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The ideomotor principle and motor sequence acquisition: Tone effects facilitate movement chunking

Accepted: 11 August 2003 / Published online: 27 November 2003
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Abstract Participants practiced short sequences of key presses; sequence length and response-effect mapping were the independent variables. Contingent, distinct key-effect relations were contrasted with either contingent but uniform or no response effects. In Experiment 1, tone effects were relevant as response-specific stimuli and also as effects. The sequence length effect for the tones group was reduced. In Experiment 2, participants were informed about the sequences to be executed and then given varying amounts of preparation time before the start signal. A reduction in the sequence length effect was observed, and initiation times and mean interresponse time (IRTs) were generally reduced in the tone group. Preparation time could compensate for some but not all of the latency reducing influence of the tone effects. The results are discussed with reference to ideomotor approaches to motor control, i.e., the notion that actions are represented in sensory format.

Introduction

The fact that the ideomotor principle (IMP), i.e., the notion that actions are cognitively represented by and accessed through their sensorial effects, has been experiencing a revival over the last few years probably need not be brought to the attention of the readers of this special issue. Sensory information about action effects has been shown to be of importance for the selection of actions (Elsner & Hommel, 2001), and for the initiation and execution of movements (Kunde, 2001, 2003; for further references see Kiesel & Hoffmann, this issue; for a historical overview see Stock, this issue).

If it is presumed that actions are indeed coded as sensory representations, one important question is how the sensory aspects of actions contribute to the acquisition and execution of sequences of actions. For many years, motor researchers (e.g., Henry & Rogers, 1960; Sternberg, Monsell, Knoll, & Wright, 1978; Rosenbaum, Inhoff, & Gordon, 1984) have assumed that motor sequences are represented in the form of commands that have to be “unpacked” and translated into concrete instructions for muscles, tendons, and joints. According to this concept, sensory action effects play a role, if at all, only for the selection of movements.

Recently, some first steps have been taken to integrate IMP reasoning into experimental paradigms pertaining to motor learning, most notably the serial reaction time task (SRT). In such tasks, participants respond to one stimulus in each trial, often with a key press that is spatially compatibly mapped to the stimulus location. Each response triggers the presentation of the next stimulus and so forth. When the stimulus sequence is structured, reaction times (RTs) decrease with practice and increase when sequence structure is subsequently removed, which is interpreted as an indication of sequence learning.

Ziessler (1998) was the first to point out that the stimuli in an SRT—which are always triggered by the participant’s previous response—may also be interpreted as action effects caused by this previous response. He showed that participants in a combined visual search and SRT experiment learned relations between a current key press and a subsequent stimulus location. This was a first indication that action-effect learning can indeed contribute to learning in SRT tasks. The sequences used by Ziessler (1998) were, however, randomly generated, i.e., there was no motor sequence learning in the original sense in his experiments.

Ziessler and Nattkemper (2001) subsequently succeeded in demonstrating the importance of response-effect relations in a traditional SRT. By mapping several stimuli onto the same response, they constructed sequences in which the complexity of stimulus-stimulus

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(S-S) and response-stimulus (R-S) relations could be varied independently of each other, while response-response (R-R) transitions were controlled. The results show that the learning effects depended on the complexity of the R-S relations but not on the complexity of S-S relations. In a second experiment, transfer of sequence knowledge from one sequence to another occurred only when both sequences shared identical R-S relations.

While the response effects in the Ziessler and Nattkemper study were task-relevant in that they also served as stimuli for upcoming responses, completely task-irrelevant response effects and their importance for sequence learning were investigated by Hazeltine (2002). He conducted a series of experiments in which motor tasks were changed while associated sequences of tone effects remained unchanged. Participants at first responded to visual stimuli with key presses of varying intensity on a pressure-sensitive device. The key presses produced tones of varying pitch. In a subsequent transfer phase, participants had to respond to the same stimulus sequence by pressing different keys with different fingers on a PC keyboard. The resulting effect sequence remained unchanged. In comparison to a control condition without tone effects, transfer was better in the group with the same effect sequence during training and transfer.

In a similar vein, Hoffmann, Sebald, and Stöcker (2001) combined a traditional SRT task with irrelevant tone effects. They instructed participants to respond to asterisks appearing in one of four locations on a screen. The four assigned response keys produced the four tones of a C-major chord, mapped onto the keys from left to right in the experimental group, and mapped to the stimulus locations from left to right in one control group. In this latter group, each key press produced different tones, depending on the current position within the repeating stimulus sequence. All participants performed the same response sequence, saw the same stimulus sequence and heard the same effect sequence—but in the control condition this effect sequence was shifted by one trial in relation to the response sequence. No tones were presented in an additional control group. The key-contingent tone effects substantially improved sequence learning, while the non-key-contingent tones had no discernible effect in comparison to the no-tones control condition. A second experiment showed that switching from a contingent to a non-contingent key-tone mapping during learning produced costs, while switching from one non-contingent mapping to another non-contingent mapping had no influence on RTs. The authors assume that the contingent action-effect relations are part of the acquired sequence-specific knowledge responsible for the increasingly fast responses. When those relations are destroyed, the benefit of contingent vs. non-contingent mapping vanishes.

The result that completely task irrelevant tone effects seem to become an integral part of the representation guiding motor behavior was replicated by Stöcker,

Hoffmann, and Sebald, (2003) with more complex sequence material. This study shows that at least three consecutive response effects can be linked by a hypothesized learning mechanism chaining sensory response images to enable anticipations of responses to be produced. A key-tone mapping variation also revealed that the tone effects must be mapped onto the keys in a compatible manner, i.e., in ascending order from left to right, in order to exert a beneficial influence on motor learning.

Greenwald (1970) suggested a learning mechanism based on the premises of ideomotor reasoning that predicts such an influence of response effects on motor learning. According to his idea, responses are first associated with their contingent effects, i.e., 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. Secondly, when stimulus–response–effect triplets are repeatedly experienced in the same order, associations are formed between the consecutive elements of the effect sequence so that producing one effect triggers the anticipation of the next effect to be produced, 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.

To accommodate the results of Hoffmann et al. (2001) and Stöcker et al. (2003), this hypothetical mechanism needs one additional assumption: Since motor learning was *improved* by the tone effects, at least when they were mapped onto the keys in a certain way, the tone effects must in some way facilitate the chaining of the effect images guiding performance. Associations between subsequent responses must develop more quickly with than without tone effects. If this is true, appropriate tone effects in general should facilitate the chunking of the elements of a motor sequence into larger units, ultimately, with sufficient training, producing an integrated representation of the entire sequence.

