スポーツ科学研究, 11, 250-259, 2014 年

On the structure of motor programming: an additive factors approach

Lu Xu[a b], Werner Sommer[c], Hiroaki Masaki[d]

[a] Graduate School of Sport Sciences, Waseda University, Japan
[b] Research Fellow of Japan Society for the Promotion of Science, Japan
[c] Department of Psychology, Humboldt University, Germany
[d] Faculty of Sport Sciences, Waseda University, Japan

Key words: motor program, finger tapping, kinematic parameter

Abstract

There is wide consensus concerning the existence of a central motor programming stage wherein movement elements are assembled prior to movement execution. The present study involved a determination of which of two types of interaction were involved in the organization of motor parameters during motor programming. One possibility involves a unitary stage with interactions between different kinds of parameters. In the other possibility each parameter is set independently of the others. To distinguish between the two possibilities, participants performed choice reaction time tasks in three experiments. In these experiments the subjects responded to one of two kanji characters (logographic Chinese characters with the meaning of left and right) by tapping their left or right fingers, respectively, with different movement duration, hand placement, or sequence complexity. All factors yielded main effects of these parameters on reaction time (RT) but no interactions were seen. These findings support the assumption that independent stages (subprocesses) exist during motor programming.

スポーツ科学研究, 11, 250-259, 2014年, 受付日:2014年5月12日, 受理日:2014年12月10日

連絡先:Hiroaki Masaki, Faculty of Sport Sciences, Waseda University
Tel & Fax: +81-4-2947-6909; E-mail: masaki@waseda.jp

Introduction

Prior to the execution of a rapid movement, our brain assembles the so-called motor program (for reviews see Keele, 1981; Rosenbaum, 1985). One important goal in motor control research is to reveal the organizational structure of this motor program. Although previous studies involving neuron encoding (Sparks & Mays, 1983) and computer simulation (Arbib, Iberall, & Lyons, 1985) suggest that motor programming consists of different substages that are associated with target location, direction and distance; it is important to validate the existence of the above substages by utilizing a different methodology. To this end we investigated the internal structure of the motor programming phase in choice reaction time (RT) tasks.

Sternberg (1969) proposed the additive factor method (AFM) as a means of investigating the organization of information processing. The basic assumption of the AFM is that information processing proceeds through a set of sequentially ordered and independent stages; the total RT is the sum of the time demands for each stage. One important issue in mental chronometry research involves clarifying the number of stages involved in the execution of a task. To determine the presence of independent processing stages with the AFM method, experimenters must orthogonally manipulate two or more experimental factors that affect RTs when different levels of difficulty of the factors are compared. These experimental factors prolong RTs by altering the time demands of processing in one or more stages. If the effect of one experimental factor depends on the difficulty level of a second factor, that is, when factors interact, they can do so only by affecting one or more common stages. In contrast, if the factors in question show main effects but do not interact, that is, when they are additive, one may conclude that they exclusively act on separate and independent stages. Systematically manipulating a set of experimental factors allows the researcher to identify the minimum number of independent stages involved in a given task.

Since the introduction of the AFM, researchers have found both additive and interactive effects among the various factors involved in choice RT tasks. Based on previous findings, Sanders, in a 1990 review, concluded that three motor-related stages are incorporated in the stage structure of choice reactions.

The first motor-related stage is called *response selection*. This stage is based on the additive effects of stimulus quality and stimulus response compatibility (SRC). During this stage, perceptual codes are translated to abstract response codes. SRC was first reported by Fitts (Fitts & Deininger, 1954; Fitts & Seeger, 1953) and refers to the observation that some tasks are easier to perform than others. This can be due to: (1) The use of particular sets of stimuli and responses or (2) The pairing of individual stimuli and responses (Kornblum, Hasbroucq, & Osman, 1990). For example, in the so-called symbolic SRC, stimuli (letters or words) signifying “left” or “right” are paired with responses in harmony with the side indicated by the stimulus (compatible) or out of harmony with the other side (incompatible). The number of response alternatives as well as precueing, and relative S-R frequency have also been shown to influence this stage (Sanders, 1998).

