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The influence of response–effect compatibility in a serial reaction time task

Christian Stöcker, Albrecht Sebald, and Joachim Hoffmann
University of Würzburg, Würzburg, Germany

Participants performed a serial reaction time task, responding to either asterisks presented at varying screen locations or centrally presented letters. Stimulus presentation followed a fixed second-order conditional sequence. Each keypress in the experimental groups produced a contingent, key-specific tone effect. The critical variation concerned the mapping of tones to keys. In Experiment 1, keypresses in one control condition produced noncontingent tone effects, while in another control condition there were no tone effects. In Experiment 2, three different key–tone mappings were compared to a control condition without tone effects. The results show that tone effects improve serial learning when they are mapped to the response keys contingently and in a highly compatible manner. The results are discussed with reference to an ideomotor mechanism of motor sequence acquisition.

In serial reaction time tasks, participants respond to sequences of stimuli with sequences of corresponding responses. Reaction times (RTs) to structured sequences typically decrease faster than RTs to random sequences, indicating that participants acquire and employ knowledge about the serial structure to accelerate their responses.

There has been a great deal of debate about the question of what is learned in serial reaction time tasks. Some authors presume that what is learned is the structure of the stimulus sequence. According to this view, primarily stimulus–stimulus associations are learned during serial reaction time tasks (e.g., Cleeremans & McClelland, 1991; Cohen, Ivry, & Keele, 1990; Frensch & Miner, 1995; Howard, Mutter, & Howard, 1992). Other authors have presented evidence suggesting that the formation of response–response associations is crucial to sequence learning (e.g., Hoffmann & Sebald, 1996; Nattkemper & Prinz, 1997; Willingham, 1999; Willingham, Wells, Farrell, & Stemwedel, 2000). Finally, there are studies that indicate that both, stimulus–stimulus as well as response–response associations develop in parallel and contribute likewise to sequence learning in serial reaction time tasks (e.g., Fendrich, Healy, & Bourne, 1991; Goschke, 1998; Mayr, 1996).

Requests for reprints should be sent to Christian Stöcker, Psychologie III, University of Würzburg, Röntgenring 11, 97070, Würzburg, Germany. Email: stoecker@psychologie.uni-wuerzburg.de

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The debate about what is learned in serial reaction time tasks has recently been expanded by the suggestion that response–effect learning may contribute to serial learning. The idea is that each response signal in an serial reaction time task is presented as a consequence of the preceding keypress—that is, it might be interpreted as an effect of the respective response. Ziessler (1998) demonstrated that relations between a current response and the location of a following response signal can contribute to serial learning independently of stimulus–stimulus, response–response, and stimulus–effect relations. Ziessler and Nattkemper (2001) also showed that predictable relations between responses and the respective following response signals improve serial learning. They concluded that "R–S learning is not only a very powerful learning mechanism but the major learning mechanism working under serial learning conditions" (Ziessler & Nattkemper, 2001).

Hoffmann, Sebald, and Stöcker (2001) further qualified the influence of response–effect learning in serial reaction time tasks by showing that even completely task irrelevant response effects are incorporated in the control of behaviour. In their experiments, participants were required to respond to asterisks appearing at four different screen locations with spatially corresponding keypresses. Stimuli and responses followed the highly redundant 10-element sequence used by Nissen and Bullemer (1987). Each response produced one of four different tone effects. Sequence learning was improved only when the tones were contingently mapped onto the responses—that is, when each response always produced the same tone (Experiment 1). When the response–effect mapping was changed during the course of learning, RTs increased, indicating that tones had been incorporated into behavioural control despite being task irrelevant (Experiment 2). Finally, the contingent tone effects only became effective when there was sufficient time to anticipate the next to-be-produced tone before the next response signal was presented (Experiment 3).

Hoffmann et al. (2001) accounted for their results with reference to an ideomotor mechanism of sequence acquisition (cf., Greenwald 1970; James, 1890/1981; see also Elsner & Hommel, 2001; Stoet & Hommel, 1999). According to this idea, responses are first associated with their contingent effects—that is, an array of sensorial feedback stimuli such as a tactile sensation on the finger that presses a response key, the proprioceptive perception of the response, and finally the tone effect. All of these form the effect image of the respective response.

Second, when stimulus–response–effect triplets are repeatedly experienced in the same order, conditioned bonds are formed between the consecutive elements of the effect sequence so that producing one effect triggers the anticipation of the next-to-be-produced effect, which in turn triggers the respective response. The sequence of anticipated response effects can thus exert control over response execution independently of the response signals.

We think it is worthwhile to pursue the idea that what is learned in serial reaction time tasks may be a sequence of desired *outcomes* or effects, since serial behaviour in everyday life is not usually equivalent to responding to a series of stimuli but to producing a series of effects. This paper has two main purposes with regard to clarifying the conditions for sequence learning with irrelevant response effects. First, sequence structure may be crucial for the associative chaining of the response effects into effect sequences. Hoffmann et al. (2001) showed response–effect learning for the highly redundant Nissen and Bullemer (1987) sequence. This sequence contains redundancy at various levels: Stimuli/responses are not equally frequent, the transitions between consecutive stimuli as well as between consecutive responses contain redundancy, and the sequence also contains relational patterns—for example, a run of four stimuli/responses from right to left at the end of the sequence. All of this makes it very difficult to determine exactly which kind of structural information is exploited during learning.

The aim of Experiment 1 was to replicate those results with a type of sequence that allows us to assess whether the beneficial influence of contingent tone effects extends to the learning of second-order transition information—that is, whether more than one element of context can be utilized to predict upcoming responses and their effects. To control for the influence of an additional stimulus sequence (the sequence of tones) emphasizing the sequence structure, we introduced a control condition with noncontingent tone effects that nevertheless led to the same tone sequence as the experimental condition, in analogy to the control condition used by Hoffmann et al. (2001).