The assumption that motor learning involves chunking of movement elements is far from new. The term usually used to refer to such internal sequence representations is “motor program” (cf. Keele 1968). Originally intended to denote a representation necessary to execute a movement independently of feedback, the term has over the years acquired a more general meaning, referring to well-practiced and possibly transferable movement representations. One of the central arguments for the existence of such programs that are supposed to be prepared in advance of the beginning of a movement sequence is the “sequence length effect.” The term refers to the fact that even fairly well-practiced longer movement sequences take more time to be initiated in comparison to shorter sequences. This increased latency has been interpreted as a reflection of time-consuming programming processes that depend on the length of the programmed movement.

Recently, a number of researchers including Klapp (1995, 1996) and Verwey (1999) have stressed the importance of chunking processes for the programming and execution of trained movements. Both present data that show that the sequence length effect can under certain conditions be reduced when participants have a chance to practice the respective sequences extensively. Both argue that this has to do with the merging of single movement elements into larger units that can then be more easily prepared, which is thought to be the reason for the reduction of the sequence length effect.

It may be speculated that tone effects like those employed by Hoffmann et al. (2001) and Stöcker et al. (2003) facilitate the chunking of sequence elements into larger units. If this was the case, influences on initiation times and the development of the sequence length effect over practice would be expected as chunking should proceed more quickly than without additional effects. The present experiments were designed to examine the role of additional tone effects on the acquisition and execution of short movement sequences. If movements are indeed represented in terms of their sensory effects, and these sensory representations are the basis for fast and efficient movement, adequate additional sensory effects should improve the acquisition of motor sequences. A pilot study we conducted suggested that the chunking of six element key press sequences is indeed facilitated with distinct tone effects, indicated by a reduction in initiation times for the tone sequences, even to the point of eliminating the sequence length effect.

In order to systematically investigate this preliminary result, participants practiced short key press sequences, in a paradigm similar to those used by Klapp (1995), Sternberg et al. (1978), Verwey (1999), and others. Groups with additional tone effects were contrasted with groups without additional tone effects. Influences on initiation times, interresponse times, and error rates were investigated.

Experiment 1

Participants practiced key press sequences for a defined period of time, short sequences were contrasted with longer sequences, and initiation and interresponse times were measured as dependent variables. Every participant practiced two different key press sequences, one of length 3 and one of length 6. The mapping of effects to keys was varied between-participants. The experiment was split up into a training phase and a test phase. No key-specific stimuli were presented during the test phase. The two sequences to be practiced were the same for all participants.

The reason for the comparatively short practice phase—it consisted of two blocks with 60 sequence presentations each—was that we wanted to investigate the influence of the tone effects on sequence production in an environment where finger specific stimuli were no longer available. In the test phase, participants had to

rely exclusively on their internal representations for executing the sequences. The practice phase was designed to enable participants to build up representations of the two sequences, but not to enable them to actively train fast movement execution. This was prevented by an 800-ms response-to-stimulus interval (RSI) in the practice phase. Participants had to wait for the next stimulus to appear before they could execute the next response in a sequence, making very fast sequence execution impossible. Movement chunking was thus investigated only in the test phase data.

Two groups that produced distinct tone effects were contrasted with two groups that produced uniform effects or no effects respectively. In three groups, i.e., all groups apart from one of the two “tone effects” groups, the letters A to F were used as key specific stimuli in the training phase. One “tone effects” group did not see any visual stimuli apart from sequence-specific cues. They practiced the sequences by reproducing, tone by tone, tone sequences played to them by the computer, i.e., they intentionally produced effect sequences. In this group, the tones were used as key-specific stimuli during the training phase and as contingent action effects throughout the experiment.

The aim of Experiment 1 was to test the hypothesis that appropriate tone effects are associated with the responses producing them and subsequently become incorporated in internal sequence representations that are consequently different from the representations normally developed in such a task. Tone effects have certain features, such as the fact that they automatically capture attention, they have a clear dimensionality, and lend themselves to serial chaining, simply due to the fact that we are used to perceiving natural tones as part of tone sequences, of melodies. Moreover, the auditory ultra short-term memory has a comparatively long retention interval (Darwin, Turvey, & Crowder, 1972), facilitating the serial chunking of auditory events in comparison to, say, visual stimuli. In short, tone effects should firstly be associated with the responses that produce them, and secondly be associated with one another, reflecting the structure of the response sequences. This in turn should enable the quick development of integrated sensory-motor sequence representations in line with considerations by Greenwald (1970), Hoffmann et al. (2001), and others. We thus expected a facilitation effect for the chunking of sequence elements into larger units for the groups with distinct tone effects. Specifically, a faster reduction of initiation times and interresponse times was expected, interresponse times being considered a global measure for the quality of movement chunking that has occurred up to a certain point. In addition, the sequence length effect, i.e., the initiation time difference between shorter and longer sequences, was expected to be reduced, as this is the case when chunking has taken place after extensive training (see Klapp, 1995; Verwey, 1999). If chunking is indeed facilitated, this should also be obviated by more homogenous interresponse time profiles in the longer,

six-element sequences for the groups with distinct tone effects. As the manipulation of the response effects was the only factor expected to play a role in Experiment 1, no differences were expected between the two groups without distinct tone effects and no differences were expected between the two groups with distinct tone effects. If this was confirmed by preliminary analyses, the respective groups were to be combined.

Method

Participants

Fifty-seven undergraduate students of psychology took part in the experiment, fulfilling a course requirement. For reasons explained below, a number of participants had to be replaced. Five participants were replaced in the "tones" group, 5 participants were replaced in the "letter/tones" group, 1 participant was replaced in the "no effects" group, and 6 participants were replaced in the "click" group. In the end each group consisted of 10 participants. In the "tones" group there were 8 female and 2 male participants, and the mean age was 26 years ($SD = 6.4$). In the "letters/tones" group there were 4 male and 6 female participants, and the mean age was 24 ($SD = 3.7$). In the "no effects" group there were 7 female and 3 male participants, and the mean age was 25 ($SD = 3.4$). In the "click" group there were 6 female and 4 male participants, and the mean age was 25 ($SD = 4.5$).

Stimuli and responses

The experiment was conducted on an IBM-compatible PC using MS-DOS. The screen was black and the stimuli were presented in either gray or red. In three groups, one of the letters A, B, C, D, E, and F in a gray 18-point "Times New Roman" font were presented in a central location in the upper half of the screen for each key press. Above this location, one of the letters X and Y was presented as the sequence-specific cue in all groups and in each sequence trial. In the "tones" group, no visual key-specific stimuli were presented. Instead, participants in the training phase heard tones presented via external speakers that they were supposed to reproduce with according key presses. In the "tones" and the "letters/tones" groups, the six response keys (the s, d, f, j, k, and l keys on a German QUERTZ-keyboard) produced one tone of a C-major scale each (c, d, e, f, g, a). The tones were assigned to the keys in ascending order from left to right. In the "click" condition, each of the six keys produced the same tone, of the same timbre as in the conditions with distinct tone effects, but two octaves higher (from here on referred to as "click"). The index, middle, and ring fingers of both hands were resting on the response keys—s, d, and f for the left hand and j, k, and l for the right hand—throughout the experiment. The presentation of tones and clicks was immediate, occurring as soon as a key was pressed.