After an observing interaction between instructed speed and movement direction, Spijkers (1987) concluded that response selection is followed by a *motor programming* stage. Kinematic parameters of the response code are specified and established during this motor programming stage. The factor of “crossed hands” can be used to manipulate compatibility for subjects performing two-choice key-presses by placing the hands in either a normal (compatible) or crossed over (incompatible) position (Kornblum, et. al, 1990). RT becomes slower when the hands are crossed (e.g. Riggio, Gawryszewski, & Umilta, 1986; Matsumoto, Misaki, & Miyauchi, 2006). It is noteworthy that an orthogonal manipulation of SRC that is thought to influence response selection, and a switch from “uncrossed” to “crossed hands” (compatible to incompatible) revealed additive effects. This suggests that crossed hands influences motor-programming but not response selection (Sanders, 1998; see also Leuthold & Sommer, 1998).

Riggio, Gawryszewski, & Umilta (1986) utilized two experiments to investigate the crossed-effector phenomenon in choice RT tasks. In experiment one, the subject’s responses were made utilizing their index fingers, which were either uncrossed or crossed. The hands were always maintained in an uncrossed position. Thus, both S-R compatibility and effector position were manipulated in this experiment. In the second experiment, participants performed the choice RT task with a stick held in each hand. In this situation, the sticks were either crossed or uncrossed instead of the effectors. This manipulation produced a spatial conflict between stimuli and response goals (i.e., response keys). The main finding of the two experiments was that there was a lengthening of RT when stimuli and response goals were conflicting. This held even when the hands were uncrossed. This result suggests that the effect of the crossed hands is due to a mismatch between the responding hand and the locus of the response goal. The additive effect of S-R compatibility and crossed hands has been demonstrated in a number of studies (Brebner, Shepard, & Cairney, 1972; Shulman & McConkie, 1973; Simon, Hinrichs, & Craft, 1970; Wallace, 1971), suggesting a motoric locus for the crossed hands effect. A neuroanatomical locus of this effect has been suggested by Matsumoto et al (2006) who, utilizing fMRI, observed that activation of the superior temporal sulcus was associated with response selection when responding hands were crossed.

A *motor adjustment* stage is thought to follow the motor-programming stage. This motor *adjustment* stage is postulated to deal with the transition from central to peripheral motor activity. Previous studies have shown that the motor adjustment stage is affected by foreperiod duration, instructed muscle tension, and response specificity (Sanders, 1998). Spijkers and Steyvers (1984) found additive effects of foreperiod duration and movement duration. If the foreperiod duration effects occurred during the motor adjustment stage, it is highly possible that movement duration affects another motor-related stage. To date, movement duration has been tested in a sliding movement task (Spijkers & Steyvers, 1984) and a key pressing task (Zelaznik & Hahn, 1985). RTs increased as the movement duration was extended for both tasks.

Another motor-related manipulation of interest concerns the complexity effect. This phenomenon was first reported by Henry and Rogers (1960) at which time it was used as evidence for their memory drum theory. In their experiments they utilized three tasks of increasing complexity. For task A, the simplest movement, participants simply lifted a finger from a key after an imperative stimulus. For task B, a movement of moderate complexity, participants were required to reach forward to grasp a tennis ball after lifting their finger from the key. For task C, the most complex movement condition, (described here according to a correction by Henry, 1981, cited after Fischman, Christina, & Anson, 2008), participants first released the key, then reached upward and to the right to strike a ball, and thence continued downward and forward to press a button. They then had to reach upward and to the left to strike another ball. Henry and Rogers found that, relative to the simplest movement, RT for key release was 20% longer for the moderately complex movement sequence of task B, and further slowing was produced by the additional complexity found in task C. A more recent study was performed in which the programming of finger movement sequences of different complexity in a response precuing task was evaluated (Leuthold & Schröter, 2011). Participants were asked to tap fingers either homogeneously (index → middle → ring or ring → middle → index) or heterogeneously (index → ring → middle or ring→index→middle). This study demonstrated the effect of response sequence complexity on RT. Faster responses were seen for homogeneous than for heterogeneous sequences.

In sum, manipulating motor-related factors in this experiment allowed us to investigate the organizational structure of motor programming. No concrete conclusion about the internal structure of motor programming can be drawn from the studies we reviewed on movement processing. Little is known about how kinematic parameters, such as movement duration or complexity, are structured by the central motor program. To further knowledge in these area we conducted three experiments, which utilized orthogonally manipulated pairs of factors that are thought to influence movement programming. If motor programming is a unitary stage, these factors should interact with each other. On the other hand, if motor programming is not unitary and consists of several independent stages or substages, the experimental factors should show additive effects on RT.

Experiment 1

Experiment 1 was designed to investigate the effects of two motor-related factors, duration and crossed hands, on RT in a choice response task. An interactive effect of these factors is predicted if the motor programming stage is unitary, and additive effects if it is not.

