The Quarterly Journal of Experimental Psychology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t716100704

Action sequences within and across hands: Evidence for hand-related sequence learning

Michael P. Berner [a]; Joachim Hoffmann [a]
[a] University of Würzburg, Würzburg, Germany

First Published on: 13 April 2009

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2009, 62 (8), 1507–1515

Psychology Press
Taylor & Francis Group

Short article

Action sequences within and across hands: Evidence for hand-related sequence learning

Michael P. Berner and Joachim Hoffmann
University of Würzburg, Würzburg, Germany

Recent research into the acquisition of action sequences involving both hands suggests that the hand-related (sub)sequences are learned at least partly independently of one another. Here we investigated hand-related sequence learning with a novel approach. Eight stimuli were divided into two sets. Participants responded simultaneously to a pair of stimuli (one from each set) with keystrokes of both hands. The stimuli from one set appeared according to a probabilistic structure; no such structure was imposed on the other set of stimuli. The structured stimuli either were assigned to keystrokes of one hand only or were evenly distributed across keystrokes of both hands. Sequence learning was more pronounced under the within-hands assignment than under the across-hands assignment. This finding corroborates hand-related sequence learning and suggests that the executing hand constitutes a dimension that facilitates learning of sequential regularities among elements that pertain to this hand.

Keywords: Sequence learning.

Everyday actions like buttoning a shirt, folding a piece of paper, or tying one's shoes require the coordinated use of both hands. Despite the involvement of both hands in almost all action sequences, this aspect of sequential performance has until recently received virtually no attention in research on sequence learning. Research on sequence learning was almost always focused on the acquisition of knowledge concerning redundancies in the overall sequence of stimuli or responses (for an overview, see Clegg, DiGirolamo, & Keele, 1998). The question of whether the subsequences pertaining to each hand, which constitute the overall sequence spanning both hands, might be learned independently of one another has been neglected so far.

Recently, Berner and Hoffmann (2008) implemented a bimanual–bisequential serial reaction time task as an experimental approximation of everyday action sequences involving both hands. On every trial two imperative stimuli appeared simultaneously indicating which response was to be performed with the left hand and the right hand, respectively. Participants were instructed to

Correspondence should be addressed to Michael P. Berner, Institut Psychologie III, Universität Würzburg, Röntgenring 11, D-97070 Würzburg, Germany. E-mail: berner@psychologie.uni-wuerzburg.de

This research was supported by Grants HO 1301/12–1 and HO 1301/12–2 awarded to J. Hoffmann by the German Research Council (DFG). We thank Benjamin Clegg for helpful comments on a previous version of this manuscript.

http://www.psypress.com/qjep
DOI:10.1080/17470210902746932

execute the two responses simultaneously. The stimuli for the left hand followed a fixed sequence independently of the stimuli for the right hand, which followed a different fixed sequence. These two hand-related sequences were of different length and were thus uncorrelated. After extensive practice, test blocks were introduced in which either only one of the hand-related sequences was replaced with a random sequence while the other one remained intact or both hand-related sequences were randomized. All test blocks yielded a significant increase in reaction time (RT) compared to adjacent regular baseline blocks. However, these RT costs were smaller when only the subsequence of one hand was randomized than when both were randomized. This pattern of results indicates at least partly independent learning of the two hand-related sequences. This conclusion is supported by error costs emerging only for the hand that lost its sequence but not for the other hand.

In additional transfer blocks the sequence that had been practised with one hand was transferred to the other hand while the former hand received a randomized sequence. Participants performed better in these transfer blocks than when both hand-related sequences were randomized, which suggests at least some intermanual transfer of the hand-related sequence knowledge. However, compared to test blocks in which one hand retained its sequence while the other hand received a randomized sequence, transfer blocks produced significant costs—that is, performance of a sequence with the "transfer hand" was not as good as it was with the practised hand. Thus, the data point to a nontransferable as well as to a transferable component of hand-related sequence knowledge.

