Transfer of Learning Among Motor Patterns With Different Relative Timing

Herbert Heuer
Universität Bielefeld
Bielefeld, West Germany

Richard A. Schmidt
Department of Kinesiology
University of California at Los Angeles

The generalized motor program concept with invariant relative timing leads one to expect nearly perfect transfer of training to a motor pattern with another duration and considerably less transfer to a pattern with a different relative timing. In two experiments, subjects were asked to learn spatial-temporal patterns of limb action at the elbow. These expectations about differential transfer were examined by the use of two target patterns that differed only by a nonlinear transformation of the time scale. Both experiments failed to provide evidence that transfer breaks down if relative timing is changed. These outcomes are taken to suggest that the often observed invariant relative timing might not be a mandatory phenomenon due to the restriction of a generalized motor program to one particular temporal pattern. Rather, this invariance could perhaps be thought of as a strategic phenomenon caused by preferences for certain temporal organizations contingent upon particular spatial patterns.

Several investigators have considered that movements are controlled by generalized motor programs which determine certain invariant features and that these invariances are preserved as other, more "superficial," movement characteristics are allowed to vary. Repeatedly it has been suggested that relative timing is such an invariant feature, whereas the overall duration of the movement is a variable characteristic determined by a parameter of the program (e.g., Carter & Shapiro, 1984; Schmidt, 1975, 1980, 1985). The purpose of the present experiment was to test the notion that a program of this kind is developed during practice. The test was based on the amount of transfer to a second task that differed systematically from the one practiced with regard to its duration and/or relative timing.

For motion of the limb at a single joint, a generalized motor program with invariant relative timing and a parameter to determine movement duration can formally be represented by a prototypical position-time curve. To produce any single example of the movement, a particular position-time function is then derived by scaling this prototypical function to the desired duration and amplitude. This, of course, is a very simple concept of a generalized motor program, in that the parameters are merely scaling factors for both kinds of axes (time and amplitude). Certainly, many other more complicated parameterizations are possible, but the existing evidence generally supports the simple parameterization (see Schmidt, 1983, 1985).

This evidence is provided by a series of studies which show that although the duration of a motor pattern may vary, its relative timing tends to remain constant. Some of the motor patterns studied have involved highly practiced actions with self-selected relative timing such as typing (Terzuolo & Viviani, 1979, 1980; Viviani & Terzuolo, 1980), writing (Viviani & Terzuolo, 1980), or walking/running (Shapiro, Zornicke, Gregor, & Diestel, 1981). At the other extreme are briefly practiced experimental patterns with somewhat arbitrary, experimenter-imposed relative timing—usually sequences of key presses (Summers, 1975) or sequential limb movements (Carter & Shapiro, 1984; Shapiro, 1977). Different durations of the motor pattern are due to spontaneous variability (e.g., Terzuolo & Viviani, 1980), or they are induced by different instructions (e.g., Shapiro et al., 1981), often combined with the request that the subjects abandon the relative timing learned previously (e.g., Shapiro, 1977; Summers, 1975). In view of these broad procedural variations, the phenomenon of invariant relative timing appears to be a rather general and robust characteristic of complex motor patterns (Schmidt, 1985). This invariant relative timing is not perfect, because deviations from invariance show up when more sensitive analytic tools are applied (e.g., Gentner, 1982, 1985, 1987; Heuer, 1984). Nevertheless, these deviations might still be considered as acceptable discrepancies between nature and human conceptualizations of it, and one can argue that they are of minor importance as compared with the conspicuous tendency toward invariance.

There is a certain weakness in inferring the existence of a generalized motor program with invariant relative timing on the basis of the various observed instances of invariant relative timing. In this viewpoint of a generalized motor program, the phenomenon of invariant relative timing is expected to be mandatory; control by the generalized motor program does not allow another, different relative timing, and being forced...
to use a new relative timing would imply control by another (new) program. The available data, however, are strong enough only to permit the argument that invariant relative timing is strategic. The fact that the subjects did not follow the request to abandon a particular relative timing is not sufficient to demonstrate that they could not do so. In the present experiments, we employ a stronger test of whether or not invariant relative timing of learned motor patterns is mandatory or merely strategic—a test consisting of asking subjects to shift to a pattern with a new, well-defined relative timing.

The concept of a generalized motor program with mandatory invariant relative timing implies that transfer to a motor pattern with a new duration should be nearly perfect, requiring merely a change in the duration parameter. On the other hand, transfer to a new relative timing (and to a new duration as well) should be poor, because here the development of a new program is required. The motor program learned during practice should be applicable only to the production of motor patterns with the same, particular relative timing. If relative timing were only strategic, however, there should be no particular difficulty in shifting to a new relative timing. The first experiment was designed to test the predictions from the mandatory versus strategic views of invariant relative timing.

Experiment 1

Method

Subjects. Students (N = 24, from 21 to 37 years old) at the University of Bielefeld took part in two sessions on successive days. Seven female and 5 male subjects were assigned randomly to each of two experimental groups. All subjects were right-handed (Edinburgh Handedness Inventory, Oldfield, 1971) and were paid 16 DM (approximately $9) independent of their performance.