Methods

Participants. The Subjects were eight participants (no history of neurological or psychiatric disorders; three females; mean age ± SD: 29.1 ± 6.6 yrs; all right-handed) who were recruited from Waseda University's Faculty of Sport Sciences. Informed consent was obtained in all cases. Our series of consecutive experiments was approved by the Waseda University Ethics Committee.

Stimuli and Responses. White single kanji characters (logographic Chinese characters with the meaning of left and right), subtending approximately 1.1 ×1.0° served as stimuli. The kanji characters were randomly presented at the center of the display against the black background of a computer monitor placed 1 m in front of the participants. The presentation of stimuli and recording of RTs were controlled by a tachistoscopic system (Iwatsu Isel Inc., IS-702).

Procedure. Each participant was tested in four blocks of 60 trials each. The blocks consisted of the factor combinations of movement duration (short vs. long press) and crossed hands (crossed vs. non-crossed hands). In the non-crossed hand condition, both left and right response button boxes were placed on the table (with left box on the left side and the right box on the right side relative to midline). Participants placed their left and right hands on left and right response button boxes respectively in a comfortable position. In the crossed-hand conditions, participants placed one forearm on the table and another arm on a wooden shelf of 11 cm height. Response button boxes were also placed either on the table or on the shelf, respectively, for each hand. The placement of the forearms was switched for the second half of the experiment. In the crossed-hand condition, participants crossed their hands and pressed the left and right key with the right and left index finger, respectively. In the short duration condition, brisk key taps were required, whereas in the long duration condition, participants were instructed to keep the key depressed for a longer time. The order of blocks was counterbalanced across participants. Both speed and accuracy were stressed in the instructions to avoid a possible speed-accuracy trade-off.

Each trial began with the presentation of a plus symbol (0.6° ×0.6°) for 500 ms, which served as a fixation aid. The plus symbol was replaced by one of the two kanji characters (i.e., 左 (left)/右 (right)), until a button was pressed. Intervals between a response and the next fixation symbol onset ranged from 1900 to 2900 ms (in increments of 200 ms). The characters for left and right were presented in a pseudo-random order. Only correct response trials with RTs ranging from 100 ms to 800 ms were analyzed. RT was defined as the interval from the onset of the imperative stimulus to the onset of the first key press. Data for the RT and error rate were submitted to analyses of variance (ANOVAs) with repeated measures using the within-subjects factors of duration (short, long) and crossed hand (uncrossed, crossed). Statistical significance was set at *p* < .05.

Results and Discussion

Figure 1 (left panel) depicts mean RT. A two-way ANOVA revealed main effects of duration (*F*(1,7) = 17.73, *p* < .01) and crossed hand (*F*(1,7) = 15.10, *p* < .01). RT was significantly shorter for short than for long movement duration (*M* = 400 vs. 463 ms, *SEM* = 15 vs. 18 ms). RT was also longer when the hands were crossed (*M* = 462 ms, *SEM* = 20 ms) than when non-crossed (*M* = 402 ms, *SEM* = 14 ms). No significant interaction was found between movement duration and crossed hand (*F*(1,7) = 0.02, *n.s.*).

Figure 2 (left panel) shows mean error rates. Errors occurred on less than 2% of the trials for each condition. Main effects did not occur for either duration (*F*(1,7) = 4.44, *n.s.*) or crossed hands (*F*(1,7) = 0.79, *n.s.*). No interaction of these factors was found (*F*(1,7) = 1.84, *n.s.*).