In the practice phase, the response-to-stimulus interval (RSI) between one key press and the presentation of the next key-specific stimulus (letter or tone) was 800 ms. This was done to prevent the effect tones and the following stimulus tones in the "tones" group from being presented immediately after one another, which would have made them virtually indistinguishable. This manipulation also prevented participants from practicing very fast sequence execution during this phase. The sequence-specific cue was shown throughout each sequence trial. Each participant learned two different sequences during the training phase. The short sequence was j-s-k for all participants, corresponding to I-r-M with the letters I, R and M indicating the index, ring, and middle fingers, and capital letters indicating the right hand. The long sequence was s-j-f-k-d-l or r-I-i-M-m-r respectively.

In the test phase, there were no key-specific stimuli, but the sequence-specific cues were still presented in each trial. The tones

and clicks that served as response effects also continued to be presented.

Procedure

Participants were instructed by onscreen texts at the beginning of all phases of the experiment. For participants in the "tones" group, the first part of the experiment was a short introductory phase during which no data were collected. Participants were allowed to freely press the response keys to give them a chance to get used to the action-effect relations. They could end this phase whenever they wanted. Usually, participants spent about 1–2 min on this.

In the second phase of the experiment, the stimulus-response mapping was to be practiced. To this end, all participants performed a serial reaction time task with randomly ordered stimuli. Participants in the groups with letter stimuli saw a single gray letter on the screen in each trial, to which they were required to react as quickly as possible by pressing the assigned key. Participants in the experimental group heard a tone in each trial that they were asked to reproduce as quickly as possible by pressing the appropriate key. This second phase consisted of two blocks of 60 trials each. The sole aim of this phase was to familiarize participants with the mappings; no data were recorded.

In the practice phase, stimuli were presented following the two sequences described above. Participants were informed that they were required to learn two key press sequences and that one of those would be labeled "X" and the other one "Y". "X" denoted the six-element sequence for all participants in all groups. Participants were instructed to make a point of learning the sequences properly, as they would be asked to reproduce them "by heart" later, and that they should focus more on memorizing and minimizing mistakes than on reacting fast. Each trial looked like this: After the presentation of a fixation cross in the cue position for 1,500 ms, the sequence-specific cue (X or Y) was displayed, which then remained onscreen until the sequence was finished. At the same time, the first tone was presented in the "tones" group and the first key-specific letter was presented in the other groups. When the participant pressed the correct key, the corresponding tone effect was presented in the "tones" group and the "letters/tones" group, a click was presented in the "click" group, and the key-specific letter stimulus vanished in the "click" and "no effects" groups. After an RSI of 800 ms, the next tone or letter was presented. When the sequence was over, a fixation cross was again shown for 1,500 ms on an otherwise empty screen. When a wrong response was given, the German word for "Error!" was flashed at the bottom of the screen in a 14-point Arial font for 50 ms. In the tones groups, a wrong key press still produced the tone contingent on the pressed key.

The practice phase consisted of two blocks of 60 sequence trials each, i.e., each sequence was practiced 30 times per block, with presentation order randomized. At the end of both blocks, the participant's mean error rate was shown on the screen for 5 s.

At the beginning of the test phase, participants were instructed that speed was now just as important as accuracy for good performance. In each trial, the sequence-specific cue was presented, after which participants were supposed to enter the whole sequence as quickly as possible. Key-specific stimuli were not presented in the test phase. In the experimental group, each key press still produced the assigned tone, in the "click" group each key press still produced a click. When a wrong response was registered, the German word for "Error!" was again presented at the bottom of the screen for 50 ms. Between trials, a fixation cross was presented for 1,500 ms. The test phase consisted of six blocks of 60 trials each. The order of trials was again randomized within a block. At the end of each block, the error rate and the mean RT for the last block were shown on the screen for 5 s. After that, participants could start the next block themselves by pressing a key. Initiation times were measured from the presentation of the cue to the registration of the first key press. Interresponse times (IRTs) were measured from the onset of one key press to the onset of the next. Initiation times and IRTs of trials in which one or more errors had been made were excluded from further analysis.

Results

Practice phase

Since there was no speed instruction in the practice phase, RTs cannot be evaluated. We thus report error rates as a measure of sequence acquisition. The error rates for the first block of the practice phase were 14.7% for the “tones” group, 2.2% for the “letter/tones” group, 2.9% for the “no effects” group, and 2.2% for the “click” group. The error rates for the second practice block were 1.7% for the “tones” group, 0.7% for the “letters/tones” group, 1.6% for the “no effects” group, and 2.0% for the “click” group.

Arcsine transformed error rates were entered into a repeated measures ANOVA with the factors condition and block. Both main effects were significant ($F(1, 36) = 20.153, p < .001$ for factor block and $F(3, 36) = 10.520, p < .001$ for factor condition), as was the interaction, $F(3, 36) = 11.364, p < .001$. This is due mainly to the very high error rate in the “tones” condition in practice block 1. Errors decreased with practice, but more strongly so in the “tones” group.

Test phase

Error data Each sequence trial containing one or more errors was excluded from the reaction time analyses. This was done because one initial error in this paradigm often produces multiple subsequent errors within the same sequence trial. Sequences were thus simply counted as faulty or correct. To prevent this procedure from producing trial numbers too small for ANOVA methodology, participants were excluded from the sample if they had produced too many faulty sequences. Data of participants with mean error trial rates of more than 10% were excluded and replaced. Many participants obviously had great difficulties in meeting this error criterion, which is why a comparatively large number of participants had to be replaced (see “Participants” section). A selection criterion like this of course forbids any further evaluation of the error data in the test phase. There were, however, no indications for speed-accuracy tradeoffs.

Preliminary analyses To assess whether the two groups with distinct tone effects on the one hand and the two groups without distinct tone effects on the other hand could be combined, two initial ANOVAs for the initiation times were conducted. They showed no significant differences between the “tones” group and the “letters/tones” group, with all F -values involving the factor condition < 1 . The same was shown for the “no effects” group and the “click” group. To check whether the same chunking processes had occurred in the two groups with distinct tone effects, an ANOVA with only the IRT data of the six element sequences, using the factors block, condition, and sequence position, was conducted (see Fig. 1).