In another study, Berner and Hoffmann (in press) explored independent learning of hand-related sequences under conditions in which the stimuli from hand-related sequences were presented in alternation and also responded to alternately with the two hands. Although consecutive responses performed with one hand were always interrupted by a response with the other hand, the data again indicated at least partly independent learning of the two hand-related sequences. There were no indications for intermanual transfer of the hand-related sequence knowledge. Thus, the evidence so far suggests that besides learning of an overall sequence spanning both hands the constituent hand-related sequences are also learned at least partly independently of one another.

The present experiment further explored hand-related sequence learning by using a new experimental approach. On each trial a pair of stimuli was presented, one of which indicated a response to be made with the left hand, while the other indicated a response with the right hand. Each stimulus pair featured one stimulus from each of two subsets. The stimuli from one subset followed each other in an unstructured order whereas the stimuli of the other subset followed a probabilistic sequence with frequent and rare stimulus transitions. The critical variation concerned the assignment of the stimuli to the responses they required. In the across-hands condition the stimuli of each subset required responses with the left hand and with the right hand. In the within-hands condition the stimuli of each subset required responses with only one of the two hands. Accordingly, in the within-hands group, the transitions of the probabilistic sequence pertained to responses with exclusively one hand whereas they pertained to responses with both hands in the across-hands group. As an additional manipulation, stimuli were either location based (i.e., spatial) or alphanumeric. Because previous demonstrations of hand-related sequence learning have relied exclusively on spatial stimuli we wanted to explore whether stimulus format might affect hand-related sequence learning.

Learning of the probabilistic stimulus sequence would express itself in performance being better on trials featuring frequent transitions than on trials featuring rare transitions (cf. Schvaneveldt & Gomez, 1998). The operation of hand-related sequence learning processes would express itself in stronger sequence learning in the within-hands assignment than in the across-hands assignment.

Method

Participants

A total of 48 individuals (mean age 22.7 years) volunteered to participate in partial fulfilment of course requirements. Out of these 48 participants, 43 reported to be predominantly right-handed, 3 professed to be ambidextrous, and the remaining 2 declared to be predominantly left-handed.

Task and design

On each trial participants responded to a pair of stimuli with a bimanual response. Stimuli were either alphanumeric or spatial. In the alphanumeric condition, the pair of stimuli consisted of one of four letters and one of four numerals. The letter appeared in navy blue, the numeral in grey. In the spatial condition, the pair of stimuli consisted of two asterisks (one navy blue, one grey) appearing in two of eight possible locations. The letters and the navy blue asterisks appeared according to a probabilistic sequence, whereas the order of the numerals and the grey asterisks was unstructured. The assignment of the letters and numerals or the navy blue and grey asterisks to the eight response keys was either such that the probabilistic sequence pertained to fingers of one hand only (within-hands assignment) or such that it pertained to fingers of both hands (across-hands assignment). One half of participants were assigned to the within-hands condition while the others were assigned to the across-hands condition. Within each of these two conditions half of the participants received alphanumeric stimuli while the others received spatial stimuli.

Apparatus and stimulus material

Stimulus presentation and response registration were controlled by the E-Prime software package (Schneider, Eschman, & Zuccolotto, 2002). A standard (German) QWERTZ keyboard was used to collect responses. Participants operated the keys Y, D, F, G with the little, ring, middle, and index fingers of the left hand and the keys J, K, L, _ with the index, middle, ring, and little fingers of the right hand.

The *structured sequence* consisted of four elements (four letters or four locations for navy blue asterisks). For each element there were one frequent successor (occurring in 80% of transitions; $1 \rightarrow 2$, $2 \rightarrow 4$, $3 \rightarrow 1$, $4 \rightarrow 3$) and one seldom successor (accounting for the remaining 20% of transitions; $1 \rightarrow 3$, $2 \rightarrow 1$, $3 \rightarrow 4$, $4 \rightarrow 2$). The accompanying *unstructured sequence* also consisted of four elements (four numerals or four locations for grey asterisks), the succession of which adhered to the following restrictions: (a) There was no immediate repetition of the same element, and all other transitions occurred equally often in each block; (b) the element was chosen so that on each trial responses of both hands were required, even in the across-hands assignment. Accordingly, every element in the structured sequence could be paired only with one of those two elements in the unstructured sequence, which required a response with the respective other hand in the across-hands assignment; (c) every possible pair of stimuli occurred equally often in each block. Both sequences were determined for every block of the experiment ahead of time so that every participant worked with the same succession of trials.