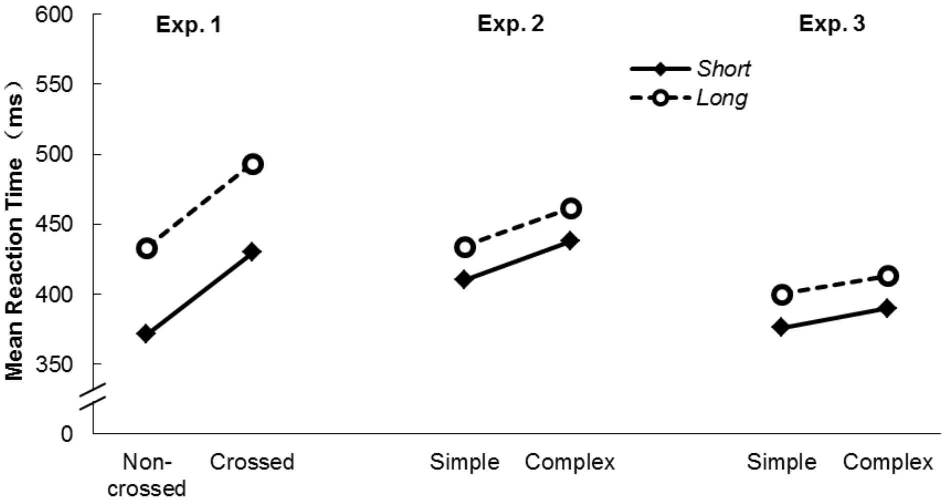

Figure 1. Effect of factors crossed-hand (Exp.1), sequence complexity (Exp. 2 and 3), and movement duration on mean RTs.

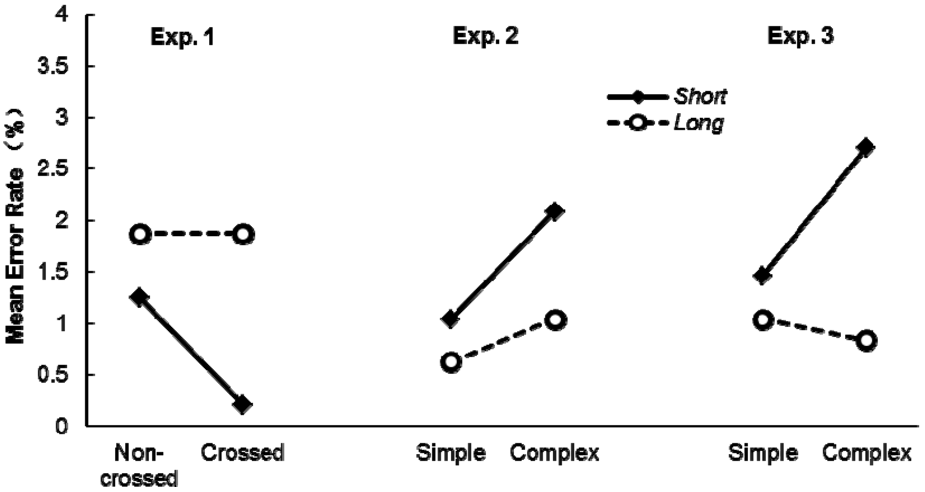

Figure 2. Effect of factors crossed-hand (Exp.1), sequence complexity (Exp. 2 and 3), and movement duration on mean error rates.

In Experiment 1 we found main effects of both duration and crossed hand on RT, but no interaction between these factors. There was no significant effect of either factor on error rate, indicating that there no speed-accuracy trade-off was present. Thus, according to the rationale of the AFM methodology, our results imply that the factors of response duration and cross-hand, which are both considered to influence motor programming, do not affect a common stage. Rather, this indicates that there are at least two distinct stages.

Experiment 2

Since experiment 1 did not reveal evidence for a unitary stage of motor programming, we explored a factor combination of movement duration with response sequence instead of crossed-hand. This response sequence manipulation is most likely to affect motor programming. Leuthold and Schröter (2011) tested the effect of finger movement sequences and found that more complex sequences resulted in longer RTs. A motoric locus of response sequence complexity is suggested because this factor affected the interval between the onset of the lateralized readiness potential (LRP) (Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988) and the response (Low, Miller, & Vierck, 2002; Smulders, Kok, Kenemans, & Bashore, 1995). SRC has been suggested to affect the response selection stage (Sanders, 1998). Since additive effects of SRC and sequence length on choice RT have been reported in a previous study (Inhoff, Rosenbaum, Gordon, & Campbell, 1984), the above evidence implies a motoric locus for the response sequence effect. However, Verwey (1994) suggests that response sequence may not influence the motor-programming stage, but rather separate sequence construction and sequence retrieval stages, which precede and follow motor programming, respectively. According to Verwey (1994), the sequence construction stage is concerned with: (1) establishing a control structure or (2) loading chunks into a motor buffer with fixed spatio-temporal properties. Thus kinematic variables such as force, speed, or limb, are specified during motor programming. Subsequently, the retrieval stage self-terminates the sequential search through a non-shrinking buffer and subsequent retrieval. Both the sequence construction and retrieval stages are affected by sequence length. To our knowledge, no study has tested the combination of movement duration and response sequences of different complexity. We predict an interaction of both factors if they affect a common stage associated with motor-programming process. If Verwey (1994) is correct, sequence length and movement duration should have independent effects.

