented and the "red 2" never followed any other card (cf. the corresponding transition matrix in the Appendix). Otherwise, the succession of stimuli and responses was random in all blocks within the constraints of the corresponding matrices. The selection of the cards between which the unique transition was realized was balanced between participants in the same way as was done in Experiment 2.

Procedure The procedure was the same as in Experiment 2, except that the RSI was reduced to 200 ms because it has been shown that reducing the RSI improves the conditions for serial learning to appear (Frensch, et al., 1994; Frensch & Miner, 1994; Stadler, 1995).

Participants Participants were 24 undergraduate students of the University of Würzburg. 16 participants were female and 8 were male. The mean age was 23.21 years (SD = 6.39).

Results

Accuracy data The evaluation of the data followed the same schema as in Experiment 2: Altogether 4.7% of errors were registered. First, the corresponding ANOVA for assessing the impact of response transitions with transition (repetition vs. alternation) and block (1–5) as repeated measures indicated a main effect of transition ($F(1,23) = 35.23$, $p < .001$), no main effect of block ($F(4,92) = 2.02$, $p > .05$), and a significant interaction ($F(4,92) = 3.80$, $p < .05$). Response repetitions were on average more error prone than the response alternations which were also triggered by ambiguous stimulus transitions (8.30% vs. 3.12%). The difference increased over blocks.

Second, the corresponding ANOVA for assessing the impact of the unique stimulus transition on response alternations with transition (unique vs. ambiguous) and block (1–3) as repeated measures indicated no main effect of transition ($F(1, 23) < 1$), a significant effect of block ($F(2, 46) = 3.75$, $p < .05$) and no interaction ($F(2, 46) = 1.09$, $p > .05$). Error rates decrease over blocks to the same extent for unique and ambiguous card transitions. A corresponding ANOVA over the error rates of Block 4 versus Blocks 3 and 5 which were collapsed together also neither revealed main effects of transition ($F(1, 23) < 1$) and block ($F(1, 23) < 1$), nor an interaction ($F(1, 23) = 2.27$, $p > .05$).

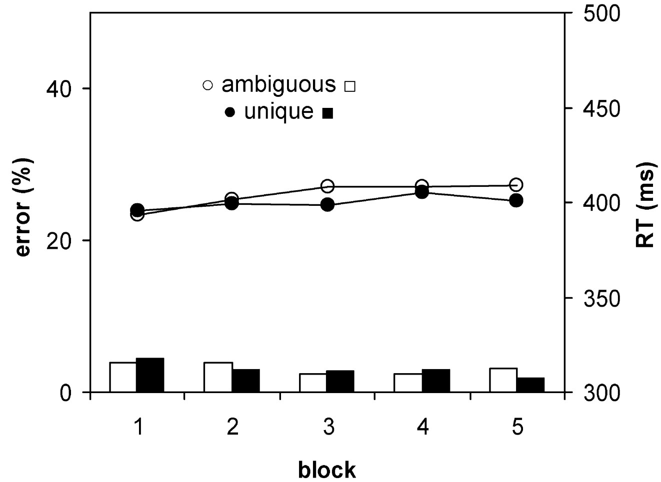

Fig. 3 Mean RTs (lines) and error rates (bars) of alternating responses in Experiment 3 plotted over blocks, separately for unique and ambiguous stimulus transitions. Block 4 is a random control block

RT data The evaluation of the data followed the same schema as in Experiment 2: All errors (4.7%), all of the remaining RTs which exceeded 2.5 standard deviations from individual means (2.3%), and the first trial of each block were discarded from RT analysis. The mean for the valid RTs was calculated for each participant and block, separately for response repetitions and for response alternations which were either triggered by the unique or by ambiguous stimulus transitions. Figure 3 shows the mean RTs and error rates for response alternations triggered either by unique or ambiguous stimulus transition plotted over blocks.

The corresponding ANOVA for assessing the impact of response transitions with transition (repetition vs.

[3] As we intended to compare the data of Experiments 3 and 4b with data collected with children (publication in preparation), we adopted the number of blocks and trials per block which were reduced in the experiments with children.

alternation) and block (1–5) as repeated measures indicated a main effect of transition ($F(1,23) = 17.77$, $p < .001$), a main effect of block ($F(4,92) = 8.37$, $p < .001$), and a significant interaction ($F(4,92) = 3.00$, $p < .05$). Response repetitions were on average slower than response alternations which were also triggered by ambiguous stimulus transitions (424 ms vs. 404 ms) and the difference increased over blocks.