Second, we were interested in the importance of response–effect compatibility. Recent results show that compatibility between responses and their effects influences choice and simple RTs (Kunde, 2001a). Participants performed a four-choice reaction time task in which they responded to a nonspatial stimulus attribute (colour) with four horizontally aligned responses (keypresses). Each response led to a certain visual effect (one of four horizontally aligned boxes on a computer screen being filled out). The critical variation of the experiment concerned response–effect mapping: The responses filled either a spatially corresponding or a spatially noncorresponding box. The incompatible response–effect mapping significantly increased mean RTs in comparison to a control condition with spatially compatible response effects. Further response–effect compatibility effects were found for other dimensions—for example, the intensity of a keypress and loudness of a subsequent tone effect and for response and effect duration (Kunde 2001a, 2001b).

It seems a plausible assumption that compatibility relations also exist between tones ordered by pitch and spatially arranged response locations, and that these compatibility relations could influence RTs and sequence learning. To examine whether this is indeed the case, we used three different response–effect mappings in Experiment 2: an ascending mapping like the one used by Hoffmann et al. (2001), a mixed mapping in which the tone effects were randomly assigned to the response keys, and a descending mapping in which the tones were mapped onto the keys in descending order from left to right. In addition, there was a control group in which no tones were presented. In terms of ideomotor theory, the question addressed by Experiment 2 is the extent to which the transfer of behavioural control from stimuli to effects is influenced by response–effect compatibility.

The introduction of a manipulation of response–effect compatibility into a task with spatial locations serving as stimuli carries one potential confound: Effects produced by the compatibility variation need not necessarily be caused by the relations between responses and their effects but between stimuli and effects. If spatially arranged response locations share compatibility with tones of ascending pitch, so might spatially arranged asterisk locations. In such a situation it is thus impossible to unambiguously attribute impacts of the compatibility variation to the relations between responses and effects. To avoid this problem, different stimulus material was used in Experiment 2: Centrally presented letters were employed. We presumed that letters presented in one single location and tones of ascending pitch would not produce any compatibility effects. This assumption was explicitly tested and confirmed by way of a within-group manipulation in Experiment 2.

The use of different stimulus material in the two experiments also opens an additional analytical possibility: The question of whether the impact of contingent tone effects in Experiment 1 was mediated by the spatially arranged stimuli could now be tested through an interexperiment comparison. The absence of a three-way interaction of stimulus material, response effects, and sequence structure would indicate that the impact of the tone effects was not mediated by the type of stimulus material.

EXPERIMENT 1

To get a more precise view of the sequence properties that can be exploited by the hypothetical mechanism of effect–sequence acquisition sketched above, so-called second-order conditional sequences were employed in the present experiments, similar to those used by Reed and Johnson (1994). In this type of sequence, all stimuli are equally frequent, and each stimulus is followed by every other stimulus exactly once. This means that the first-order transition probabilities between all stimuli are equal. Any learning occurring with such a sequence must be due to the acquisition of at least second-order dependencies.

Several authors have shown that subjects in serial reaction time tasks are able to encode an increasing amount of temporal context and increasingly make use of such higher order dependencies within a sequence during the course of training (e.g., Cleeremans & McClelland, 1991; Stadler, 1992). The question in Experiment 1 was whether learning with a second-order conditional sequence can also benefit from contingent action effects. Formulated in terms of the ideomotor principle: Can subjects in a serial reaction time task with additional tone effects only associate tones that immediately follow each other—that is, does one tone trigger the anticipation of the one by which it is immediately followed, and thus speed up the upcoming response, or can longer tone sequences be encoded, anticipated, and used to improve performance? If serial learning in a serial reaction time task with a second-order conditional sequence and contingent tone effects is improved, then the mechanism that construes a representation of the effect sequence must be able to utilize at least second-order dependencies or, to put it differently, relations between three consecutive response effects.

Stimuli were asterisks presented at four screen locations. Participants had to respond by pressing a spatially compatibly mapped key for each asterisk location. There were two control conditions: one without tone effects and one with noncontingent tone effects. This makes Experiment 1 essentially a replication of Experiment 1 of the Hoffmann et al. (2001) study, with the alteration of using two different second-order conditional sequences instead of the Nissen and Bullemer (1987) sequence and a quasirandom transfer sequence.

Method

Participants

There were 19 participants in group contingent tones (mean age = 23 years, *SD* = 5.4), 19 participants in group no tones (mean age = 23 years, *SD* = 3.6), and 20 participants in group noncontingent tones (mean age = 24 years, *SD* = 4.9). of the participants, 4 in group contingent tones, 4 in group no tones, and 5 in group noncontingent tones were male. Due to reasons explained below, 2 participants were replaced in group contingent tones. About half of the participants in each group were students fulfilling a course requirement, the rest were volunteers rewarded with the equivalent of about €6.

Stimuli and responses

All experiments were conducted on MS-DOS compatible personal computers. The screen was blue, and the display and the stimuli were coloured white. In Experiment 1, the display consisted of four horizontal lines about 1 cm wide, visible in the lower half of the screen. The lines were situated about 4.5 cm apart, which is equivalent to a visual angle of about 4.5 degrees given a viewing distance of approximately 57 cm. On each trial, an asterisk 4 mm in diameter was presented approximately 1.3 cm above one of the four lines. The keys "c", "v", "n", and "m" of a German QWERTZ-keyboard were used as response keys in all groups.

Participants' index and middle fingers of both hands were resting on those keys during the experiment. Each of the four asterisk locations was assigned to the respective spatially compatible key, which was to be pressed as quickly as possible when the corresponding asterisk appeared. Each response triggered the presentation of the next asterisk/letter after a response–stimulus interval (RSI) of 150 ms. In the case of a wrong response, the word "Fehler!!" (German for "error") was briefly presented at the bottom of the screen during the RSI.

In groups contingent tones and noncontingent tones, each keypress also triggered the immediate presentation of a tone: C, E, G, or C′ (the octave to C). These tones correspond to the notes of a C major chord with an added octave.

In the contingent tones group, the four tones C–E–G–C′ were assigned to the four response keys in ascending order from left to right. Each keypress always produced the same tone, regardless of whether the response was correct or erroneous. The same mapping was again used in the "ascending" condition of Experiment 2.