Methods

Participants. Twelve healthy (no history of neurological or psychiatric disorders) participants (four females; mean age ± SD: 27 ± 6.1 yrs; all right-handed) were recruited for this study. Five of them participated in Experiment 1.

Stimuli and Responses. Stimuli were the same as in Experiment 1. Responses were recorded with three keys for each hand assigned to index, ring, and middle fingers. Participants had to either press three times with the index finger (simple sequence) or press a sequence of index, ring and middle finger (complex sequence). In addition, the first index finger press was to be either short or long according to the same criteria as in Experiment 1.

Procedure. As in Experiment 1, the conditions were orthogonally combined in separate blocks, and counterbalanced in order across participants. There were four conditions consisting of factor combinations of movement duration (short → short → short vs. long → short → short) and sequence order (index→ index → index vs. index → ring → middle). The procedure for stimulus presentation was the same as in Experiment 1.

Results and Discussion

The results are depicted in Figures 1 and 2 (middle panels). A two-way ANOVA revealed a significant main effect of response duration ($F(1,11) = 7.64$, $p < .05$), indicating slower responses for long-duration ($M = 449$ ms, $SEM = 18$ ms) as opposed to short-duration presses ($M = 422$ ms, $SEM = 16$ ms). It also showed significant effect of response complexity ($F(1,11) = 5.35$, $p < .05$). Numerically, RT was longer for complex responses ($M = 448$ ms, $SEM = 20$ ms) than simple ones ($M = 424$ ms, $SEM = 15$ ms). No interaction between these two factors was present ($F(1,11) = .001$, *n.s.*).

Error rate was again low ($M = 1.46\%$, range: 1.11 to 2.08 %). No main effect of either duration ($F(1,11) = 4.00$, *n.s.*) or complexity ($F(1,11) = 0.62$, *n.s.*) was found and there was no interaction ($F(1,11) = 0.48$, *n.s.*). Thus no speed-accuracy trade-off occurred.

In Experiment 2, both the longer duration of response and the more complex response sequences tended to result in longer RTs. Since there was no interaction between these factors, the data are again consistent with a non-unitary view of movement programming.

Experiment 3

To test a different response sequence in experiment 3, we adopted three-press responses with either one or two fingers (rather than the three as performed in exp. 2). The response sequence manipulation was orthogonally combined with the duration of the third rather than the first element in the movement sequence. Keeping the first element of the movement sequence identical among conditions allowed us to observe purer sequential effects on RTs, because the effects of implementation of the first element were eliminated.

Methods

Participants. Eight healthy (no history of neurological or psychiatric disorders) participants (two females; mean age± SD: 28.6 ± 6.9 yrs; all right-handed) were recruited for this study. Six of them participated in Experiment 1. Five of them participated in Experiment 2.

Stimuli and Responses. We presented the same stimuli as used in experiments 1 and 2. The factor duration, defined as in experiments 1 and 2, now concerned the duration of the third element in the response sequence and the factor sequence involved the levels of three presses with the index finger (simple) and two presses with the index followed by one press with the ring finger (complex).

Procedure. As before, four conditions were conducted in separate blocks. The order of conditions was counterbalanced across participants. Conditions consisted of factor combinations of movement duration (short → short → short vs. short → short → long) and sequence order (index→ index → index vs. index → index → ring). In this experiment, conditions only differed in the third button press. The procedure for stimulus presentation and recording responses was the same as in experiments 1 and 2.

Results and Discussion

Mean RTs and error rates are shown in Figures 1 and 2 (right panels), respectively. In this experiment, longer RTs – to the first element in the sequence – were found for longer key presses as the third sequence element ($M = 407$ ms, $SEM = 11$ ms) than for shorter presses ($M = 383$ ms, $SEM = 6$ ms). RTs were also longer for the complex sequence condition ($M = 402$ ms, $SEM = 9$ ms) than for the simple condition ($M = 388$ ms, $SEM = 9$ ms). A two-way ANOVA revealed main effects of both response duration ($F(1,7) = 11.83$,

$p < .05$) and sequence complexity ($F(1,7) = 10.59$, $p < .05$). However, as in the two previous experiments, no interaction of these factors was found ($F(1,7) = .02$, *n.s.*).

The mean error rate was 1.51%, ranging from 0.83% to 2.71 % across conditions. There was no experimental effect of duration ($F(1,7) = 4.44$, *n.s.*), or, sequence complexity ($F(1,7) = 1.84$, *n.s.*), nor was there an interaction of these factors ($F(1,7) = 4.81$, *n.s.*).