The crucial interaction in this analysis is between condition and sequence position. It is significant, indi-

cating that the descriptively different interresponse time profiles in the groups with tone effects and the other two groups do indeed differ, $F(12, 144) = 2.68, p < .01$. IRTs are more homogenous in the groups with distinct tone effects. This interpretation was confirmed in two additional IRT ANOVAs with the two groups with tone effects and the two groups without distinct tone effects respectively. Again, all results involving the factor condition were far from significant. The groups with tone effects were thus combined to form the “tone effects” group and the “no effects” group and the “click” group were combined to form the “no tones” group.

Initiation times Test phase initiation times were subjected to a repeated measures ANOVA with the factors practice (6 blocks), sequence length (3 elements vs. 6 elements), and condition (tone effects, no tones; see Fig. 2a).

The factors critical for the hypotheses formulated earlier had a significant influence. Sequences in the “tone effects” conditions were initiated faster than sequences in the “no tones” conditions, $F(1, 38) = 8.69, p < .01$. The sequence length effect is smaller in the “tone effects” conditions, $F(1, 38) = 4.23, p < .05$.

In addition, initiation times decreased with practice, $F(5, 190) = 19.01, p < .001$, more so in the “no tones” condition than in the “tone effects” condition, $F(5, 190) = 7.11, p < .001$. The overall sequence length effect is also significant, $F(1, 38) = 18.27, p < .001$. No other influences approached significance.

Mean IRTs Mean IRTs were computed for each factor combination. A repeated measures ANOVA with the factors practice (6 blocks), sequence length (3 elements vs. 6 elements) and condition (tone effects, no tones; see Fig. 2b) again yielded a significant speed advantage for the “tone effects” conditions, $F(1, 38) = 6.07, p < .05$. The sequence length effect in the IRTs was reduced for the “tone effects” conditions, $F(1, 38) = 8.80, p < .01$.

IRTs decreased over practice, $F(5, 190) = 84.95, p < .001$, more strongly so in the “no tones” condition than in the “tone effects” condition, $F(5, 190) = 4.81, p < .001$. There was a significant overall sequence length effect, $F(1, 38) = 49.48, p < .001$, and this sequence length effect was slightly reduced during practice, $F(5, 190) = 3.00, p < .05$. The three-way interaction did not approach significance.

Discussion

The results of Experiment 1 are clear-cut and in line with the hypotheses: Distinct tone effects associated with the key presses led to faster chunking of the six-element sequences into one integrated representation and thus ultimately to more homogenous IRT profiles. Chunking also influences initiation times and mean IRTs. Sequences are initiated and executed faster. The difference between the initiation times and execution speed of the

Fig. 1a–d Mean interresponse times for the long sequences of the four groups, plotted over test phase blocks and divided by sequence position (T2–T6)

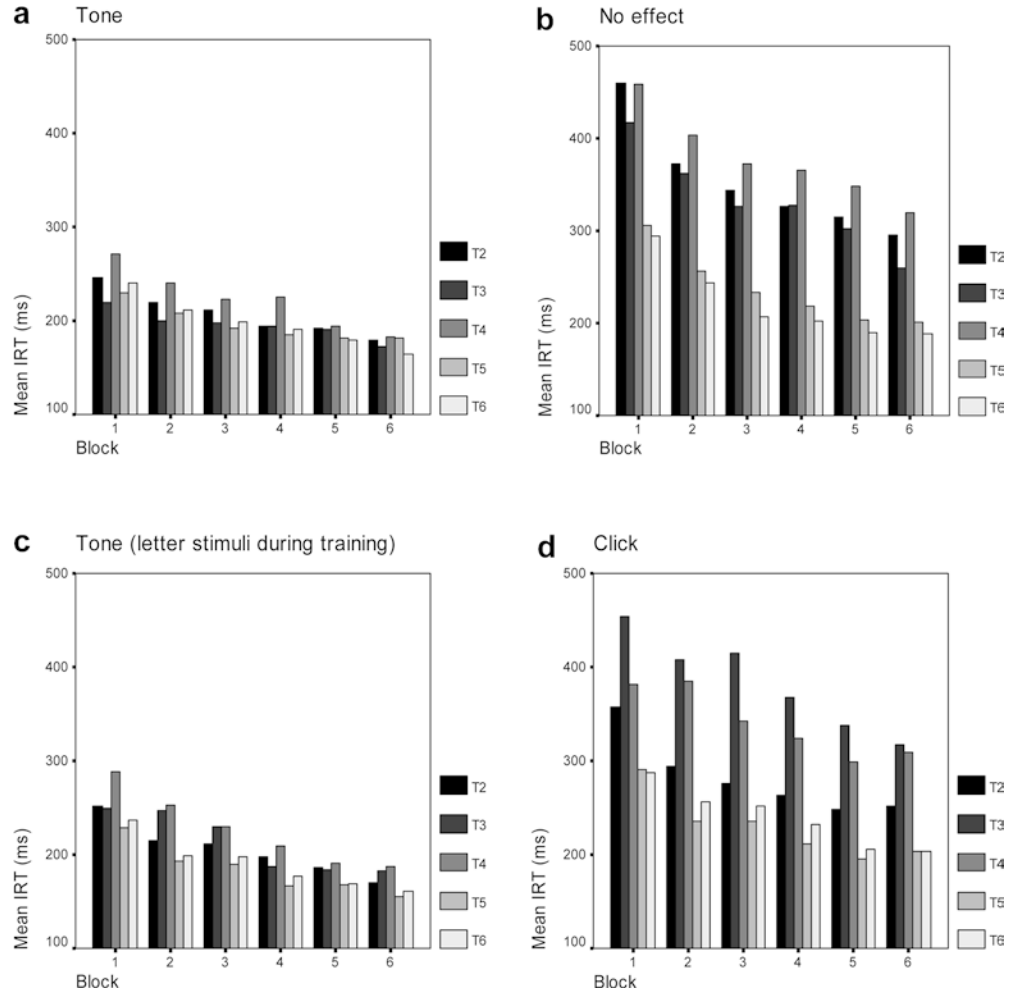
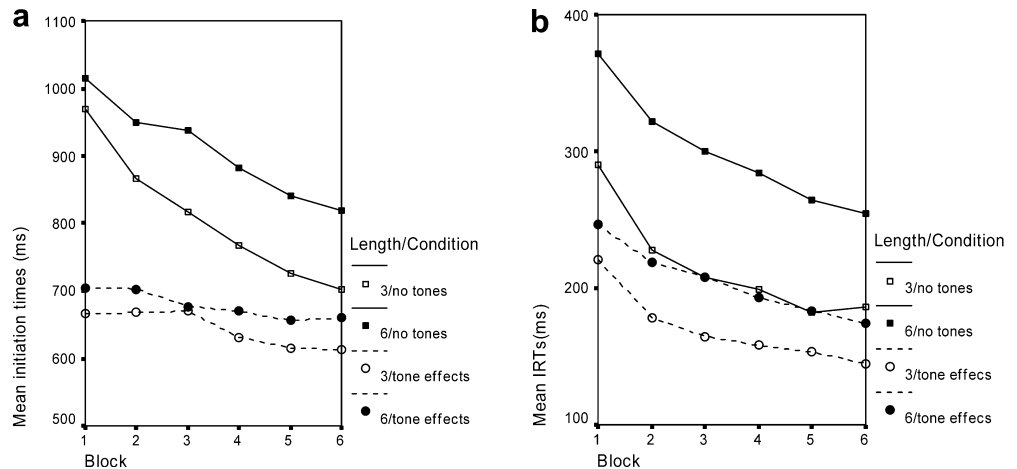