In the noncontingent tones group, the four tones C–E–G–C′ were assigned to the four screen locations from left to right, and each keypress triggered the tone that corresponded to the previous asterisk location in the sequence, with the result that each keypress produced three different tone effects, depending on its position within the sequence. The leftmost key, for example, could produce the tones E, G, and C′, depending on the location in which the asterisk had appeared in the previous trial. Note that this manipulation carries the benefit of producing the same tone sequence for the contingent tones and noncontingent tones groups—provided that the contingent tones group responds correctly. Only in the contingent tones group, however, is there a contingent relationship between responses and tones. No additional effects were presented in the no tones group.

The presentation of the stimuli followed a fixed serial order. Two 12-element second-order conditional sequences were used, similar to those used by Reed and Johnson (1994). We used two different second-order conditional sequences that do not share any second-order conditional information. This means that every pair of two successive stimuli has a different successor in Sequence 1 than in Sequence 2. Both 12-element sequences can be found in the Appendix.

Procedure

Participants were unaware that the presented stimulus material would be structured—that is, they expected to perform an ordinary choice reaction task. They were instructed by an onscreen text at the beginning of the experiment explaining that asterisks would appear on the screen and that they should respond by pressing the assigned key as quickly as possible. It was stressed in the instructions that speed and accuracy were equally important for good performance. Participants in the respective groups were informed of the fact that they would hear a tone after each response.

The experiment consisted of a total of 10 experimental blocks, with 10 sequence presentations or 120 single trials each. Sequence 1 was presented in Blocks 1, 2, and 9, and Sequence 2 in Blocks 3 to 8 and 10.

At the end of each block of 120 trials, an onscreen message informed the participants about their mean reaction time and error rate in the last block and encouraged them to improve their performance further.

After a short break, participants started the next block by pressing a key. The RT of each correct response was recorded from the onset of stimulus presentation until the execution of the response.

Postexperimental interview

After finishing the experiment, participants were asked whether they had noticed anything about the stimulus material, and their answers were recorded. They were then informed that there had been a repeating sequence of stimulus locations in Blocks 3 to 8 and 10, and they were asked to recall as much of that sequence as they could. This was done through a paper and pencil test: Participants received a sheet of paper with the four asterisk locations marked with the numbers 1 to 4. They were encouraged to note down every sequence or sequence fragment of stimulus/response locations that they could recall using those numbers. Recalled sequences and sequence fragments were recorded as a measure for explicit sequence knowledge. The results of this free recall task were scanned for triplets of stimuli/keypresses that can be found in the training sequence presented in Blocks 3 to 8 and 10. Each correctly reproduced triplet was rewarded with one point. The total number of triplets within the sequence is 12, if sequence repetition is taken into account. A total of 12 points were awarded for correctly recalling the entire sequence. Every participant thus received an "explicit knowledge score" of between 0 and 12 points.

There is an ongoing discussion about the effectiveness of various measures for explicit sequence knowledge. Some researchers (cf., Cohen & Curran, 1993; Destrebecqz & Cleeremans, 2001; Jimenez, Mendez, & Cleeremans, 1996) have argued that implicit and explicit learning can be separately measured by appropriate means like RT measures and free or guided sequence generation tasks, while others are of the opinion that it remains to be shown that truly implicit learning is actually taking place in such tasks, underlining a lack of sensitivity or specificity in the respective learning measures (cf., Perruchet & Amorim, 1992; Shanks & St. John, 1994; see also Shanks & Lovibond, 2002). We tend to agree with Shanks and St. John on this issue, who state that "no convincing evidence of implicit learning has yet emerged in sequential RT tasks" (Shanks & St. John, 1994, p. 389). Thus, it is not our chief aim to provide evidence for learning without awareness. Our main interest is to clarify precisely *what* is learned in serial reaction time tasks, not whether it is learned consciously or unconsciously (cf., also Koch & Hoffmann, 2000; Hunt & Aslin, 2001, for a similar approach). Since we know, however, that many researchers in the field will be interested in implicit/explicit distinctions and possible implications for our data we decided to gather and present postexperimental interview data here in any case.

Results

Error data

Since the tones assigned to the response keys in group contingent tones were key contingent, every erroneous response produced a tone that deviated from the tone sequence that the structure of the training sequence entailed. Excessive error rates thus led to participants experiencing a different effect sequence. To achieve comparability between the tone sequences that participants heard during the experiment, all participants with error rates higher than 10% were excluded from the sample and replaced (for details see section "Participants"). This procedure of course precludes any further examination of the error data. It should be sufficient to say that there were no indications of speed–accuracy tradeoffs in the data. RTs that were more than 3 standard deviations from the individual means of each participant were discarded as outliers. These amounted to 1.3% of all correct responses, with no significant differences between groups.

RT data

RT data (see Figure 1) were subjected to a 3 (conditions) × 6 (Training Blocks 3 to 8) analysis of variance (ANOVA) with blocks as repeated measures. There was a significant decrease of mean RT over Blocks 3 to 8, $F(5, 275) = 37.06$, $p < .001$. Condition also had a significant influence, $F(2, 55) = 2816.61$, $p < .01$. Participants responded the fastest in group contingent tones (mean = 364 ms), more slowly in group no tones (mean = 395 ms), and the slowest in group noncontingent tones (mean = 428 ms). Single contrasts revealed that only the difference between groups contingent tones and noncontingent tones is statistically significant, $t(37) = –3.61$, $p < .001$. The interaction of block and condition was also significant, $F(10, 275) = 2.23$, $p < .05$. RTs decreased faster in group contingent tones (–70 ms) than in groups noncontingent tones (–37 ms) and no tones (–43 ms).