The stimuli in the *alphanumeric condition* were the letters A, B, X, Y and the numerals 1, 2, 8, 9. The stimuli were chosen to allow for easy discrimination between the stimuli assigned to each hand, not only in the within-hands assignment (e.g., numerals assigned to the left, letters assigned to the right hand) but also in the across-hands assignment (e.g., numerals and letters that appear early in their respective rank order, 1, 2, A, B, assigned to the left hand; numerals and letters that appear late in their respective rank order, 8, 9, X, Y, assigned to the right hand). The respective assignment was displayed at the bottom of the screen in black in 14-point Arial font throughout the entire session (see Figure 1A). The imperative stimuli were presented in 24-point bold Arial font. Letters were presented in navy blue, numerals in grey. On each trial one letter–numeral pair was presented centred on the screen. Whether the letter or the numeral of the pair appeared as the left one or the right one of the two stimuli was determined randomly on each trial under the restriction that both combinations occurred equally often; this was true for frequent transitions as well as for rare transitions.

In the *spatial condition* the imperative stimuli were asterisks 9 mm in diameter. There were

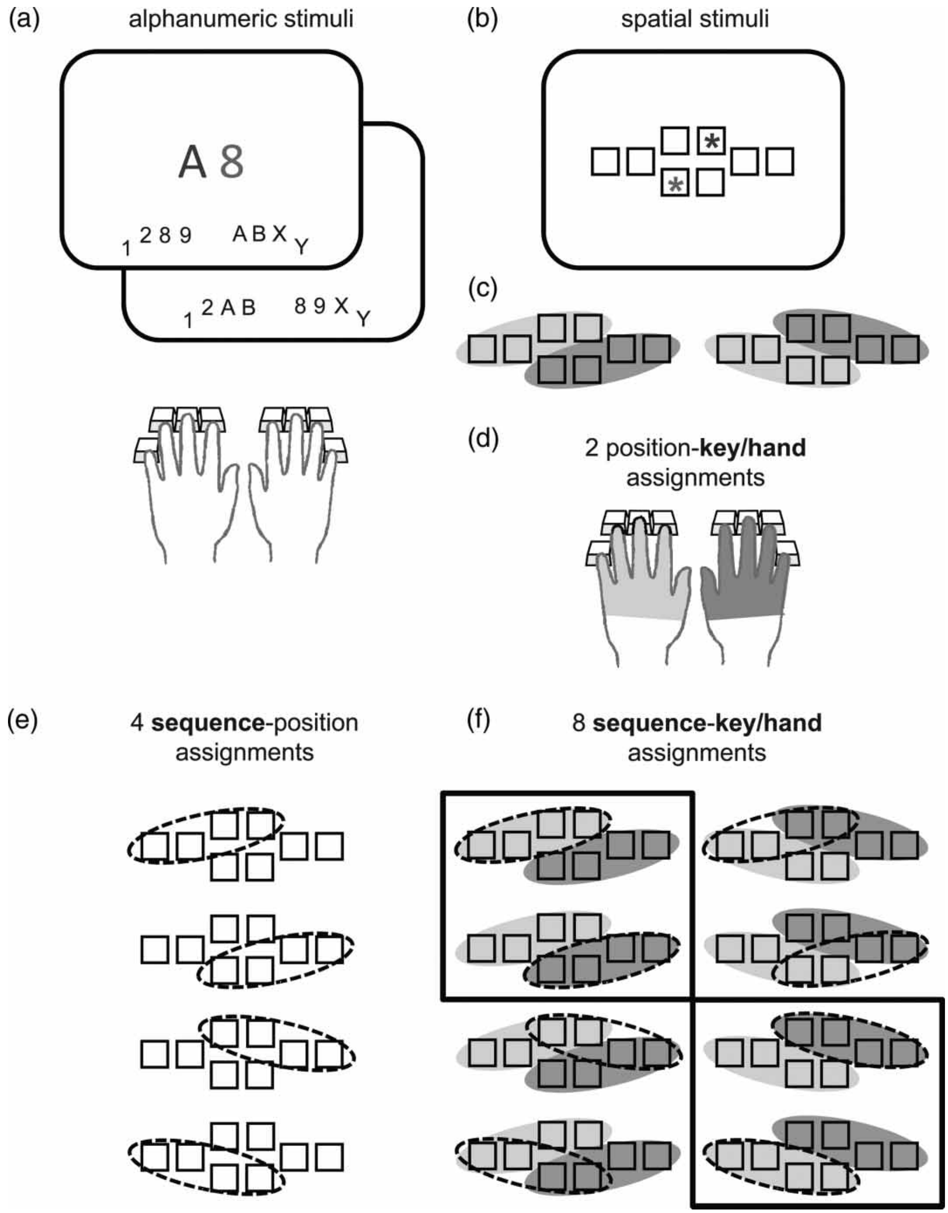

Figure 1. *Illustration of (A) the alphanumeric stimulus display (depicting the within-hands assignment condition on the front screen and the across-hands assignment condition on the back screen), (B) the spatial stimulus display, (C) the two ways of dividing the positions in the spatial condition into two rows, (D) the two assignments of positions to the left and the right group of keys and thus to the left and the right hand, (E) the four possible assignments of the structured sequence to positions in the stimulus display ("structure positions" are encircled with a dotted line), and finally (F) the within-hands assignment (enclosed in boxes) and the across-hands assignment of the structured sequence to keys and thus fingers of the two hands resulting when fully crossing the assignments depicted in Panels C/D and E. In the alphanumeric stimulus display (A), the letter appeared in navy blue and the numeral in grey. In the spatial stimulus display (B), the pair of stimuli consisted of two asterisks (one navy blue, one grey) appearing in two of eight possible locations. (To view a colour version of this figure, please see the online issue of the Journal.)*