Fig. 2a, b Mean initiation times and mean interresponse times, plotted over test phase blocks and divided by action effects and sequence length



six-element and three-element sequences is reduced, i.e., the tone effects help to build up a representation of the sequence for which the sequence length is less important.

The results are well in line with the notion that tone effects have a beneficial influence on the linking of single key presses to chunks. Effectively chunked key presses should, according to the reasoning of Klapp (1995),

Verwey (1999), and others, be initiated faster. In addition, it seems plausible that during the execution of one chunk, subsequent key presses can be prepared more easily, which should affect the sequence length effect in the IRTs. Both results occur in the “tone effects” group.

The tone effects lead to the development of a sequence representation of a different quality, namely a

representation that integrates the entire sequence into one single chunk. This does not mean, however, that an entirely integrated, one-chunk sequence representation cannot be achieved without tone effects. As previous results by Klapp (e.g., 1995), Verwey (1999), and others have shown, extensive practice can eliminate the sequence length effect in similar tasks, indicating the existence of fully chunked representations for longer sequences in those experiments. Nevertheless, the tones seem to drastically reduce the amount of training necessary for the development of such a representation.

Taken together, the results suggest that the tone effects are indeed integrated into an internal sequence representation on which performance is based. In line with general IMP reasoning, and specifically with the learning mechanism sketched by Greenwald (1970), response effects seem to become associated with the responses that produce them. Note that this seems to be independent of the task relevance of the tone effects. There were no distinguishable differences in the test phase between the “letters/tones” group and the “tones” group, indicating that the tone effects exert their influence regardless of whether they are also task-relevant stimuli (“tones” group) or only task-irrelevant effects (“letters/tones” group).

On the other hand, the two tasks do seem to differ with regard to the initial difficulty of the training phase. In the first training block, participants obviously found it somewhat difficult to respond to the stimulus tones with appropriate key presses, indicated by a high error rate. It is plausible that this is due to a generally lower distinguishability of tones of varying pitch in comparison to letter stimuli, especially for participants who have no musical training. This initial difficulty is, however, quickly overcome, presumably as a sequence representation is developed, progressively making participants independent of the actual stimuli. The error rate of the “tones” group dropped dramatically in training block 2, and after the training phase, the “tones” participants performed just like the “letters/tones” participants.

The results provide an explanation for the learning-improving influence of tone effects in serial learning tasks found by Hoffmann et al. (2001) and Stöcker et al. (2003). The mechanism at work in the present experiment can account for the improved sequence learning in those studies. Note that in both studies it was found that only key-contingent tone effects had an influence on learning. Stimulus-contingent tones that emphasized the sequence structure in the same way did not have any influence. This suggests that it is indeed crucial that the tones serve as response effects, and that they can only serve to speed up the formation of a response-based sequence representation. Simply providing an auditory addition to the stimulus sequence is not sufficient.

Experiment 2

Although the results of Experiment 1 are clear enough with regard to the question whether tones become

associated with the key presses and subsequently influence movement chunking, they say little about the influence of the tones on various stages of the process ultimately leading to sequence execution. If a simple stage model of sequence production is assumed, at least sequence selection, sequence programming, and sequence execution can be distinguished. Selection can take place before the actual starting signal has been perceived, given that advance information about the sequence to be executed is available. There is some debate about the locus of the programming stage. Sternberg and his co-workers (1978) assumed that response sequence programming is a process that occurs after the presentation of the starting signal. Rosenbaum et al. (1984) and Klapp (1995, 1996), on the other hand, suggest that some aspects of the programming process can, under certain circumstances, occur before a starting signal is presented, while others take place after the presentation of the starting signal. The execution stage encompasses all processes that take place after the first response has been initiated. In Experiment 1, selection, programming, and execution processes all had to occur after cue presentation, i.e., there was no way of distinguishing which stages were affected.

There were two aims of Experiment 2. Firstly, the result that the tone effects influence chunking processes and thus initiation times and IRTs was to be replicated. Secondly, we wanted to address the question whether the tone effects mainly reduce initiation times by facilitating sequence selection or whether they also play a role in the programming of sequences.

To this end, participants were given varying amounts of time to prepare sequences before a starting signal instructed them to begin sequence execution. The rationale behind this manipulation is that if the tone effects do not influence sequence selection, a variation of the available preparation time should have no differential influence on groups with tone effects and groups without tone effects. An interaction between preparation time and condition, specifically an interaction demonstrating that the initiation time difference between “tones” groups and “no tones” groups reduces with increasing preparation time would indicate that some of the benefit of the tone effects can be compensated for with additional preparation time. This would suggest that the tone effects do contribute to selection and/or programming processes. If the initiation time advantage of the tone group participants is *eliminated* by a sufficiently long preparation interval, it can be ruled out that the tone effects play a role in the programming of the sequences that occurs after the starting signal has been presented, i.e., this result would indicate that the initiation time influence of the tone effects is due purely to a selection advantage.

The basic setup of Experiment 2 was identical to that of Experiment 1, with the difference that participants now had a varying amount of preparation time before sequence initiation in the test phase. A cue informed them about the sequence they would be asked to per-

form, and after a certain time interval a starting signal told them to begin executing the sequence. The stimulus onset asynchrony (SOA) between cue and starting signal was varied in the steps of 0, 100, 300, 500, 700, and 900 ms. Since Experiment 1 showed no differences between a group with letter stimuli and tone effects (“letters/tones”) and a group with tone stimuli and tone effects, only one group with letter stimuli and no effects and one group with tone stimuli and tone effects were compared in Experiment 2.