As a pure measure for sequence specific learning, another ANOVA with the factors sequence structure (mean of Block 8 and 10 vs. Block 9) and group (contingent tones vs. no tones vs. non-contingent tones) was conducted (Figure 1). A significant effect for the factor sequence structure was found, $F(1, 55) = 159.63$, $p < .001$. RTs increased in Block 9. The effect of the factor group was also significant, $F(2, 55) = 7.03$, $p < .01$. Again, participants responded fastest in group contingent tones, slightly slower in group no tones and slower still in group noncontingent tones. The crucial interaction of sequence structure and group was also significant, $F(2, 55) = 3.58$, $p < .05$. The change in sequence structure in Block 9 caused

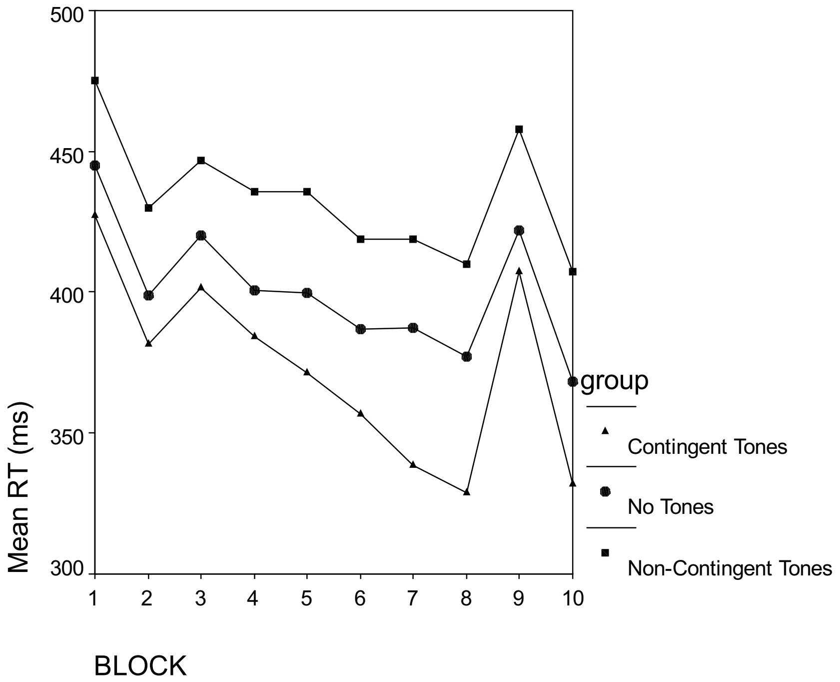

Figure 1. Mean RT in ms for all groups in Experiment 1, plotted over experimental blocks. Sequence 1 was presented in Blocks 1, 2, and 9, and Sequence 2 in Blocks 3 to 8 and 10. The key–tone mapping of group contingent tones is equivalent to that of group ascending of Experiment 2.

the greatest RT disruption in group contingent tones (75 ms) and a smaller RT increase in groups no tones and noncontingent tones (49 ms in both groups). Post hoc comparisons confirmed this result: The RT difference between the mean of Blocks 8 and 10 and Block 9 is significantly higher in group contingent tones than in group no tones, $t(36) = 2.08$, $p < .05$, and group noncontingent tones, $t(37) = 2.35$, $p < .05$. There is no difference between groups no tones and noncontingent tones, $t(37) = -0.017$, $p > .05$.

Postexperimental interview

A total of 17 participants (89%) in group contingent tones, 13 participants (68%) in group no tones, and 14 participants (70%) in group noncontingent tones reported after the experiments that they had noticed repetitions in the stimulus material. A total of 9 participants in group contingent tones (47%), 9 participants in group no tones (47%), and 4 participants in group noncontingent tones (20%) reported that they had noticed that the repeating pattern had changed at some point. The mean explicit knowledge scores for the free generation task (possible range 0 to 12 points) were 3.9 points ($SE = .80$) for group contingent tones, 2.7 points ($se = .62$) for group no tones, and 1.4 points ($SE = .26$) for group noncontingent tones. Post hoc comparisons revealed a significant difference in explicit knowledge between groups contingent tones and noncontingent tones, $t(37) = 3.14$, $p < .01$, and also a significant difference between groups no tones and noncontingent tones, $t(37) = 2.24$, $p < .05$. Groups contingent tones and no tones did not differ with regard to explicit knowledge about sequence structure, $t(36) = 1.1$. When computed across all groups, there was a significant correlation between the performance-based learning measure (difference between Block 9 and the mean of Blocks 8 and 10) and the explicit knowledge scores, $r = .608$, $p < .01$. When computed groupwise, significant correlations resulted for groups contingent tones ($r = .622$, $p < .01$) and no tones ($r = .648$, $p < .01$), but not for group noncontingent tones ($r = .250$, $p > .10$).

Discussion

Experiment 1 replicated the findings of Hoffmann et al. (2001). First, sequence learning took place in all three groups, and RTs decreased across the training blocks and increased again when sequence structure was changed in Block 9. Second, sequence learning was more pronounced in the group with contingent tone effects (contingent tones). RTs decreased faster in Blocks 3 to 8, and the increase between Blocks 8 and 10 was more pronounced in group contingent tones.

The results also extend the findings of Hoffmann et al. (2001): Since the predictive information required to learn a second-order conditional sequence must encompass at least three consecutive stimuli/responses, it is safe to assume that the mechanism that binds contingent response effects into representations of effect sequences is capable of linking at least three consecutive effects.

With regard to the question of whether the observed sequence learning was "implicit" or "explicit", the significant overall correlation between RT-measured and explicitly measured learning is instructive: As observed in many other studies (see Perruchet & Amorim, 1992), the two measures do not seem to be entirely independent. It is interesting that the correlation does not even approach significance in group noncontingent tones, the group that also displays the smallest degree of "explicit sequence knowledge". This result might, however, be related to statistical power and should thus be interpreted cautiously.

The beneficial influence of the tone effects in group contingent tones cannot solely be attributed to an additional gain in explicit knowledge, since there is no reliable difference in explicit knowledge scores between group contingent tones and the group without tone effects (no tones). Interestingly, however, the consistent and stimulus-contingent tones in group noncontingent tones seem to have impaired the acquisition or expression of explicit knowledge rather than to have improved it. Although participants heard the same 12-note melody over and over again for six blocks, and then a different but consistent melody for another block, fewer of them became aware of, or reported their awareness of, the fact that the repeating pattern eventually changed, and they recalled fewer sequence fragments than did participants in the other two groups.