eight locations in which the asterisks could appear, each marked by a square black outline (side length 21 mm). The squares were arranged in two rows of four squares, which overlapped in the centre of the screen (see Figure 1B; the distance between squares was 6 mm horizontally and, if applicable, 12 mm vertically). This layout can be divided either into an upper left row and a lower right row of four squares each or, alternatively, into a lower left row and an upper right row of squares (see Figure 1C). The squares in the left row (either upper left or lower left) were always assigned from left to right to the fingers of the left hand. Likewise, the squares in the right row (either lower right or upper right) were always assigned from left to right to the fingers of the right hand. The assignment of the two rows of squares to the two hands (see Figure 1D) either coincided with the assignment of the structured sequence to the rows of squares (see Figure 1E) or varied orthogonally to it. The resulting assignment of the structured sequence and the unstructured sequence to the hands is within hands in the former case and across hands in the latter case (see Figure 1F). All four possible within-hands and all four possible across-hands assignments were implemented for an equal number of participants.

The alphanumeric stimuli were assigned to the elements in the underlying structured or unstructured sequence in ascending order; the spatial locations were assigned from left to right. All stimuli were presented on a white background.

Procedure

Participants were tested individually. The experiment was conducted in two sessions scheduled for separate days with a maximum of one day off between the sessions (all but 4 participants completed the experiment on consecutive days). Session 1 consisted of 14 blocks; Session 2 comprised 16 blocks. Both sessions started with a warm-up block in which all stimuli were random. In all other blocks (henceforth, regular blocks) a structured sequence was combined with an unstructured sequence as described above. Each block comprised 80 trials. Participants took self-terminated rest periods between blocks. At the beginning of each session, participants received written instructions presented on the screen informing them about the assignment of the alphanumeric stimuli or the locations to keys on the keyboard and to fingers of the two hands as described above. Written instructions were augmented by an illustration similar to Figure 1. No mention was made of sequences. Both speed and accuracy were stressed in the instructions.