Method

Participants

Thirty-two participants took part in the experiment. As in Experiment 1, a number of participants had to be replaced. Two participants were replaced in the experimental group because they did not meet the error criterion. The experimental group consisted of 16 participants, and the control group of 14. There were 14 female and 2 male participants in the “tones” group, and their mean age was 22 ($SD = 2.1$). In the “no effects” group there were 10 female and 4 male participants, and their mean age was 24 ($SD = 3.5$). All participants were students of psychology fulfilling a course requirement.

Stimuli and responses

Display and response keys were the same as in Experiment 1, with one exception. In the test phase, the sequence cue was presented in gray instead of red in those trials with an SOA different from 0 ms. After the SOA had passed, the color changed to red, indicating to the participant that he or she should now start entering the sequence. There were SOAs of 0, 100, 300, 500, 700, and 900 ms.

Procedure

The introductory and training phases were the same as in Experiment 1. In the test phase, the SOA was varied in random order. To obtain enough data for ANOVA measures with the added new factor, the number of trials was doubled in comparison to Experiment 1. Participants now worked through six blocks with 120 trials, i.e., 60 trials per sequence each.

Initiation times were measured from the moment the cue turned red to the registration of the first key press. IRTs were measured

from the onset of one key press to the onset of the next. Initiation and interresponse times of sequences during which one error or more had occurred were excluded from subsequent analyses.

Results

Training phase

Since there was no speed instruction in the training phase, RTs will again not be reported here. The error rates for training block 1 were 2.4% in the “no effects” group and 10.5% in the “tones” group. The error rates for training block 2 were 1.8% in the “no effects” group, and 2.0% in the “tones” group.

Arcsine transformed error rates were again subjected to a repeated measures ANOVA with the factors block and condition. Training block has a significant influence, $F(1, 29) = 17.75, p < .001$, as well as condition, $F(1, 29) = 9.22, p < .01$. Error rates decreased across the training phase. More errors were made in the “tones” group than in the “no effects” group. The interaction is also significant, $F(1, 29) = 13.22, p < .001$. The error rate decreased more in the “tones” group.

Test phase

Error data As in Experiment 1, each sequence containing one or more errors was excluded from further analysis. Since the error criterion of 10% had proved slightly too difficult for many participants, the criterion was relaxed to 15% in Experiment 2. The trial number ensured that a sufficient amount of data would be available for ANOVA measures. Because of this error-based selection, error rates are not reported. There were, however, no indications for speed-accuracy-tradeoffs.

Interresponse time profiles Figure 3a and b shows the IRT profiles for the six-element sequences. The analysis of the IRT profiles once again yields evidence of a facilitation of chunking processes in the “tones” group. In this group, IRTs are very homogenous from the

Fig. 3a, b Mean interresponse times for the long sequences of the two groups, plotted over test phase blocks and divided by sequence position (T2–T6)

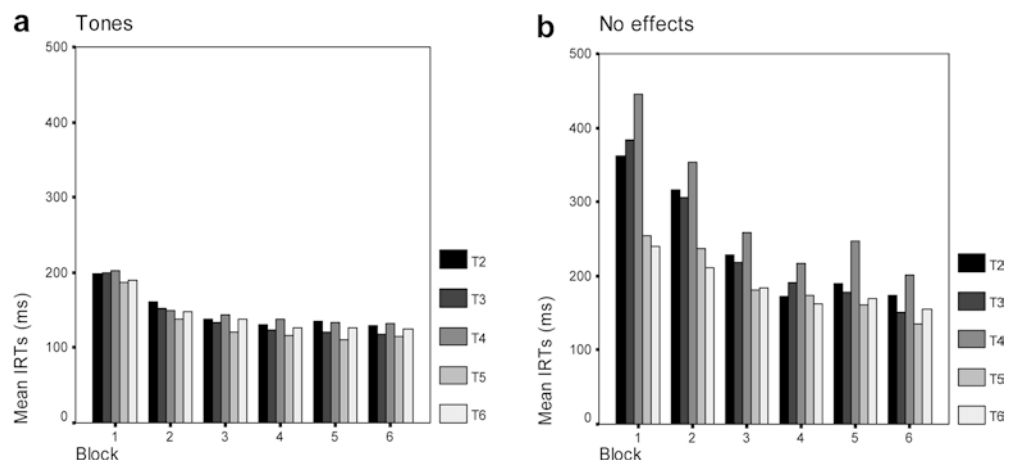
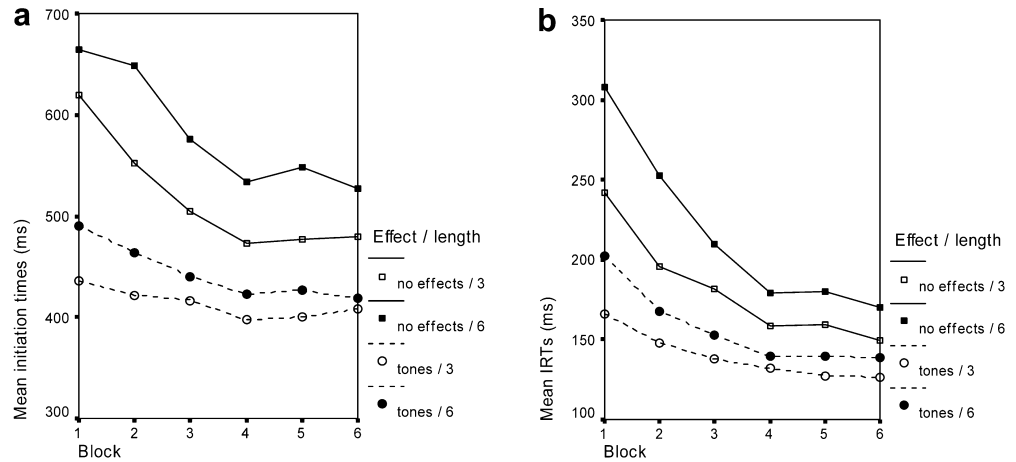


Fig. 4a, b Mean initiation times and mean interresponse times, plotted over test phase blocks and divided by action effects and sequence length



beginning of the test phase onward. In the “no effects” group there is a substantial IRT increase at position T4, which favors the interpretation that a second chunk is initiated there.

An ANOVA with the IRT data of the long sequences again yielded a significant F -value for the critical interaction of condition and sequence position, $F(4, 112) = 6.85, p < .001$. The IRT differences are larger in the “no effects” group than in the “tones” group.