The fact that the noncontingent tone effects in group noncontingent tones seem to have *hindered* the acquisition of explicit knowledge points to an interesting possibility: Noncontingent action effects might work against the formation or retention of explicit knowledge about event sequences. Low explicit knowledge scores in some experiments on sequence learning might thus be due to the fact that nonunique stimulus transitions were used, and thus noncontingent effects are produced by each keypress! When one stimulus can be followed by two or more other stimuli, that also means that one response is followed by two or more "effects" (see Ziessler, 1998; Ziessler & Nattkemper, 2001, for an illustration of the fact that upcoming stimuli may really be perceived like response effects in serial reaction time tasks).

EXPERIMENT 2

Experiment 1 showed that contingent tone effects can improve sequence learning even with a second-order conditional sequence in which immediate stimulus transitions alone do not yield any information about sequence structure. Experiment 2 was designed to extend these findings to a situation in which compatibility relations between stimuli and response effects could not play a role. Centrally presented letters now served as stimulus material. We presumed that there is no dimensional overlap between letters and horizontally aligned response keys. This assumption was tested through a separate manipulation of the stimulus–response mapping within one group.

The critical variation concerned the mapping of tones to response keys. The relationship between keys and tones was now contingent in all groups except the no tones control group, but the mapping of key location to pitch was varied between groups. An "ascending" mapping, identical to the contingent tones group of Experiment 1, was contrasted with a "descending" mapping in which the order of pitches from left to right was reversed and a "mixed" mapping in which there was no systematic relationship between key location and pitch. The ascending and the descending key–tone mapping produce a tone sequence that runs in parallel to the sequence of response locations. In contrast, with the mixed mapping, there is no systematic rule for the prediction of the tone of a key further to the left or further to the right. If a structural parallel between the response sequence and the effect sequence is crucial, ascending and descending mapping should both produce benefits. If, however, there is a strong enough stereotype for lower tones being situated on the left-hand side of a keyboard (induced, for example, by the fact that this is the common mapping on western keyboard instruments), then only keys ordered from left to right and tones ordered from lower to higher pitch should be compatible (e.g., Kornblum, 1992). In this case, only the ascending mapping would be expected to produce benefits. If response-effect contingency alone is sufficient to improve serial learning, then all three tone groups should benefit in comparison to the no tones control condition.

Method

Participants

There were 18 participants in group ascending (mean age = 21 years, *SD* = 1.7), 19 participants in group no tones (mean age = 21 years, *SD* = 1.2), 19 participants in group descending (mean age = 23 years, *SD* = 4.7), and 19 participants in group mixed (mean age = 22 years, *SD* = 4.7). A total of 5 participants in group ascending, 3 participants in group no tones, 7 participants in group descending and 3 participants in group mixed were male. As in Experiment 1, some participants had to be replaced due to error rates above 10%: 4 participants in group ascending, 3 participants were replaced in group no tones, 1 participant in group descending and 4 participants in group mixed. About half of the participants in each group were students fulfilling a course requirement; the rest were volunteers rewarded with the equivalent of about €6.

Stimuli and responses

The basic setup of Experiment 2 was the same that as in Experiment 1, with the exception that centrally presented letters now served as stimuli instead of asterisks appearing in different locations. One of the letters F, G, H, or I was presented in a 20-point Times New Roman font at a central position in the lower half of the screen on each trial. The keys “c”, “v”, “n”, and “m” of a German QWERTZ-keyboard were used as response keys in all groups.

The stimulus–response mapping was displayed at the bottom of the screen throughout the experiment, with the four stimulus letters arranged above the spatially compatibly displayed key names “c”, “v”, “n”, and “m”. To test whether stimulus–response compatibility plays a role when letters are used as stimuli, the mapping of stimulus letters to response keys was manipulated in one group (ascending). For half of the subjects in this group the keys were mapped onto the letters in alphabetical order from left to right (F → key “c”, G → key “v”, H → key “n”, I → key “m”); for the other half of the subjects the alphabetical order was abandoned (G → key “c”, F → key “v”, I → key “n”, H → key “m”).

The mapping of effect tones to response keys was varied between groups. All key–tone mappings were contingent in Experiment 2—that is, each keypress always produced the same tone. The manipulation concerned the pitch-to-key-location mapping. The exact key–tone mappings are displayed in Table 1. In the ascending group the tones were assigned to the keys in ascending order from left to right. In the descending group, tones were assigned to the keys in descending order from left to right. In the mixed group, tones were arbitrarily distributed over the key locations, with the result that one lower and one

TABLE 1
Key–tone mappings for the three experimental conditions

	Condition											
Mapping	*Ascending*				*Mixed*				*Descending*			
Keys	c	v	n	m	c	v	n	m	c	v	n	m
Tones	C	E	G	C′	C′	E	C	G	C′	G	E	C

higher tone were produced by either hand (the tones C′–E–C–G were assigned to the keys from left to right). As in Experiment 1, there was a control group in which no tone effects were presented.

Procedure and postexperimental interview

As in Experiment 1, participants were unaware that the presented stimulus material would be structured—that is, they expected to perform an ordinary choice reaction task. The basic procedure was the same as in that Experiment 1, with the exception that the stimulus material now consisted of letters. The same order of blocks and the same sequences as those in Experiment 1 were used.

The postexperimental interview was also the same as that in Experiment 1, with the exception that participants were now asked to write down sequences of letters, not stimulus locations, as a measure for explicit knowledge about sequence structure.

Results

Error data

Once again, all participants with error rates higher than 10% were excluded from the sample and replaced (for details see section "Participants"), precluding any further examination of the error data. There were no indications of speed–accuracy tradeoffs in the data. Again, RTs more than 3 standard deviations from the individual means of each participant were discarded as outliers. These amounted to 1.5% of all correct responses, with no significant differences between groups.