After completing the SRT task participants were debriefed about the presence of frequent transitions among the letters or the locations of navy blue asterisks and the assigned keys/fingers as well. Subsequently, they were asked to write down these frequent transitions, and they were encouraged to guess if unsure. Participants were also told that they could use their hands during recall.

Results

RTs from error trials (at least one incorrect response; 10.9%) were excluded from analysis, as were outlier RTs (more than 3 *SD*s above or below the mean RT as determined separately for each participant and each epoch; 1.5%). Furthermore, we excluded RTs from those trials on which participants failed to give simultaneous responses (if RTs for the left and right hands differed by more than 200 ms; 1.0%).

For the remaining trials the RTs of the left and the right hand were averaged. From these mean bimanual RTs for each trial the mean RTs for frequent and rare successor elements were computed separately for each of nine epochs. Likewise, error frequencies (i.e., percentage error; henceforth, PE) for trials featuring frequent successor elements and trials featuring rare successor elements were computed separately for each epoch. Epochs comprised three consecutive regular blocks with the exception of Epoch 1, which comprised the first four regular blocks. Blocks were combined into epochs to ensure an adequate number of data points for rare successor elements, which are by definition relatively rare.

RT costs as an index of sequence learning were computed for each epoch by subtracting the mean

RT for frequent successor elements from the mean RT for rare successor elements. Error costs were computed in an analogous manner. RT costs and error costs were analysed separately in 2 (assignment: within-hands vs. across-hands) × 2 (material: alphanumeric vs. spatial) × 9 (epochs) analyses of variance (ANOVAs) with repeated measures on the last factor. Whenever necessary, the degrees of freedom were adjusted with the Greenhouse-Geisser epsilon (ε_{GG}) in order to correct for any significant violations (Mauchly test) of the sphericity assumption. If a correction has been carried out, the unadjusted degrees of freedom are reported together with the respective ε_{GG}, and the corresponding reported *p*-values reflect the adjusted degrees of freedom.

RT costs and error costs were higher in the within-hands assignment than in the across-hands assignment, both $F(1, 44) > 5.28$, both $p \leq .027$, both $\eta_p^2 > .107$ (see Figure 2). RT costs increased over the first couple of epochs, $F(8, 352) = 8.67$, $p \leq .001$, $\eta_p^2 = .165$, $\varepsilon_{GG} = .702$, but this effect did not significantly moderate the observed within-hands advantage, $F(8, 352) < 0.91$, $\eta_p^2 = .020$. For error costs there was also a significant main effect of epoch, $F(8, 352) = 2.26$, $p \leq .05$, $\eta_p^2 = .049$, but no other effects or interactions were significant, all $F < 1.17$, all $\eta_p^2 < .026$. Furthermore, RT costs were higher in the alphanumeric condition ($M = 209.7$ ms) than in the spatial condition ($M = 149.1$ ms), $F(1, 44) = 6.00$, $p \leq .018$, $\eta_p^2 = .120$, but this effect did not significantly moderate the observed within-hands advantage either, $F(1, 44) = 1.07$, $\eta_p^2 = .024$. No other interactions were significant, both $F(8, 352) < 1.54$, both $\eta_p^2 < .034$.

RT costs and error costs were significant in every epoch in both assignment conditions, all $t(23) > 2.37$, all $p \leq .026$, except for the first epoch in the across-hands condition where error costs missed significance, $t(23) = 1.94$, $p \leq .065$.

There were no differences between the two assignments in terms of absolute RTs or absolute error frequencies, both $F(1, 44) < 0.42$, both $\eta_p^2 < .01$. Relevant absolute means averaged across epochs are given in Table 1.