Experiment 3 yielded significant main effects of both response duration and response sequence on RT. However, no interactions were present. Again, error rates were very small, and no evidence of a speed-accuracy trade-off was observed. These findings argue against a common locus of the factors investigated.

General Discussion

We conducted three experiments, which as a group were designed to reveal the internal structure of motor programming processes. To this end we orthogonally manipulated three pairs of experimental factors. Each pair contained movement duration as a common factor, which is considered to affect the setting of parameters in the motor programming stage (Klapp & Erwin, 1976). The other factors manipulated in our study (i.e., crossed-hands in experiment 1, and movement sequence complexity in experiments 2 and 3) have also been related to motor programming stage (Sanders, 1998). We repeatedly obtained main effects for all of the experimental factors. Importantly, in no case did we obtain an interaction between two of the factors manipulated in a given experiment.

According to the rationale of the AFM methodology, our results suggest that both crossing hands and sequence complexity affect different processing stages than the one affected by movement duration. Given that all factors manipulated motor programming in one or the other way, we can conclude that the motor programming stage is not unitary but rather consists of separate or even isolated (sub)stages.

It should be noted that a number of premises must be met in order to utilize the AFM methodology (Sanders, 1998). First, one cannot apply the AFM to data when processing stages overlap each other in time. That is, stages must be arranged in series and information transmission must be discrete. Second, the quality of stage output must not be impaired, and thus stage intactness should be invariant. Given that these premises hold, our additive results suggest the existence of at least one motoric stage concerned with movement duration, as well as one or two stage(s) associated with the crossed-hand and response sequence factors, respectively.

An intact output system may be assumed from the rather low error rates in our experiments, which did not show significant effects of the experimental factors. Therefore, one may conclude that each stage accomplished its function well and transmitted high-quality information to the next stage.

Our results support a hierarchical organization of motor control, and can be well explained by the hierarchical editor (HED) model of Rosenbaum, Inhoff, & Gordon (1984); for a review, see Schröter & Leuthold (2008). The basic assumption of the HED model is that the motor programs for response sequences are hierarchically structured before the imperative stimulus is discerned. In choice RT tasks, once the stimulus is identified, two processing phases occur one after another; both are controlled by the central component enumerated in the HED model. This process can be conceived of as successive “unpacking” of nested subprograms. The first phase is the so-called *edit pass*, during which any uncertain response compositions are unpacked and specified hierarchically without physical execution. After the first phase, the *execution pass* starts, wherein the motor response program is unpacked into smaller elements that cannot be further decomposed. These elements are then executed successively.

Our evidence for independent stages concurs with the tenets of the HED model. Each of our experiments consisted of two motor-related dimensions. For example, in experiment 3, both movement duration and sequence complexity were manipulated. Thus, combinations of the two factors resulted in four different conditions; the simple-short, the simple-long, the complex-short, and the complex-long conditions. In the simple-short condition, response finger (index) was certain, and thus participants merely needed to respond with the correct finger and hand as quickly as possible without considering the duration of the key-press. Thus, only the responding hand had to be specified as a motor-related feature. In the simple-long condition, the participants had to specify both response hand and movement duration. In the complex-short condition participants were also required to specify two features, both the responding hand and the fingers (index → index → ring). However, the motor specifications were more complicated in the complex-long condition. Here the participants had to specify the responding hand, finger, and duration. Thus the number of motor features to be specified in the four conditions was one, two, two, and three, respectively. It is plausible to assume that RT becomes longer as a function of the number of motor features. The additive effects of two factors in our experiments can be perfectly accounted for by the HED model. First, all of the motor-related parameters manipulated in our experiments were not specified a priori because we obtained significant effects of these factors on RT. Second, these parameters were programmed in a hierarchical manner, in which initially response hands were specified. This was then followed by the establishment of the entire motor program (Schröter & Leuthold, 2008).

Because the design of experiment 2 was similar to that of experiment 3, the same reasoning that follows from the HED model can explain the results. In experiment 1, we manipulated both crossed-hand and movement duration. To understand the application of the HED model to explain these results, one can replace the sequential order in experiment 3 by the crossed-hand task of experiment 1.