Initiation times The test phase initiation times were subjected to a repeated measures ANOVA with the factors practice (6 blocks), SOA (6 levels), sequence length (3 vs. 6 elements) and condition (tones vs. no effects, see Fig. 4a). Once again, the “tones” group initiated sequences faster than the control group, $F(1, 28) = 7.55, p < .01$. The interaction of sequence length and condition is not significant. The interaction of practice and sequence length also failed to reach significance, $F(5, 140) = 2.04, p = .076$. Since a reduction of the sequence length effect had been expected for the “tones” group, two additional within-group analyses were carried out. They yielded the result that this marginally significant interaction is due to a significant interaction between practice and sequence length in the “tones” group (see Fig. 4a), $F(5, 75) = 4.68, p < .001$. The sequence length effect decreases with practice in this group, which is not the case in the control group, $F < 1$.

SOA and condition do interact, $F(5, 140) = 2.88, p < .05$. The initiation time difference between the “tones” group and the “no effects” group is reduced when preparation time increases (see Fig. 5; a more in depth analysis of the SOA influence follows below).

Other results are in line with the expectations. Initiation times decrease with practice, $F(5, 140) = 30.25, p < .001$. Sequences are initiated faster the more preparation time is available, $F(5, 149) = 333.16, p < .001$. Short sequences are initiated faster than long sequences, $F(1, 28) = 18.70, p < .001$. Practice interacts with condition, $F(5, 149) = 7.91, p < .001$, and initiation times decrease more in the control than in the experimental group, especially in the early practice blocks. The

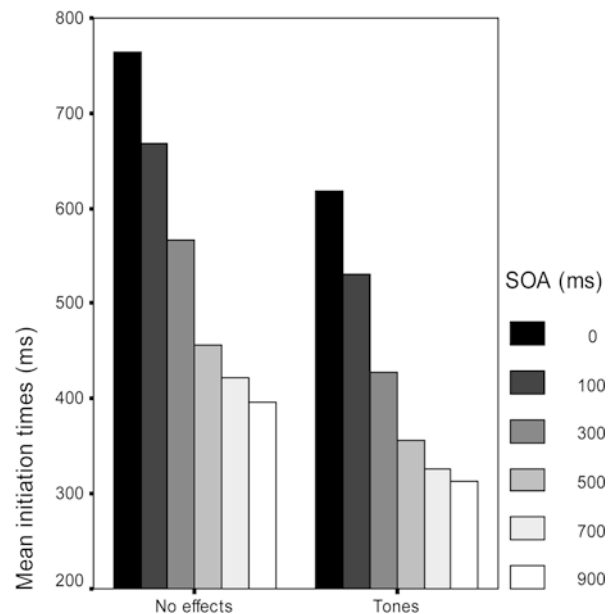


Fig. 5 Mean initiation times for the two groups, divided by levels of preparation interval (SOA)

interaction of practice and SOA is non-significant. No other interaction approached significance.

Mean IRTs Mean IRTs were computed for each subject and factor combination. These were entered into a repeated measures ANOVA with the factors practice (6 blocks), SOA (6 levels), sequence length (3 vs. 6 elements) and condition (tones vs. no effects, see Fig. 4b).

Participants in the “tones” group executed the sequences faster than participants in the “no effects” group, $F(1, 28) = 7.98, p < .01$. IRTs decreased with practice, $F(5, 140) = 37.89, p < .001$. There is a significant interaction of practice and condition, $F(5, 140) = 5.86, p < .001$. IRTs decreased more strongly in the “no effects” group, which may be due to a floor effect in the “tones” group (Fig. 4b).

There is a significant but difficult to interpret influence of SOA, $F(5, 140) = 8.21, p < .001$. Key presses within short sequences were executed faster than key presses inside long sequences, $F(1, 28) = 27.22, p < .001$. There is a significant interaction of SOA and condition, $F(5, 140) = 3.70, p < .01$. An additional analysis revealed that this is due to a significant influence of the factor SOA in the “tones” group, $F(5, 75) = 13.61, p < .001$ (Fig. 6). In the “no effects” group, on the other hand, there is no systematic influence of the SOA variation on IRTs, $F(5, 65) = 1, 13, p > .1$.

The interaction of practice and sequence length is significant, $F(5, 140) = 14.09, p < .001$, the sequence length effect in the IRTs decreases with practice. No other interaction approached significance.

Discussion

A number of results from Experiment 1 was replicated in Experiment 2. The mean level of initiation times and IRTs is significantly lower in the “tones” group. Again, there is evidence of more efficient chunking in the “tones” group, indicated by more homogenous IRT profiles. There is a significant sequence length effect in the “tones” group as well as in the “no effects” group, but in the “tones” group it decreases further throughout practice, while it remains on the same level in the control condition.

Participants in the “tones” group again made more errors in the first half of the training phase. In the test phase, initiation times and IRTs decreased with practice. Short sequences were initiated and executed faster than

long sequences. Initiation times and IRTs decreased faster in the control group, especially early on in the test phase.

The difference in initiation times between the “tones” group and the “no effects” group decreased with increasing preparation time, modestly but significantly. It seems that some of the beneficial influence of the tone effects can be compensated through additional preparation time. This interaction should, however, be interpreted cautiously. Since the difference between the initiation times in the “tones” group and the “no effects” group only begins to become smaller with the longest SOAs, this may also be to do with a floor effect in the “tones” group, as one anonymous reviewer pointed out. Whether or not this is the case cannot be unambiguously decided on the basis of the present data. In any case, a good deal of the advantage produced by the tone effects seems to be on the programming side of the process, i.e., concerning processes taking place after the perception of the starting signal, since the mean initiation time difference between the groups is still substantial, even with an SOA of 900 ms. If the tones only provided a selection advantage, an SOA of 900 ms should have been more than sufficient to compensate for this, given that the mean initiation time advantage is 146 ms in the trials with an SOA of 0 ms. Even in the 900-ms SOA trials, however, there is still a group difference of 83 ms with regard to initiation time. This strongly suggests that the initiation time benefit produced by the tone effects is not purely due to selection facilitation, but that the tone effects also contribute to programming processes occurring after the presentation of the starting signal.

The influence of SOA on the mean IRTs at first glance seems to be difficult to interpret. While there is no systematic influence in the “no effects” group, there is a systematic and significant but non-linear influence in the “tones” group. The editors of this special issue offered an interpretation that may explain these results. It is possible that the sequences in the “no effects” group were not fully prepared, which would explain the absence of an SOA influence in this group. In the “tones” group, on the other hand, the influence of SOA on IRTs seems somewhat systematic, if non-linear. The data pattern (Fig. 6) may indicate that the fully prepared sequence representation can only be maintained for a limited amount of time, reaching its peak activation about 100 ms after cue onset. When the SOA is longer than that, the representation begins to decay, causing the gradual increase in IRTs over SOAs. Further research will have to test the viability of this interpretation.