Participants' performance in the postexperimental recall task was scored by determining the number of recalled frequent transitions. Those participants recalling all four frequent transitions were considered explicit learners; the remaining participants, who recalled a mean number of 0.96 ($SEM = 0.10$) frequent transitions, were classified as largely implicit learners. Importantly, the number of explicit and largely implicit learners did not differ between the within-hands assignment and the across-hands assignment, $\chi^2 = 0.83$, $p \leq .773$ (see Table 2). Numerically there were more explicit learners than implicit learners in the alphanumeric condition but more implicit learners than explicit learners in the spatial condition (see Table 2). However, this pattern was not statistically significant either, $\chi^2 = 2.09$, $p \leq .149$.

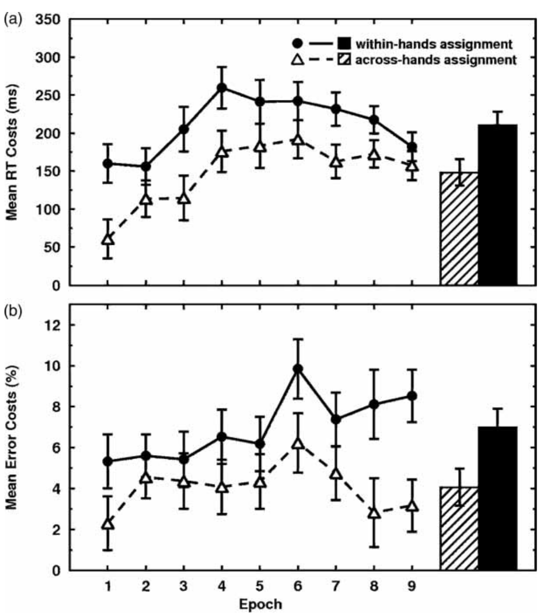

Figure 2. *(A) Mean RT costs and (B) mean error costs (* ± *1* SEM, *respectively) for the within-hands assignment and the across-hands assignment separately as well as across the epochs.*

Discussion

In the present experiment we implemented a variant of a bimanual–bisequential serial reaction time task. On each trial participants responded bimanually to a pair of stimuli. One of the two

Table 1. *Mean reaction time and mean percentage error for frequent and rare successor elements as a function of sequence-key/hand assignment and stimulus material format*

		Assignment											
		Across hands				*Within hands*				*Overall*			
		RT (ms)		*PE (%)*		*RT (ms)*		*PE (%)*		*RT (ms)*		*PE (%)*	
Material		*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*
Alphanumeric	Frequent	1,075.3	59.2	6.5	1.2	931.9	59.2	3.6	1.2	1,003.6	41.8	5.1	0.9
	Rare	1,260.4	66.2	9.8	1.9	1,166.2	66.2	10.6	1.9	1,213.3	46.8	10.2	1.4
Spatial	Frequent	859.5	59.2	15.3	1.2	958.2	59.2	13.3	1.2	908.8	41.8	14.3	0.9
	Rare	970.6	66.2	20.1	1.9	1,145.2	66.2	20.3	1.9	1,057.9	46.8	20.2	1.4
Overall	Frequent	967.4	41.8	10.9	0.9	945.0	41.8	8.5	0.9	956.2	29.6	9.7	0.6
	Rare	1,115.5	46.8	15.0	1.4	1,155.7	46.8	15.5	1.4	1,135.6	33.1	15.2	1.0

Note: RT = reaction time. PE = percentage error.

stimuli was selected according to a probabilistic regularity such that it was either a frequent or a rare successor of a preceding stimulus. The other stimulus was selected according to an unstructured sequence. The extent of learning the probabilistic sequential regularity was assessed by the costs incurred in terms of RTs and error rates on trials featuring a rare successor element compared to trials featuring a frequent successor element. The critical experimental variation concerned the assignment of the stimuli of the probabilistic sequence either to responses of the same hand (within hands) or to responses of both hands (across hands). The unstructured stimuli were assigned to the remaining responses; that is, they also pertained either to responses of one hand (the other hand) or to responses of both hands. Additionally, imperative stimuli were either alphanumeric or spatial.