The corresponding ANOVA for assessing the impact of the unique stimulus transitions on response alternations with transition (unique vs. ambiguous) and block (1–3) as repeated measures indicated no main effect of transition ($F(1, 23) < 1$), no main effect of block ($F(2, 46) = 1.49$, $p > .05$), and no interaction ($F(2, 46) < 1$). RTs neither are affected by card transitions nor by practice. A corresponding ANOVA over the mean RTs of Block 4 versus Blocks 3 and 5 which were collapsed together indicated no main effect of transition ($F(1, 23) = 1.05$, $p > .05$), no main effect of block, and no interaction (F's < 1). The change from an embedded unique stimulus transition in Blocks 3 and 5 to ambiguous transitions between all stimuli in the random Block 4 had no effects at all on mean RTs of the alternating responses.

Explorative data The unique stimulus transition was correctly indicated by 13 of 24 participants, i.e. by 54.17 percent, which differs significantly from chance (25%, Binomial $P = .002$). In order to assess a possible influence of "correctness" on the behavioral effects of the unique stimulus transition we recalculated the corresponding ANOVAs over the data of alternating responses with "correctness" as an additional post hoc variable between participants. The ANOVAs over mean RTs and error rates of Block 1 to 3 revealed no influence at all of correctness (all p's $> .1$). Also the ANOVAs over Block 4 versus Blocks 3 and 5 revealed no impact of correctness, neither on mean RTs nor on error rates (all p's $> .1$).

Discussion

Experiment 3 replicates the basic findings of Experiment 2: Participants again adapted to the different frequencies of response repetitions and response alternations but they did not adapt to the unique stimulus transition. Although now about half of the participants seemed to be aware of the unique stimulus transition and although the numerical data show marginally better performance for the unique transition (cf. Figure 3), the effects are far too small to approach significance. Thus, a unique transition even between more distinct stimuli than those used in Experiment 2 again has no significant impact on performance in the present SRT task, irrespective of whether or not participants were aware of the unique transition. On the one hand, the result is in sharp contrast to the widely accepted notion that learning of unique transitions between consecutive stimuli is an ubiquitous and robust phenomenon for which to appear neither attention nor the intention to learn are necessary (e.g. Cohen, et al., 1990; Lewicki, 1986; Lewicki, Hill, & Czyzewska, 1992, 1997). On the other hand, the result is consistent with recent findings that raise some doubts about the ubiquity and unavoidability of stimulus transition learning (Hendrickx, de Houwer, Baeyens, Eelen, & van Avermaet, 1997; Jiménez & Méndez, 1999).

In the present context the study of Jiménez & Méndez (1999) is of special concern. In an SRT task, participants were required to respond to spatially distributed stimuli with spatially compatible responses. As stimuli, four different shapes (x,*,?,!) were used, i.e. the locations of the stimuli were response relevant, whereas their shapes were not. The sequence of locations and responses was structured according to a noisy finite-state grammar. In addition to the probabilistic sequence of locations/responses, the shape of the stimulus predicted the location of the next stimulus (and response) with a probability of .80 in each trial. Besides robust performance effects of the probabilistic sequence of locations/responses, the predictability of the next location by the present shape affected performance only if participants were required to keep count of the number of trials in which either one of two target shapes occurred. Moreover, the data suggest that participants did not rely on the unequivocal relationships between each individual shape and the next location but rather on the relationship between the actually identified shape category (target versus non-target) and the next location. The authors conclude that transitions between stimuli and the next stimulus/response locations become effective only when participants need to pay attention to and to respond to the predictive stimuli (the shapes) and moreover that not individual stimulus-location transitions are established but rather transitions between the response relevant stimulus categories and the location of the next stimulus/response (cf. also Ziessler, 1994, 1998).

If one applies these considerations to the settings of Experiments 2 and 3, it becomes obvious that the transitions between the response relevant values of the cards, to which participants only need to pay attention and to respond, were ambiguous. In fact, the transitions between jacks and kings in Experiment 2 and between the digits 1 and 2 in Experiment 3 were kept constant in all blocks, corresponding to the constant transition rates between the two responses. Thus, if indeed only redundancies in the transitions between response relevant stimulus information affect performance, there were no redundancies at all which could become effective. In other words, what presumably matters in stimulus transition learning is not the distinctiveness of the stimuli per se, but rather the distinctiveness with regard to response relevant features. Experiments 4a and 4b were performed in order to explore whether at least unique transitions between distinct response relevant features have an impact on performance.