RT data

An initial ANOVA for group ascending revealed that the factor letter–key mapping had no significant influence and did not interact with any of the other factors. We concluded that stimulus–response compatibility is not involved when the letters F, G, H, and I are mapped onto response keys in various orders. The data of the two halves of group ascending were thus collapsed together.

The RT data (see Figure 2) were again subjected to a 4 (conditions) × 6 (Training Blocks 3 to 8) ANOVA with blocks as repeated measures. Subsequently, the RT differences between the mean of Blocks 8 and 10 and the transfer Block 9 were subjected to another ANOVA with repeated measures. There was a significant decrease of mean RT over blocks 3 to 8, $F(5, 355) = 39.21, p < .001$. Mean RT decreased by 171 ms in group ascending, by 98 ms in group no tones, by 111 ms in group descending and by 91 ms in group mixed. Condition also had a significant influence, $F(3, 71) = 2.79, p < .05$. Participants responded fastest in condition ascending (mean = 564 ms), followed by participants in groups mixed (620 ms), no tones (639 ms), and descending (671 ms). Single contrasts revealed that only the differences between groups ascending and no tones, $t(35) = -2.14, p < .05$, and between groups ascending and descending, $t(35), = -2.74, p < .01$, are significant. The interaction of block and condition failed to reach significance, $F(15, 355) = 1.21, p > .05$.

When comparing the mean of Blocks 8 and 10 to Block 9 (see Figure 2), there was a significant influence of the factor block, $F(1, 71) = 81.54, p < .001$. RTs were higher in Block 9 than in Blocks 8 and 10. There was no main effect of the factor condition, $F(3, 71) = 2.15, p < .102$.

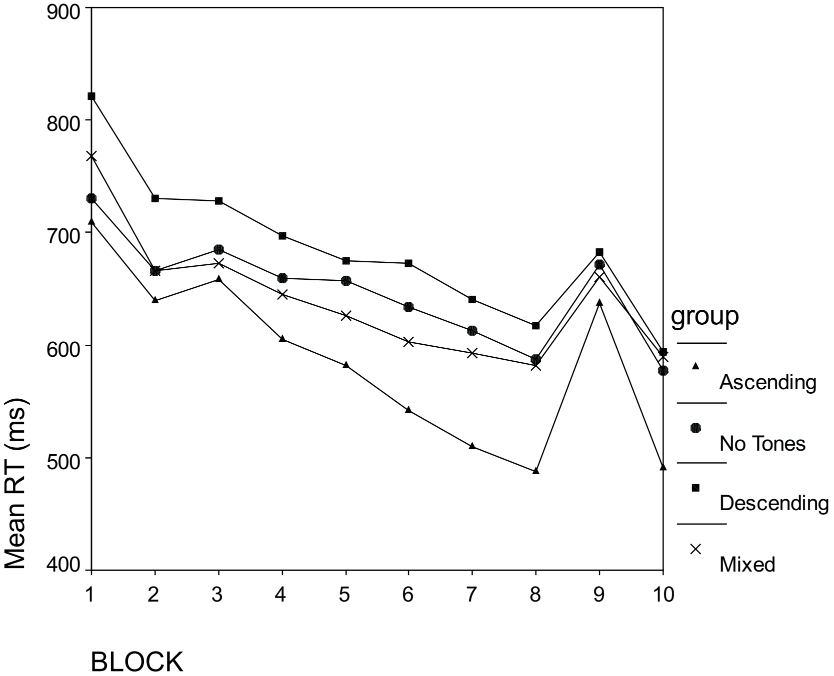

Figure 2. Mean RT in ms for all groups in Experiment 2, plotted over experimental blocks. Sequence 1 was presented in Blocks 1, 2, and 9, and Sequence 2 in Blocks 3 to 8 and 10.

The interaction of block and condition just failed to reach significance, $F(3, 71) = 2.49$, $p < .067$.

Single contrasts of the learning measure, however, revealed a significant advantage for the ascending group compared to all three other groups: $t(35) = 1.71, p < .048$ (one-tailed p-value) for ascending versus no tones; $t(35) = 2.21$, $p < .034$, for ascending versus descending; and $t(35) = 2.27$, $p < .029$, for ascending versus mixed. There were no significant differences between the groups mixed, descending and no tones (all ts < 1).

To assess the interaction of spatial stimuli versus letters with tone effects versus no tone effects, the data for the contingent tones and the no tones groups of Experiment 1 and groups ascending and no tones of Experiment 2 were subsequently subjected to an additional, across-experiments ANOVA. The rationale behind this was that not only response-effect compatibility but also stimulus–effect compatibility might have contributed to the results of Experiment 1. A significant three-way interaction of stimuli, response effects, and sequence structure would indicate a differential impact of the tone effects with spatially defined stimuli—that is, an influence of stimulus–effect compatibility.

The interexperiment ANOVA was conducted with the factors stimuli (asterisks versus letters), response effects (ascending versus no tones), and sequence structure (mean of Blocks 8 and 10 vs. Block 9). Although there was a significant interaction of stimuli and sequence structure, $F(1, 71) = 9.91, p < .01$, and also a significant interaction of response effects and sequence structure, $F(1, 71) = 5.51$, $p < .05$, the crucial three-way interaction of stimuli, effects, and sequence structure did not approach significance ($F < 1$). Participants showed stronger sequence learning with letters as stimuli, but the impact of tone effects on learning was not mediated by the type of stimulus material.

Post experimental interview

A total of 15 participants (83%) in group ascending, 14 participants (73%) in group no tones, 16 participants (84%) in group descending, and 11 participants (58%) in group mixed reported after the experiments that they had noticed repetitions in the stimulus material. A total of 8 participants in group ascending (44%), 7 participants in group no tones (37%), 3 participants in group descending (16%), and 2 participants in group mixed (10%) reported that they had noticed that the repeating pattern had changed at some point. The mean explicit knowledge scores for the free generation task (possible range 0 to 12 points) were 5.4 points ($SE = 1.01$) for group ascending, 3.5 points ($SE = .89$) for group no tones, 1.7 ($SE = .37$) for group descending, and 1.8 points ($SE = .53$) for group mixed. Post hoc comparisons revealed a significant difference in explicit knowledge between groups ascending and descending, $t(35) = 3.30$, $p < .01$, and also a significant difference between groups ascending and mixed. $t(35) = 3.03$, $p < .01$. The difference between groups no tones and group descending failed to reach significance, $t(36) = 1.860$, $p < .071$. No other comparisons of the explicit knowledge scores approached significance (all ps > .10).