Table 2. *Number of implicit learners and explicit learners as a function of sequence-key/hand assignment and as a function of stimulus material format*

	Assignment		*Stimulus material*	
	Across hands	*Within hands*	*Alphanumeric*	*Spatial*
Implicit	12	11	9	14
Explicit	12	13	15	10

The results showed more pronounced learning of the probabilistic sequential regularity in the within-hands condition than in the across-hands condition. In other words, the probabilistic regularity was learned better if it appeared among responses of only one hand than if it appeared among responses of both hands. This within-hands advantage was independent of the amount of practice. Also, it was not influenced by stimulus format although sequence learning was generally more pronounced with alphanumeric material than it was with spatial material. Furthermore, the within-hands advantage appeared to be not due to differences between the two assignments in the degree of explicit learning.

The data confirm the well-known sensitivity for the probability of transitions between successive elements (e.g., Cleeremans & McClelland, 1991) even if the transitional regularities are accompanied by an irregular stream of other stimuli. Previous research has shown that sequence learning can pertain to sequential regularities in the order of stimuli (e.g., Clegg, 2005) as well as in the order of responses (e.g., Hoffmann, Martin, & Schilling, 2003; Nattkemper & Prinz, 1997). Furthermore, regularities in the relations between responses and the next stimulus (i.e., action−effect relations) have also been shown to affect sequence learning (e.g., Hoffmann, Sebald, &

Stöcker, 2001; Stöcker & Hoffmann, 2004; Stöcker, Sebald, & Hoffmann, 2003; Ziessler, 1998; Ziessler & Nattkemper, 2001). The finding that sequence learning was more pronounced in the within-hands assignment than in the across-hands assignment could be due to any one, some, or all of these modes of sequence learning.

The finding of better sequence learning with alphanumeric stimuli than with spatial stimuli points to a contribution of stimulus sequence learning. However, an impact of the within-hands assignment versus the across-hands assignment on learning of stimulus sequences is not to be expected prima facie because in both assignments the probabilistic sequence pertained to the same sequence of either letters or blue asterisks. Only if one assumes that the assigned responses become a feature of the imperative stimuli (e.g., Hasbroucq & Guiard, 1991) could the stimulus response assignments affect learning of the stimulus sequences. In this case, regularities among stimuli assigned to fingers of the same hand might be easier to learn than regularities among stimuli assigned to fingers of both hands because the respective stimulus set becomes more distinct from the other stimuli among which no regular relations exist.

As far as learning about the order of responses is concerned, the within-hands assignment differs from the across-hands assignment in that the former involves learning transitions among responses of exclusively one hand, whereas the latter involves learning transitions among responses of both hands. This difference is relevant to the extent that response sequence learning pertains to the optimization of transitions between single movements in terms of improved coarticulation of successive movements (e.g., Verwey & Clegg, 2005; see also Berner & Hoffmann, 2009; Jordan, 1995; Park & Shea, 2005). In particular, Verwey and Clegg (2005) have argued that such coarticulatory optimization might play a more prominent role for within-hand sequence execution than for across-hands sequence execution because biomechanical interactions among fingers of one hand are more severe than those between hands. In this view the within-hands advantage observed here would come about because within-hands transitions are subject to coarticulatory optimization whereas across-hands transitions are not.

Finally, with regard to learning of action–effect relations it is to be noted that in the within-hands condition the responses of one hand always trigger the imperative stimuli for responses of the same hand whereas in the across-hands condition responses of one hand also trigger imperative stimuli for responses of the other hand. It might well be that for the purpose of efficient sensory-motor coordination responses become more easily associated with sensory effects that determine responses of the same hand than with sensory effects that require responses of the other hand. According to this speculation, the within-hands advantage would be due to enhanced action–effect learning compared to the across-hands condition.

It is not possible to distinguish between these accounts on the basis of the experiment reported here, and each of the discussed factors might have contributed to the observed within-hands advantage. Irrespective of the underlying mechanism or mechanisms, the present data provide new evidence in support of the notion that the executing hand constitutes a dimension that facilitates learning of sequential regularities among elements that pertain to this hand (cf. Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003, p. 317).