Experiments 4a and 4b

In Experiment 4a we replicated Experiment 2 by replacing the jacks and the kings of hearts and spades, by the

9 of clubs, the 10 of hearts, the jack of spades, and the queen of diamonds. Participants were required to respond to the cards with the values 9 and 10 with the left key and to the jack and the queen with the right key. Likewise, in Experiment 4b we replicated Experiment 3 by replacing the yellow/red cards with the digits 1/2 by a "red 1", a "green 2", a "blue 3", and a "yellow 4". Participants were required to respond to cards with the digits 1 and 2 with the left key and to cards with the digits 3 and 4 with the right key. Consequently, in both experiments the unique transitions now refer to cards which were completely distinct not only with respect to their response relevant values but also with respect to their response irrelevant suit or color.

Method

Task and apparatus Task and apparatus were the same as in the previous experiments.

Design In Experiment 4a the design of Experiment 2 and in Experiment 4b the design of Experiment 3 was replicated.

Procedure The procedures in Experiments 4a and 4b were the same as in Experiments 2 and 3, respectively.

Participants 24 undergraduate students of the University of Würzburg served as participants in Experiment 4a and 4b each. In Experiment 4a, there were 17 female and 7 male participants. The mean age was 23.38 years (SD = 3.85). In Experiment 4b, 19 participants were female and 5 participants were male. The mean age was 21.38 years (SD = 1.86).

Results of Experiment 4a

Accuracy data The evaluation of the data followed the same schema as in Experiment 2: Altogether 6.0% of errors were registered. First, the corresponding ANOVA to assess the impact of the response transitions with transition (repetition vs. alternation) and block (1–7) as repeated measures indicated a main effect of transition ($F(1,23) = 16.19$, $p = .001$) and a main effect of block ($F(6,138) = 2.54$, $p < .05$). The interaction missed significance ($F(6,138) = 1.40$, $p = .218$). Response repetitions were on average more error prone than the response alternations which were also triggered by ambiguous stimulus transitions (9.08% vs. 4.31%).

Second, the corresponding ANOVA to assess the impact of the unique stimulus transition on response alternations with transition (unique vs. ambiguous) and block (2–5) as repeated measures indicated no main effect of transition ($F(1, 23) < 1$), no effect of block ($F(3, 69) < 1$) and no interaction ($F(3, 69) < 1$). A corresponding ANOVA over the error rates of Block 6 versus the data of Blocks 5 and 7 which were collapsed together also revealed neither main effects of transition ($F(1, 23) = 1.078$, $p > .1$) and block ($F(1, 23) < 1$), nor an interaction ($F(1, 23) < 1$).

RT data The evaluation of the data followed the same schema as in Experiment 2: All errors (6.0%), all of the remaining RTs which exceeded 2.5 standard deviations from individual means (2.2%), and the first

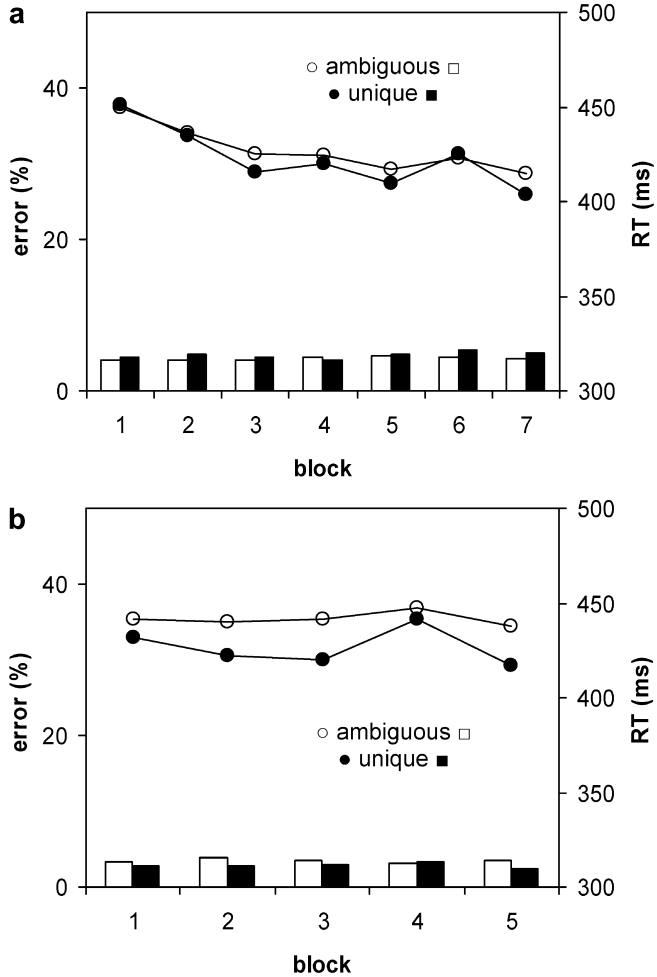

Fig. 4 **a** Mean RTs (lines) and error rates (bars) of alternating responses in Experiment 4a plotted over blocks, separately for unique and ambiguous stimulus transitions. Blocks 1 and 6 are random control blocks. **b** Mean RTs (lines) and error rates (bars) of alternating responses in Experiment 4b plotted over blocks, separately for unique and ambiguous stimulus transitions. Block 4 is a random control block