Spijkers and Steyers (1984) argued that movement duration can be preprogrammed in sliding movements. This assertion is at variance with the HED model. However, it does not concur with our results which indicate that movement duration affects RT. Thus movement duration appears not to be preprogrammed (at least not fully). One possible explanation for the discrepancy between our results and those of and Spijkers and Steyers (1984) may be that in their study participants were instructed to prepare for the response as far in advance as possible, whereas in the present study we only instructed the participants to respond to the stimulus as quickly and accurately as possible.

We kept the stimuli constant throughout our three experiments, and found near-identical main effects for movement duration. This confirms the validity of duration as a motor-related parameter, even though only a single element of the processed sequence, either the first or the last element, was programmed.

One might argue that the additive effects on RT were due to the block-wise manipulation of the conditions present in our study. However, van Duren and Sanders (1988) have tested the interactions of three experimental variables (signal intensity, signal quality, and SRC) in a two-choice reaction task under both blocked and mixed conditions. Although the effects of signal quality and SRC were smaller in the mixed condition, the additive effects of all the three variables were robust. Therefore, it is unlikely that the present additive effects would be very different in a mixed manipulation. Moreover, according to a study by Schröter & Leuthold (2008), the responding hand is activated before the entire motor program is established. In our experiments, the responding hand (left or right) was unknown before the imperative stimulus. Therefore, although the participants had preliminary information about all other movement parameters, they were unable to institute the motor program until the responding hand was specified. Moreover, if the participants were able to take full advantage of the block-wise design, the effects of motor parameters on RT should not have been observed. In other words, the additive effects we found were largely due to our valid manipulation of those motor-related factors.

However, it is somewhat unclear as to how these independent stages are structured. Keele (1981) suggested that the increased time demands of programming for slower movements might be due to a longer interval between the onsets of accelerative and decelerative forces. This possibility was tested by Wallace & Wright (1982) in a study, in which a pronounced effect of movement duration was found on the timing of electromyographic (EMG) activity. The above studies suggest that movement duration should affect a stage associated with response execution, including motor adjustments. However, in a study by Spijkers & Steyvers (1984) that adopted a precue paradigm in a sliding movement task, an under-additive interaction between duration uncertainty and direction uncertainty was observed. This result suggested a parallel processing of duration and direction. Our results cast doubt on the controversial functional loci of movement duration effects. It is noteworthy that in experiment 3 we kept the first two elements of the response sequence constant (same fingers and same duration) but varied the last element. Nevertheless, we still found a duration effect on RT. Therefore, the functional locus of the duration effect cannot be due to the motor adjustment stage.

In conclusion, we performed a series of experiments in which we manipulated different combinations of motor-related factors, movement duration, crossed-hand, and sequence complexity. Main effects of each factor were observed without any interactions. These results can be accounted for by the hierarchical editor model proposed by Rosenbaum et al. (1984). Additionally, according to the rationale of the AFM methodology, at least two independent motor programming processes are exist. This argues against the view that motor programming involves a unitary stage.

Acknowledgements

This study was supported by JSPS Research Fellowships for Young Scientists, and GCOE scholarship for international student to L. Xu, and a Grant-in-Aid for Scientific Research (C) 24530925 from the JSPS to H. Masaki.

References

- Arbib, M.A., Iberall, T., & Lyons, D. (1985). Coordinated control programs for movements of the hand. *Hand function and the neocortex*, 111-129.
- Brebner, J., Shepard, M., & Cairney, P. (1972). Spatial relationships and S-R compatibility. *Acta Psychologica*, *36*, 1-15.
- Fischman, M.G., Christina, R.W., & Anson, J.G. (2008). Memory drum theory's C movement: Relations from Franklin Henry. *Research Quarterly for Exercise and Sport*, *79*, 312-318.
- Fitts, P. M., & Deininger, R. L. (1954). S-R compatibility: Correspondence among paried elements within stimulus and response codes. *Journal of Experimental Psychology*, *48*, 483-492.
- Fitts, P. M., & Seeger, C. M. (1953). S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*, 199-210.
- Gratton, G., Coles, M. G., Sirevaag, E. J., Eriksen, C. W., & Donchin, E. (1988). Pre-and poststimulus activation of response channels: a psychophysiological analysis. *Journal of Experimental Psychology: Human perception and performance, 14*(3), 331.
- Henry, F. M., & Rogers, D. M. (1960). Incresed response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly of the American Association foe Health, Physical Education, & Recreation*, *31*, 448-458.
- Inhoff, A., Rosenbaum, D., Gordon, A., & Campbell, J. (1984). Stimulus-response compatibility and motoe programming of manual response sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 724-733.
- Keele, S. W. (1981). Behavioral analysis of movement. In V. Brooks, *Handbook of physiology: Sec. 1. The nervous system: Motor control.* (Vol. 2, pp. 1391-1414). Bethesda, MD: American Physiological Society.
- Klapp, S. T., & Erwin, C. I. (1976). Relation between programming time and duration of the response being programmed. *Journal of Experimental Psychology: Human Perception and Performance*, *2*, 591-598.
- Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility. A model and taxonomy. *Psychological Review*, *97*, 253-270.
- Leuthold, H., & Schröter, H. (2011). Motor programming of finger sequences of different complexity. *Biological Psychology*, *86*, 57-64.
- Leuthold, H., & Sommer, W. (1998). Postperceptual effects and P300 latency. *Psychophysiology, 35*(1), 34-46.
- Low, K. A., Miller, J., & Vierck, E. (2002). Response slowing in Parkinson's disease: A psychophysiological analysis of premotor and motor processes. *Brain*, *125*, 1980-1994.
- Matsumoto, E., Misaki, M., & Miyauchi, S. (2006). Neural mechanisms of spatial stimulus-response compatibility: the effect of crossed-hand position. *Experimental Brain Research*, *158*, 9-17.