Taken together, the results of Experiments 1 and 2 yield reliable evidence of the integration of tone effects into sequence representations that control behavior and that the execution of the motor sequences is based on. They facilitate the integration of single movement elements into chunks. These chunks can then be selected, programmed, and executed faster.

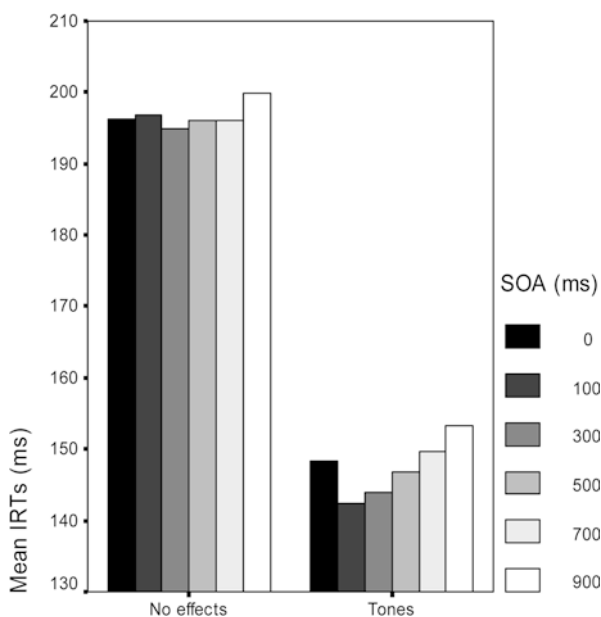


Fig. 6 Mean interresponse times for the two groups, divided by levels of preparation interval (SOA)

General discussion

In Experiment 1, participants in the groups with distinct tone effects initiated and executed sequences faster in the test phase. The sequence length effect in both initiation times and IRTs was reduced. These results seem to be based on the fact that chunking processes are influenced by the tone effects. Apart from the reduction in the sequence length effect, the homogenization of IRT profiles yielded evidence of more effective chunking in the tones groups.

In Experiment 2, preparation time was varied in addition to the presentation of tone effects. There was again an advantage for the tones group, in initiation times as well as in IRTs. The sequence length effect in the “tones” group was only numerically reduced, but a significant reduction continued throughout the test phase. The initiation time difference between the experimental and control groups decreased with increasing SOA but did not vanish. It may thus be possible to compensate for the advantageous impact of the tones on selection or preparation processes, at least in part, through additional preparation time in the control group. Since there is a substantial advantage for the “tones” group even at an SOA of 900 ms, it seems likely that the tone effects have a beneficial effect on sequence programming as well. This interpretation is again in line with the notion that the tone effects become part of the sequence representation used to control behavior. Again, the tone effects produced improved chunking, the IRTs developed into a very homogenous pattern at a low overall level. This was not observed in the control group.

Taken together, the results count in favor of the interpretation that contingent tone effects facilitate the integration of movement elements into motor chunks, which affects initiation as well as execution. It may be speculated, following the argumentation of Greenwald (1970), that the tone effects are first associated with the actions that produce them, a process probably influenced by factors such as compatibility and contingency. In a next step, effect images consisting of proprioceptive, tactile, and auditory consequences of an action are serially chained, the length of the interlinked units increasing with practice. This interpretation suggests that the sequence representations developing in the tones groups are qualitatively different in that they do not only contain representations of the movements themselves, but also of the additional, external effects associated with the movements. The particular properties of these external effects in the present experiments lead to the fast development of a single-chunk representation even for the six-element sequences.

This is not to say that such a completely chunked representation could not develop without additional, external effects as well. Earlier work by Klapp (1995), Verwey (1999), and others suggests that extensive training can also lead to the development of one-chunk

representation for longer movement sequences. In these studies, the sequence length effect decreased and eventually disappeared over the course of training. The most basic interpretation for the influence of the tone effects would thus be that they facilitate the chunking process, reducing the amount of training necessary to reach a fully integrated sequence representation.

A question arising from the present results concerns the generality of the observed influence of response effects. Tones may have specific properties that make them particularly valuable for chunking processes. The first evidence for this assumption comes from another experiment we conducted that is not presented in detail here for the sake of brevity. In an experimental setup identical to that of Experiment 1, but with the visually presented digits 1 to 6 instead of tones as stimuli/effects in the experimental condition, there was a slight numerical advantage for the effect group, but no significant difference between the effect group and the no effects group.

Tones seem to be particularly suited to be associated with key presses on the one hand, and to aid the linking of those key presses to each other to form motor chunks on the other hand. This may have to do with the fact that we are used to perceiving tones as tone sequences, i.e., as melodies. Another important factor is probably the comparatively long temporal capacity of the auditory ultra short-term memory. As Darwin et al. (1972) demonstrated, the “echo-memory” has an effective retention time of 2–4 s, many times more than the visual ultra short-term memory. Auditory stimuli are thus available for further processing much longer than visual stimuli. In addition, visual effects can easily be ignored in a paradigm like the present one, which is much harder to do with tone effects.

The pure presence of an additional stimulus sequence highlighting the structure of the movement sequences alone is obviously not enough for the tone effects to exert their beneficial influence. The results of Hoffmann et al. (2001) and Stöcker et al. (2003) suggest that it is crucial for the tones to improve sequence acquisition so that they are presented as response effects. Stimulus-contingent tones did not produce benefits in these studies.

The reported results count in favor of the notion that the effects, and thus usually also the aims of voluntary behavior play a central role not only for the selection, but also for the initiation and execution of movement sequences, as well as for the acquisition of such sequences. Converging evidence for this interpretation comes from functional brain imaging studies. Bangert, Parritz, and Altenmüller (1998), for example, showed that in the brains of trained pianists as well as those of beginners after short practice, motor and sensory cortical regions are activated at the same time. This is independent of whether the participants hear the tone sequences or play them on a normal or even a muted piano. For the beginners, this co-activation occurred

only when they had experienced contingent key-tone relations during their training sessions; with a key-tone mapping randomized on each trial there was no sensory co-activation.

The close ties between motor and sensory activation and contingent response effects is in line with our ideas about an ideomotor sequence representation. Traditional theoretical notions about motor programming and motor learning are, in view of this evidence, if not wrong, at least incomplete. Our expectations about the sensory consequences of our actions are closely linked to the control of our motor apparatus, and not just as feedback for error control, but also for the construction and execution of motor programs. Future theories on motor control and motor learning should take the importance of sensorily represented behavioral goals into account.

Acknowledgements Funding for this research was provided by the Deutsche Forschungsgemeinschaft (German Research Council). We thank Herbert Heuer, Dieter Nattkemper, Michael Ziessler and one anonymous reviewer for helpful comments on earlier versions of this paper.

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