trial of each block were discarded from RT analysis. The mean for the valid RTs was calculated for each participant and block, separately for response repetitions and for response alternations which were either triggered by the unique or by ambiguous stimulus transitions. Figure 4a shows the mean RTs and error rates for response alternations triggered either by unique or ambiguous stimulus transitions plotted over blocks.

The corresponding ANOVA to assess the impact of the response transitions with transition (repetition vs. alternation) and block (1–7) as repeated measures indicated no main effect of transition ($F(1,23) = 1.98$, $p = .173$), a main effect of block ($F(6,138) = 9.95$, $p < .001$), and no interaction ($F(6,138) = 1.35$, $p = .238$). RTs of response repetitions and of those response alternations which were also triggered by ambiguous stimulus transitions likewise decreased over blocks.

The corresponding ANOVA to assess the impact of the unique stimulus transition on response alternations with transition (unique vs. ambiguous) and block (2–5) as repeated measures indicated no main effect of transition ($F(1, 23) < 1$), a main effect of block ($F(3, 69) = 6.836$, $p < .001$), and no interaction ($F(3, 69) < 1$). RTs do not differ for unique and ambiguous stimulus transitions and they likewise decrease with practice. A corresponding ANOVA over mean RTs of Block 6 versus Blocks 5 and 7, which were collapsed together, revealed no main effect of transition ($F(1, 23) < 1$), a main effect of block ($F(1, 23) = 5.161$, $p < .05$), and no interaction ($F(1, 23) = 1.573$, $p > .1$). The change from an embedded unique stimulus transition in Blocks 5 and 7 to ambiguous transitions between all stimuli in the random Block 6 results into a general increase of RTs.

Explorative data The unique stimulus transition was correctly indicated by 18 of 24 participants, i.e. by 75 percent, which differs significantly from chance (25%, Binomial, $p < .001$). In order to assess a possible influence of "correctness" on the behavioral effects of the unique stimulus transition, we recalculated the corresponding ANOVAs over the data of alternating responses with correctness as an additional post hoc variable between participants. The ANOVAs over mean RTs and error rates of Block 2 to 5 revealed no influence at all of correctness (all *p's* $> .1$). Corresponding ANOVAs over the data of Block 6 versus Blocks 5 and 7 indicated significant interactions between correctness and transition in the error data ($F(1, 22) = 4.515$, $p < .05$) and in the RT data ($F(1, 22) = 4.479$, $p < .05$). Participants who correctly indicated the unique card transition showed a smaller error rate (4.46 vs. 4.53) and faster responses (421 vs. 431 ms) for the unique transition, whereas participants who failed to indicate the unique transition showed a higher error rate (7.23 vs. 4.28) and slower responses (400 vs. 384 ms) for the unique transition. The triple interaction between correctness, transition, and block did not reach significance, neither for the error rates ($F(1, 22) = 1.039$, $p > .1$) nor for the RT data ($F(1, 22) = 2.107$, $p > .1$).

Results of Experiment 4b

Accuracy data The evaluation of the data followed the same schema as in Experiment 2: Altogether 4.2% of errors were registered. First, the corresponding ANOVA to assess the impact of the response transitions with transition (repetition vs. alternation) and block (1–5) as repeated measures indicated a main effect of transition ($F(1,23) = 8.53$, $p < .05$) and a main effect of block ($F(4,92) = 2.55$, $p < .05$). The interaction shortly missed significance ($F(4,92) = 2.43$, $p = .053$). Response repetitions were in average more error prone than response alternations which were also triggered by ambiguous stimulus transitions (6.14% vs. 3.50%) but the increase of the difference over blocks was only marginally significant.