Again, there was a significant overall correlation between explicit knowledge score and RT learning measure: $r = .498$, $p < .001$. When computed separately for each group, however, a significant correlation between RT measure and explicit knowledge emerged only for group no tones ($r = .709$, $p < .01$; all others, ps > .10).

An interexperiment comparison concerning explicit knowledge scores of the contingent tones, no tones (Experiment 1), ascending, and no tones (Experiment 2) groups revealed no significant differences in explicit knowledge, except for the comparison of group Ascending (Experiment 2) and group no tones (Experiment 1): $t(35) = -2.10$, $p < .05$. Participants in group no tones expressed significantly less explicit knowledge than participants in group ascending.

Discussion

As in Experiment 1, there is clear evidence for sequence learning in all four groups. RTs decreased over the training blocks and increased when sequence structure was changed in Block 9. The interaction of condition and practice in the training blocks, however, failed to reach significance. This may have to do with the overall difficulty of the task: As indicated by the substantially higher RT level and the steeper decline of RTs over Blocks 3 to 8, responding to letters with keypresses is obviously more difficult than responding to spatially compatibly presented asterisks. The group-specific differences in sequence learning might thus have been overshadowed by other, task-specific learning processes common to all groups, like acquiring a stable representation of the stimulus–response mapping. This kind of influence should, however, become less and less important during the course of practice, and it should not interfere with the effect of the change of sequence structure in Block 9. This is in line with the data: Although the interaction of sequence structure and condition is only marginally significant, the RT increase in Block 9 is significantly larger in group ascending than in all other groups, indicating once again the beneficial influence of tone effects mapped onto the response keys in ascending order from left to right. The two other tone groups show no benefit. Rather, they appear to show a numerical disadvantage with regard to the learning measure when compared to the no tones control group. Compatibility of responses and their effects seems to be a prerequisite for the effect-based learning process sketched above to work.

Stimulus–effect compatibility, on the other hand, does not seem to have had any influence. The interexperiment comparison of the groups with an ascending mapping and the no tones groups revealed no interaction of sequence structure, stimulus material and response effects. Obviously, the observed impact of the tone effects is due to response–effect compatibility relations and not caused by stimulus–effect compatibility.

As in Experiment 1, the group with an ascending key–tone mapping also reported the largest amount of explicit sequence knowledge, as indicated by the spontaneous reports of a repeating pattern and of an eventual change in this pattern, and by the amount of correctly reproduced sequence fragments. Once again, there was no statistically significant difference in explicit knowledge between the ascending and the no tones group. Both the descending and the mixed group, however, show reduced explicit knowledge when compared to group ascending.

GENERAL DISCUSSION

The study yielded four main results:

1. The tone effects have a clear effect on learning: In the groups with an ascending key-tone mapping, substantially more learning than that in the control conditions was observed. Thus, the basic finding of Hoffmann et al. (2001) was replicated: Task-irrelevant tone effects can become incorporated into the control of behaviour in a serial learning situation. In the present experiments, this beneficial influence of irrelevant effects is evident even in a statistically and relationally less predictable environment, namely with second-order conditional sequences. This means that the chaining mechanism assumed to be responsible for creating "anticipatable" effect sequences must be able to link at least three consecutive response effects.
2. The impact of tone effects is independent of the stimuli employed. Although the overall learning rate as well as the overall RT level is higher in Experiment 2, the three-way interaction of type of stimuli, response–effects, and sequence structure is not significant. Although the benefits from contingent tone effects are numerically larger for the letter groups, the effects of stimulus–response mapping and response–effect mapping seem to be additive.

   This result is instructive with regard to the question of whether stimulus–effect compatibility played a role in the experiment: If this was the case, an interaction between stimuli and response–effect mapping would have been expected, with greater benefits from ascending key–tone mapping for Experiment 1—since asterisks ordered from left to right have the same kind of dimensional overlap (Kornblum, 1992) with ascending tones as response locations ordered from left to right. As this is not the case, it seems safe to assume that response–effect compatibility—and not stimulus–effect compatibility—is indeed the crucial factor.

3. The impact of contingent tone effects on learning is modified by response–effect mapping. Tones mapped to keys in ascending order from left to right substantially improve sequence learning in comparison to a control condition without tone effects as well as in comparison to conditions employing a descending or a mixed key–tone mapping. One anonymous reviewer of an earlier version of this paper pointed out that the ascending mapping in Experiment 2 is analogous to that used on western keyboard instruments and that this might have influenced the results. We completely agree with this. We do not believe that there is an innate preference for producing low tones with the left hand and higher tones with the right hand. The compatibility effects observed between horizontally aligned response locations and tones ordered by pitch presumably are an outcome of culturally influenced learning processes, just like compatibility relations that exist between, say, numerically ordered digits and response locations. We also agree with another anonymous reviewer who pointed out that additional practice might affect the results with the two incompatible mappings (cf., Barber & O'Leary, 1997).
4. Expressed explicit knowledge tends to be higher with more pronounced sequence learning, as indicated by the significant correlations between RT measure and explicit knowledge scores. This means that the learning we observed was probably not entirely "implicit", not surprisingly as we did not employ a secondary task normally used to distract participants' attention from the sequential nature of the stimulus material. Interestingly, although many subjects spontaneously reported that they had noticed repetitions in the sequence, the reported explicit knowledge is rather fragmentary: The overall scores indicate that even in the groups with very pronounced learning subjects mostly failed to report more than half of the training sequence. This might have to do with the rather conservative nature of our measure of explicit knowledge.