It remains to discuss the possible role of the somewhat unusual experimental set-up used here, in which learning of a sequential regularity occurs in the presence of a second unstructured sequence. It might be that the observed within-hands advantage does not reflect facilitation of sequence learning in the within-hands condition but rather the disruption of sequence learning when stimuli from the structured sequence and stimuli from the unstructured sequence are assigned to the same hand in the across-hands condition. If that were the case it would imply that a similar within-hands advantage might not show up—for example, in a setting in which only one sequence is implemented, and no second unstructured sequence is present that could disrupt sequence learning in the across-hands condition.

Additional research is necessary to elucidate whether the observed within-hands advantage reflects facilitation or disruption of sequence learning and which mode or modes of sequence learning are responsible for this effect. Irrespective of the outcome of this future research the within-hands advantage reported here constitutes evidence for hand-related sequence learning and suggests that the way in which people bodily interact with their environment during sequence production influences the cognitive processes involved in sequence learning.

Original manuscript received 11 August 2008
Accepted revision received 2 November 2008
First published online 13 April 2009

REFERENCES

Berner, M. P., & Hoffmann, J. (2008). Effector-related sequence learning in bimanual–bisequential serial reaction time task. *Psychological Research*, *72*, 138–154.

Berner, M. P., & Hoffmann, J. (2009). On the acquisition of effector-specific and effector-independent components of sequencing skill. *Journal of Motor Behavior*, *41*, 30–44.

Berner, M. P., & Hoffmann, J. (in press). Integrated and independent learning of hand-related constituent sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Cleeremans, A., & McClelland, J. L. (1991). Learning the structure of event sequences. *Journal of Experimental Psychology: General*, *120*, 235–253.

Clegg, B. A. (2005). Stimulus-specific sequence representation in serial reaction time tasks. *Quarterly Journal of Experimental Psychology*, *58A*, 1087–1101.

Clegg, B. A., DiGirolamo, G. J., & Keele, S. W. (1998). Sequence learning. *Trends in Cognitive Science*, *2*, 275–281.

Hasbroucq, T., & Guiard, Y. (1991). Stimulus–response compatibility and the Simon effect: Toward a conceptual clarification. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 246–266.

Hoffmann, J., Martin, C., & Schilling, A. (2003). Unique transitions between stimuli and responses in SRT tasks: Evidence for the primacy of response predictions. *Psychological Research*, *67*, 160–173.

Hoffmann, J., Sebald, A., & Stöcker, C. (2001). Irrelevant response effects improve serial learning in serial reaction time tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*, 470–482.

Jordan, M. I. (1995). The organization of action sequences: Evidence from a relearning task. *Journal of Motor Behavior*, *27*, 179–192.

Keele, S. W., Ivry, R., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The cognitive and neural architecture of sequence representation. *Psychological Review*, *110*, 316–339.

Nattkemper, D., & Prinz, W. (1997). Stimulus and response anticipation in a serial reaction task. *Psychological Research*, *60*, 98–112.

Park, J.-H., & Shea, C. H. (2005). Sequence learning: Response structure and effector transfer. *Quarterly Journal of Experimental Psychology*, *58A*, 387–419.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime user's guide.* Pittsburgh, PA: Psychology Software Tools.

Schvaneveldt, R. W., & Gomez, R. L. (1998). Attention and probabilistic sequence learning. *Psychological Research*, *61*, 175–190.

Stöcker, C., & Hoffmann, J. (2004). The ideomotor principle and motor sequence acquisition: Tone effects facilitate movement chunking. *Psychological Research*, *68*, 126–137.

Stöcker, C., Sebald, A., & Hoffmann, J. (2003). The influence of response-effect compatibility in a serial reaction time task. *Quarterly Journal of Experimental Psychology*, *56A*, 586–703.

Verwey, W. B., & Clegg, B. A. (2005). Effector dependent sequence learning in the serial RT task. *Psychological Research*, *69*, 242–251.

Ziessler, M. (1998). Response-effect learning as a major component of implicit serial learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 962–978.

Ziessler, M., & Nattkemper, D. (2001). Learning of event sequences is based on response-effect learning: Further evidence from a serial reaction task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*, 595–613.