Second, the corresponding ANOVA to assess the impact of the unique stimulus transition on alternating responses with transition (unique vs. ambiguous) and block (1–3) as repeated measures indicated no main effect of transition ($F(1, 23) = 2.129$, $p > .1$), no main effect of block ($F(2, 46) < 1$), and no interaction ($F(2, 46) < 1$). Error rates tend to be smaller for the unique transition (2.82 vs. 3.58) but this difference does not approach significance. A corresponding ANOVA over the error rates of Block 4 versus Blocks 3 and 5 which were collapsed together also revealed neither main effects of transition ($F(1, 23) < 1$) and block ($F(1, 23) < 1$), nor an interaction ($F(1, 23) = 1.213$, $p > .1$).

RT data All errors (4.2%), all of the remaining RTs which exceeded 2.5 standard deviations from individual means (2.5%), and the first trial of each block were discarded from RT analysis. The mean for the valid RTs was calculated for each participant and block, separately for response repetitions and for response alternations which were either triggered by the unique or by ambiguous stimulus transitions. Figure 4b shows the mean RTs and error rates for response alternations triggered either by unique or ambiguous stimulus transitions plotted over blocks.

The corresponding ANOVA to assess the impact of the response transitions with transition (repetition vs. alternation) and block (1–5) as repeated measures indicated a main effect of transition ($F(1,23) = 6.29$, $p < .05$), no main effect of block ($F(4,92) = 2.25$, $p > .05$), and a significant interaction ($F(4,92) = 3.74$, $p < .05$). Response repetitions were faster than response alternations which were also triggered by ambiguous stimulus transitions (430 ms vs. 442 ms) but this advantage was reduced over blocks.

The corresponding ANOVA to assess the impact of the unique stimulus transition on response alternations with transition (unique vs. ambiguous) and block (1–3) as repeated measures indicated a main effect of transition ($F(1, 23) = 8.55$, $p < .01$), no main effect of block ($F(2, 46) < 1$), and no interaction ($F(2, 46) = 1.67$, $p > .1$). Participants respond faster to unique than to ambiguous card transitions (425 vs. 441 ms). A corresponding ANOVA over mean RTs of Block 4 versus the data of Blocks 3 and 5, which were collapsed together, revealed a main effect of transition ($F(1, 23) = 6.644$, $p < .05$) and a main effect of block ($F(1, 23) = 13.161$, $p < .01$). The shift to the random Block 4 leads to a steeper increase of RTs for formerly unique transitions (from 418 to 441 ms) than for formerly ambiguous transitions (from 439 to 447 ms). However, the critical interaction between transition and block shortly missed significance ($F(1, 23) = 3.266$, $p = .084$).

Explorative data The unique stimulus transition was correctly indicated by 18 of 24 participants, i.e. by 75 percent, which differs significantly from chance (25%, Binomial, $p < .001$). In order to assess a possibly influence of "correctness" on the behavioral effects of the unique stimulus transition we recalculated the corresponding ANOVAs over the data of alternating responses with "correctness" as an additional post hoc variable between participants. The ANOVAs over mean RTs and error rates of Block 1 to 3 revealed no influence at all of correctness (all *p's* $>.1$). In the ANOVAs over the data of Block 4 versus Blocks 3 and 5 only the mean RTs showed a marginally significant correctness x block interaction ($F(1, 22) = 3.438$, $p = .077$). Mean RTs of participants who correctly indicated the unique card transitions increased less in the random Block 4 (428 vs. 439 ms) than RTs of participants who were incorrect (431 vs. 460 ms). However, the critical triple interaction between correctness, block and transition was far from being significant ($F(1, 22) < 1$).

Discussion

Experiments 4a and 4b were conducted mainly in order to explore whether at least unique transitions between stimuli which were distinct with regard to both their response relevant values and their response irrelevant suit or color as well would affect behavior. Otherwise the conditions of Experiment 2 and 3 were replicated in which stimuli were distinct only with respect to conjunctions of the response relevant values and the response irrelevant suits or color.

Regarding the impact of the response transitions, the accuracy data again confirmed that participants adapted to the different frequencies of response repetitions and response alternations. The more seldom response repetitions were substantially more error prone than the more frequent response alternations. That this disadvantage of response repetitions was not likewise manifest in the RT data as in Experiments 2 and 3 is presumably due to the more complex stimulus response mappings which resulted in a general increase of RTs: Whereas in Experiments 2 and 3 each response was assigned to only one definite value of the stimulus cards, in Experiments 4a and 4b each response was assigned to two different card values.