The "dissociation" of knowledge about the fact that there was a repeating pattern to be learned and the failure to reproduce much of this pattern when asked to do so may seem paradoxical. But in our view it only illustrates, in combination with the substantial impact of the tone effects on RTs, that what is primarily learned in a serial reaction time task, and what affects performance, is (ideo)motor knowledge. Participants mainly acquire associations between sensory effect representations of their actions. The acquisition of these associations can be helped by adequate additional sensory effects. Adequate means that these additional effects allow the formation of a consistent sensory image of the respective action. The fact that tone effects lend themselves to serial chaining—since we are used to perceiving tones not by themselves but as part of melodies—might be another factor that contributes to their beneficial impact.

The formation of consistent sensory effect images is impaired when action effects are not contingent on the actions, or when action effects are incompatible with the actions that produce them. This has interesting consequences for the two different learning measures: When compared to the no tones control groups, the groups with noncontingent or incompatible tone effects reach similar levels of RT-measured sequence knowledge, but mostly achieve poorer explicit knowledge scores. The groups with contingent and compatible tone effects, when compared to the no tones groups, on the other hand, reach comparable—if numerically slightly higher—levels of explicit knowledge and higher levels of RT-measured learning. Note that this result also precludes the interpretation that the beneficial influence of the tone effects in the contingent tones and ascending groups is purely due to an increase in explicit knowledge in these groups. In short: Adequate tone effects seem to mainly improve motor learning, while inadequate tone effects leave motor learning largely unaffected but impair the acquisition or expression of explicit sequence knowledge. What exactly causes this pattern of results remains to be clarified. One interpretation would be that the ongoing attempt to integrate actions and effects into consistent images takes up resources that could otherwise be devoted to monitoring one's own motor behaviour and thus gaining and storing explicit sequence knowledge.

A question that cannot be resolved based on the current data alone is whether the noncontingent and the incompatible response effects are not actually associated with the responses that produce them, or whether they are associated with the responses but cannot be used to improve sequence learning. In the latter case, from an ideomotor point of view, an impairment in performance would be predicted, because incompatible effects would, when anticipated, prime false responses, just like an incompatible stimulus would activate a false response (see Kunde, 2001a). Particularly in Experiment 2, however, there is no systematic decrement in performance in the groups with incompatible response effects when compared to the no tones controls. Thus, based on the current data, the most parsimonious explanation for the absence of an impact of the noncontingent and incompatible tone effects on the RT data is that they are not integrated into the response images.

All in all, the results correspond well with the ideomotor sequence learning account presented in the Introduction section of this article. Participants form sequence representations that are based on the series of response effects that they produce and experience. The anticipation of forthcoming response effects, made possible by structured response–effect sequences, leads to more efficient sequence learning. The mechanism that chains response effects into sequences is obviously capable of exploiting at least second-order redundancy. For the mechanism to work, response effects must fulfil at least two conditions: They must be contingent on the responses and compatible with the responses.

We believe that our results have interesting implications when reviewed together with recent work by Schmidtke and Heuer (1997) and Rah and Reber (2000). These papers criticize the standard tone counting task used to distract participants in many serial learning experiments. Schmidtke and Heuer report experiments in which they combined a tone sequence with a sequence of visual response stimuli. For some participants, the two sequences, were correlated, leading to a constant audiovisual sequence, which was cyclically presented, as was the case in our experiments. For another group of participants, the two sequences were uncorrelated. The results clearly indicated better serial learning with correlated than with uncorrelated sequences (Schmidtke & Heuer, 1997, Exp. 1). However, the correlated tone sequence only improved serial learning if participants had to respond to the tones (pressing a foot pedal to tones of either high or low pitch) but not if the tones were merely presented without requiring any response (Exp. 3).

Rah and Reber (2000) also had participants respond to stimuli while counting tones that were presented in each RSI. They showed that contingent relations between presented tones and subsequent stimuli were learned, indicated by the fact that performance was disrupted when these relations were changed. They conclude that "the 'secondary' tone-counting task may be profitably viewed, not as some 'other' invasive element that compromises learning of a 'primary' task, but as an integral component of a complex stimulus environment" (Rah & Reber, 2000, p. 312).

We would like to extend this conclusion by assuming that the tones in these tasks are not only an integral part of a complex stimulus environment, but capture the fact that the environments we deal with are usually interactive: When we do something, something happens. If there is sufficient contingency between actions and subsequent events, these events will not be perceived as exogenous stimuli but as self-produced action effects. Under these conditions, even completely task-irrelevant stimuli—as opposed to the task-relevant tones in the studies by Schmidtke and Heuer (1997) and Rah and Reber (2000)—will influence behavioural learning. We believe that all sorts of structures within an environment can be learned, but also that there is a primacy of learning what the outcomes of our own actions will be, because this is the sort of knowledge necessary for voluntary behaviour.

An interesting question to be addressed by future research is how responses and response effects are represented. If one assumes that what is learned in a serial reaction time task is an increasingly refined representation of sequences of forthcoming response effects, be they proprioceptive or external (like the tones we used), it remains to be clarified when these anticipations are activated and how the links between anticipated effects in different sensory domains are established. Motor theorists (e.g., Henry & Rogers, 1960; Sternberg, Monsell, Knoll, & Wright, 1978; Verwey, 1999) have long been advocating a "motor buffer"—that is, some kind of storage unit that can hold motor representations ("motor programmes" or "motor chunks") in an activated state before response execution. Analogously, according to ideomotor reasoning and our current results, one could assume an "effect buffer" that allows the representation of forthcoming response effects. A way to systematically investigate these assumptions would be to introduce additional, external effects to a sequence preparation paradigm like that used by Sternberg et al. (1978) or Rosenbaum and his colleagues (Rosenbaum, Inhoff, & Gordon 1984; Rosenbaum, Kenny, & Derr, 1983). Such experiments are in preparation.

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APPENDIX

The two second-order conditional sequences used in the experiment.
A, B, C, and D denote response locations from left to right for all groups. The two sequences do not share any second-order conditional information—that is, each stimulus pair has a different successor in Sequence 1 and Sequence 2.
Sequence 1: ACDBABCBDCAD
Sequence 2: BADCDABDBCAC