・Riggio, L., Gawryszewski, G., & Umilta, C. (1986). What is crossed in crossed-hand effects? *Acta Psychologica*, 62, 89-100.

・Rosenbaum, D. A. (1985). *Motor programming: A review and scheduling theory*. In H. Heuer, U. Kleinbeck, & K. -H. Schmidt, Motor behavior: Programming, control, and acquisition (pp. 1-33). Berlin: Springer-Verlag.

・Rosenbaum, D. A., Inhoff, A. W., & Gordon, A. M. (1984). Choosing between movement sequences: A hierarchical editor model. *Journal of Experimental Psychology: General*, *113*, 372-393.

・Sanders, A. F. (1990). Issues and trends in the debate on discrete vs. continuous processing of information. *Acta Psychologica*, *74*, 1-45.

・Sanders, A. F. (1998). *Elements of Human Performance: Reaction Processes and Attention in Human Skill*. Mahwah, NJ: Erlbaum.

・Schröter, H., & Leuthold, H. (2008). Effects of response sequence length on motor programming: A chronometric analysis. *Acta Psychologica*, *128*, 186-196.

・Shulman, H. G., & McConkie, A. (1973). S-R compatibility, response discriminability, and response codes in choice reaction time. *Journal of Experimental Psychology, 98,* 375-378.

・Simon, J. R., Hinrichs, J. V., & Craft, J. L. (1970). Auditory S-R compatibility: Reaction time as a function of ear-hand correspondence and ear-response-location correspondence. *Journal of Experimental Psychology*, *86,* 97-102.

・Smulders, F. T.Y., Kok, A., Kenemans, J. L., & Bashore, T. R. (1995). The temporal selectivity of additive factor effects on the reaction process revealed in ERP component latencies. *Acta Psychologica, 90,* 97-109.

・Sparks, D. L., & Mays, L. E. (1983). Role of the monkey superior colliculus in the spatial localization of saccade targets. In *Spatially Oriented Behavior,* (pp. 63-85). Springer New York.

・Spijkers, W. A. (1987). Programming of direction and velocity of an aiming movement: The effect of probability and response-specificity. *Acta Psychologica, 65*(3), 285-304.

・Spijkers, W. A., & Steyvers, F. J. (1984). Specification of direction and duration during programming of discrete sliding movements. *Psychological Research*, *46*, 59-71.

・Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica*, *30,* 276-315.0

・van Duren, L. L., & Sanders, A. F. (1988). On the robustness of the additive factors stage structure in blocked and mixed choice reaction designs. *Acta Psychologica*, *69*, 83-94.

・Verwey, W. B. (1994). *Mechanisms of skill in sequential motor behavior*. Doctoral Dissertation.

・Wallace, R. J. (1971). S-R compatibility and the idea of a response code. *Journal of Experimental Psychology*, *88,* 354-360.

・Wallace, S. A., & Wright, L. (1982). Distance and movement time effects on the timing of agonist and antagonist muscles: a test of the Impulse-Timing theory. *Journal of Motor Behavior, 14,* 341-352.

・Zelaznik, H. N., & Hahn, R. (1985). Reaction time methods in the study of motor programming: The precuing of hand, digit, and duration. *Journal of Motor Behavior*, *17*(2), 190-218.