Regarding the impact of the unique stimulus transitions, the manipulation of the distinctiveness of the used stimuli modified the findings of Experiments 2 and 3 in three respects: First, the number of participants who correctly indicated the unique stimulus transition substantially increased from 33% in Experiment 2 and 54% in Experiment 3 to 75% in both Experiments 4a and 4b. Second, the numerical data now reveal marginal performance advantages for the unique stimulus transitions. Participants tend to respond faster to unique stimulus transitions and RTs increase somewhat stronger with the switch to a random block. However, the effects are still so small that they are only partly statistically reliable. Finally, whether or not participants correctly indicated the unique stimulus transition influenced the impact of the unique transition inconsistently. In Blocks 5–7 of Experiment 4a there is a reliable advantage of unique transition only for "correct participants", whereas in Experiment 4b the increase of RTs in the random Block 4 (an indirect measure of the impact of the unique transition) was reliably stronger for the "incorrect participants".

The findings reveal that unique transitions between response relevant stimulus features to which participants have to attend and to respond have a good chance of becoming detected and in this sense learned explicitly. However, this knowledge seems to be of little benefit for performance. One might argue that participants choose between only two response alternatives already so fast that only slight improvements can be reached by predictions of the forthcoming stimulus (floor effect). However, remember that in Experiment 1 participants reached mean RTs of about 340 ms for the unique response transition within a four-choice SRT task, whereas RTs for the unique stimulus transition decreased in Experiment 4a (after comparable training) not below 400 ms and in Experiment 4b (after less training) not below 415 ms. Thus, the predictability of the next stimulus per se seems to be of little use for an improvement of performance in SRT tasks.

General Discussion

The present experiments aimed at separating the impact that stimulus predictions and response predictions have on serial learning and performance in SRT tasks. In Experiment 1, participants performed a four-choice SRT task in which a unique transition between two responses was embedded in an otherwise random response sequence. Each response was triggered by four different stimuli and the unique response transition was invoked by ambiguous transitions between the response signals of the first and the second response. Accordingly, the first response of the unique transition reliably predicted the next response whereas the concrete stimulus which would trigger it was not predictable. In Experiments 2 to 4b, participants performed a two choice SRT task. There were four distinct stimuli, two of which respectively triggered one of the two responses. A unique transition between two of the four stimuli was embedded in an otherwise random stimulus sequence in such a way that the transitions between the responses were kept ambiguous. Thus, the first stimulus of the unique transition reliably predicted the next stimulus whereas the next response was not predictable from the current one.

The data of Experiment 1 confirm the known finding that unique transitions in SRT tasks are well learned and effectively used to improve performance (Cohen, et al., 1990; Frensch, et al., 1994). Experiment 1 extends the available evidence in showing that unique transitions between two consecutive responses also become effective if they are confounded neither with unique stimulus transitions nor with higher order sequential redundancies. Obviously, local predictions of the following response on the basis of the current response, irrespective of the concrete response signals, are an important part of what is learned in SRT tasks (Hoffmann & Sebald, 1996; Grafton, Hazeltine, & Ivry, 1995, 1998; Nattkemper & Prinz, 1993, 1997; Willingham, 1999). Under the present conditions, all participants except one seemed to be aware of the unique response transitions. However, in face of the numerous studies which have demonstrated serial learning of less redundant transitions by "unaware participants" it can be assumed that learning of response predictions does not presuppose awareness of the underlying sequential regularities. That the one participant who seemed to be unaware of the unique stimulus transition shows the same transition benefit as the "aware" participants (cf. Figure 1) is in line with this assumption, although we, of course, do not want to rely on the data of only one participant.

Learning of response transitions was also confirmed in Experiments 2 to 4b. In these experiments the transitions between the two responses were kept constant in such a way that in each block about one third of all trials required response repetitions and about two thirds required response alternations. Participants clearly adapted to these different frequencies, i.e. to probabilistic transitions: The comparisons between response repetitions and those response alternations which were likewise triggered by ambiguous stimulus transitions showed in all four experiments that the seldom response repetitions were more error prone than response alternations. In Experiments 2 and 3 the disadvantage of response repetitions was additionally confirmed by the RT data.

In contrast to the clear behavioral effects of a unique response transition in Experiment 1 and of probabilistic response transitions in Experiment 2 to 4b, Experiments 2 and 3 showed that a local unique stimulus transition which was confounded neither with unique response transitions nor with higher order serial dependencies, did not affect performance. This unexpected finding is in contrast with numerous SRT studies which showed adaptation of RTs and error rates to redundancies in the succession of stimuli independently of the structure of the response sequence (see below). However, a recent study by Jiménez & Méndez (1999) suggests a necessary sophistication of the issue of pure stimulus sequence learning. According to this study, stimuli in SRT tasks become predictors only to the extent participants have to respond and attend to the stimuli. In other words, the stimuli seem to be reliably encoded only with respect to their response relevant features and only what is reliably encoded can be used for reliable predictions of forthcoming events (cf. also Mack & Rock 1998). The stimuli we used in Experiment 2 and 3 were distinct only with respect to conjunctions of a response relevant and a response irrelevant feature so that despite a unique stimulus transition the transitions between the stimulus features were ambiguous. Thus, the inefficacy of the unique stimulus transitions in Experiments 2 and 3 is presumably due to the fact that the transitions between the response relevant features were *not* unique. In this view, Experiments 2 and 3 provide further evidence for the notion that only those features of stimuli become predictors to which participants have to respond or to which they attend for other reasons.

In Experiments 4a and 4b stimuli were used which where distinct with regard to both their response relevant and their response irrelevant features. Otherwise the same settings were applied as in Experiments 2 and 3. According to the foregoing considerations, clear effects of the unique stimulus transitions were now expected.[4] The results were twofold. On the one hand, there was a substantial increase of the number of participants who seemed to be aware of the unique stimulus transition. On the other hand, the performance effects were marginal, only partially reliable, and unsystematically influenced by awareness of the unique transition. Even if one assumes that with more training and more statistical power more consistent performance effects would result, it remains noticeable that pure transitions between response relevant stimulus features result in much less performance effects in comparison to pure response transitions (in all experiments), although predicting the next response relevant stimulus does logically also entail a prediction of the next response.

In our view, the comparatively small performance effects even of detected unique stimulus transitions point to another factor that deserves discussion in the context of pure stimulus sequence learning: Besides attention to the predictors, the usefulness of what can be predicted also seems to matter. In Experiments 4a and 4b the values of the cards were to be attended but predicting them did not provide features of the to-be-executed responses. Rather, the card values were first to be transferred into either key locations or finger/hand specifications before the required response could be initiated. In other words, stimulus predictions were of less gain for response acceleration because the predicted stimuli did not *directly* specify which response is to be prepared. And it is presumably for that reason that we observed only marginal performance effects of the unique stimulus transition in Experiments 4a and 4b, despite many participants becoming aware of the transition (cf. also Kunde, 2001; Kunde, Hoffmann, & Zellmann, 2002; Rosenbaum, 1980, 1983; for the relative

[4]It is to be noted that in the Jiménez & Méndez (1999) study participants did not adapt to the unequivocal transitions between individual stimuli but rather to transitions between the response-relevant categories of the used stimuli (shapes and locations). Accordingly, merely the use of distinct response relevant features should not suffice in order to evoke stimulus transition learning unless not different responses are required by the different features. However, as the data will show, the present experiments indicate substantial explicit learning of the unique transition between individual stimuli despite the fact that transitions between the response-relevant stimulus categories were still ambiguous. The different results may be due to the fact that in the Jiménez & Méndez study, the predictive stimuli were to be attended to in the context of a secondary task, whereas in the present experiments the unique transition referred to the imperative stimuli of the only reaction time task.

uselessness of stimulus predictions for response preparation).

Accordingly, performance effects of pure stimulus structures would be expected first, if the predictive stimulus features are to be attended and second, if the predictable features present response specific information. Almost all studies in which robust performance effects of pure stimulus structures were found are consistent with this expectation: In some studies learning of pure locational sequences was shown (Howard, et al., 1992; Koch & Hoffmann, 2000; Mayr, 1996; Stadler, 1989). For example, in the study by Mayr (1996) participants responded to geometrical objects by pressing assigned response keys. The objects were presented at different locations on the screen. The sequence of the response irrelevant locations was varied independently of the sequence of objects/key-presses. Performance data clearly indicated learning of the sequence of the response irrelevant stimulus locations. However, despite being irrelevant for the required key presses, stimulus locations were to be attended in order to identify the response relevant objects. Furthermore, predicted locations directly specified in advance where attention or gaze is to be directed in the next trial. Thus, learning occurs, as we argue, precisely because the apparently response irrelevant locations were nevertheless to be attended and provide information that directly specify what is to be done next. It is in line with this account that sequence learning of "response irrelevant" stimulus locations vanishes if attending the stimulus location is no longer needed because the response relevant feature (colour) could be preattentionally identified (Willingham, Nissen, & Bullemer, 1989).

There are other studies in which the location of the forthcoming stimulus was predictable not from the location but from the identity of the preceding stimulus. The mentioned experiments of Jiménez & Méndez (1999) already gave an example. Remember that the predictability of the location of the next stimulus (and the next response) by the response irrelevant shape of the current stimulus was only learned if participants were required to attend the shapes in order to count the occurrence of certain target shapes. Moreover, the influence of already learned shape-location transitions vanished if participants were suspended from counting target shapes, i.e. if participants no longer had to attend the shapes. Comparable data have been reported by Ziessler (1994, 1998). In his experiments, participants were required to respond to 8 target letters by 4 assigned key presses. Target letters were embedded in a 5 by 5 matrix of distractor letters, so that they had to be searched for. The identity of the current target letter predicted the location of the next target. This predictability of the forthcoming target location results in substantial performance benefits. However, as in the Jiménez & Méndez (1999) study, the data clearly suggest that location predictions do not base on individual target letters but rather on the response category of the current target, which let Ziessler (1998) assume that not letter-location transitions but response-location transitions were learned. However, regardless of whether in these experiments the location predictions based on the previous stimulus category or the previously executed response, the data support the point that the predictors have to be attended and the predicted information has to provide direct response specific information (the location to attend), for stimulus predictions to be learned and used.

Finally, also learning of redundant transitions between stimulus identities has been shown (Frensch & Miner, 1995; Goschke, 1998). In these experiments, a target stimulus and an additional array of four horizontally aligned further stimuli were presented in each trial. One stimulus in the array was always identical to the target and participants were requested to respond to the position of the target in the array with a spatially compatible key press. The location of the targets in the array, and by this the target-response mappings, were changed from trial to trial so that target sequences could be varied independently of the sequences of keystrokes. The results show that participants acquired knowledge about a redundant target sequence in the absence of regularities in the required response sequence. Again, the predictive targets had to be attended in order to accomplish the task and the predictable next target directly specified in advance which target had to be searched for in the next stimulus array, i.e. response relevant information was predicted directly.

The review reveals that the available evidence for pure stimulus sequence learning has been collected exclusively in settings in which first the predictive information was to be attended and the predictable information directly specified features of the forthcoming required actions, either of the required manual response or of the search for the relevant response signal (cf. also Willingham, 1999). In the present Experiments 2 and 3, both conditions were absent. Accordingly, no learning was found, even though the unique transitions represent a much stronger redundancy in the succession of stimuli than usually applied. In Experiments 4a and 4b the predictive stimulus information was to be attended but the predictable stimulus information (the value of the next card) did not directly specify features of the to be executed response. Accordingly, substantial explicit detection of the unique stimulus transition but only marginal performance effects were indicated.

In summary, we argue that in situations in which participants are required to quickly respond to successively presented stimuli, primarily learning mechanisms are addressed that strive for reliable predictions of what is to be done next. Secondly, for these mechanisms to work a reliable encoding of the predictive information is a prerequisite that is presumably accomplished only if the possible predictors are attended. Redundant transitions between responses are easily learned and effectively used because both criteria are fulfilled: In each trial the current response was to be selected from the response set, which ensures directing of attention to it, and predicting the next response *is* a prediction of what is to be done next. In contrast, the mere prediction of the next stimulus is of less use as long as the predicted stimulus information does not directly specify features of the to be executed actions. Thus, pure stimulus transitions only have a chance to be learned in SRT tasks if the predictive stimulus features are attended, and learned stimulus transitions become effective only to the extent that the predicted stimulus features directly specify features of the required actions.

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Appendix

Transition matrices of Experiment 1

Experimental Blocks 2–6 and 8					
	key 1	key 2	key 3	key 4	
key 1	22	21	–	21	64
key 2	–	–	64	–	64
key 3	21	22	–	21	64
key 4	21	21	–	22	64
Control Blocks 1 and 7					
Key 1	16	16	16	16	64
key 2	16	16	16	16	64
key 3	16	16	16	16	64
key 4	16	16	16	16	64

Transition matrices of Experiment 2 and 4a

Experimental Blocks 2–5 and 7					
	card 1	card 2	card 3	card 4	
card 1	22	21	–	21	64
card 2	–	–	64	–	64
card 3	21	22	–	21	64
card 4	21	21	–	22	64
Control Blocks 1 and 6					
card 1	11	10	21	22	64
card 2	11	11	21	21	64
card 3	21	22	11	10	64
card 4	21	21	11	11	64

Transition matrices of Experiment 3 and 4b

Experimental Blocks 1–3 and 5					
	card 1	card 2	card 3	card 4	
card 1	10	11	–	11	32
card 2	–	–	32	–	32
card 3	11	10	–	11	32
card 4	11	11	–	10	32
Control Block 4					
card 1	5	5	11	11	32
card 2	5	6	11	10	32
card 3	11	10	5	6	32
card 4	11	11	5	5	32

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