Experimental conditions. The two experimental groups learned to reproduce, by means of elbow flexion movements, two different target patterns of 3-s duration. For reasons given below, these patterns are called "harmonic" and "nonharmonic." Before the start and after the end of practice, subjects were tested on the harmonic pattern, but the pattern was "expanded" so that the duration was now 4 s. Thus, both groups were required to change duration of their movement in the final test trials, but only the nonharmonic group had to change relative timing as well.

Target patterns. The position-time curves of the two target patterns are presented in Figure 1. The harmonic target pattern was derived from a harmonic function, here regarded as the underlying acceleration-time function for the movement. The amplitude of the harmonic function was changed stepwise at every zero crossing. After double integration to obtain the position-time curve, it was scaled to the desired duration (3 s or 4 s) and amplitude (see Apparatus section). Perfect reproduction of this pattern required alternating periodic net forces in both directions that were modulated in amplitude but not in duration. The pattern is called "harmonic" because its acceleration-time curve was no longer a harmonic function.

Although one may argue that the target patterns used here are representative of all movement tasks in general, the actual patterns used in this study are somewhat artificial and arbitrary. Although invariant relative timing has been reported for more natural patterns several times (e.g., Schmidt, 1985), this invariance was initially recognized in tasks with relatively artificial patterns, with a movement apparatus much like that used here (Armstrong, 1970; Pow, 1974). Since then, it has been observed repeatedly for only briefly practiced, more or less arbitrary, patterns. Further, as explained in more detail below, the particular patterns chosen here do have certain characteristics that make them consistent with the current understanding that oscillators are involved in motor control. Viewed in this way, the arbitrariness of the patterns is perhaps not a particularly serious concern.

Apparatus. A video monitor placed approximately 100 cm from the subject's eyes was used to display target patterns and the subject's reproductions. For presentation of target patterns, a small rectangle (with a width of 3 mm and height of 2 mm) was used; a larger rectangle (5 x 4 mm) was used for presentation of the subject's reproductions. The amplitude of the target patterns was set in such a way that the maximal horizontal excursion of the small rectangle from the display midline was 4.8 cm. Whenever a target pattern or a reproduction was presented, vertical motion of constant velocity of one or both rectangles (3.4 cm/s) indicated the passage of time. Three light-emitting diodes (LEDs), a green one flanked by two red ones (4-mm diameter, 3-cm lateral separation), were placed on top of the video monitor.

Subjects sat on a height-adjustable chair. The upper arm was horizontal, and the elbow was placed on a support directly above the pivot of a 53-cm horizontal lever. Subjects grasped a vertical handle on the lever, whose distance from the pivot was adjustable. Lever position was recorded by a potentiometer coupled to the lever shaft, whose output was sampled at 500 Hz. An angle of 90° at the elbow joint corresponded to the middle position of the larger rectangle on the screen, and a rotation of 1° corresponded to a displacement of 1.6 mm. The usable range was 45°-135°, corresponding to ±7.2 cm around the screen midline.

![Figure 1. Position-time curves of the target patterns.](image-url)
Transfer of Relative Timing

Design and procedure. In a familiarization period, subjects were presented 12 tracking trials in which a target pattern different from the ones in the experiment proper was used. After the two rectangles were aligned on the screen, both started to move downward for 4 s, with the small rectangle producing a harmonic motion in the horizontal dimension. Subjects were instructed to keep the rectangles aligned with appropriate elbow movements. The purpose of this initial task was to make subjects familiar with the apparatus, with the relation between movement of the forearm and motion of the large rectangle on the screen, and with the general experimental procedure.

Familiarization was followed by the first test period, which consisted of a single block of 12 test trials. In each trial the harmonic pattern was presented and was to be reproduced without knowledge of results (KR). The following practice period consisted of 9 blocks of 12 practice trials in the first session on the first day, and 9 further 12-trial blocks in the second session on the next day. One group of subjects practiced the harmonic pattern ("harmonic practice") while the other group practiced the nonharmonic pattern ("nonharmonic practice"). KR was presented on each trial after presentation of the target pattern and its reproduction by the subject. Breaks between blocks lasted several seconds, and after every three blocks there was a break of 4 min during which subjects could leave the chair. Breaks of 4 min were also inserted before the start of the practice period in the first session and after its end in the second session. Finally, after the first session, subjects were tested for outliers and for values outside the range of measurement. The results were analyzed separately for practice and test trials. For practice trials, all dependent variables were subjected to a three-way fixed-effects analysis of variance (ANOVA) with groups, sessions, and blocks as factors. The duration of the reproductions was not different between groups, being initially too long (about 3.5 s in the first practice block), but declining rapidly during the first three blocks. Generally, duration remained about 100–200 ms longer than the target duration. The main effects of sessions, $F(1, 22) = 17.6$, and blocks, $F(8, 176) = 13.3$, as well as the

1. The whole experimental set up was tested by replacing the potentiometer signal at the A/D-converter by the analog signal that controlled the horizontal motion of the small rectangle (corresponding to the target pattern). This allowed us to detect errors easily, and it gave descriptive indices for the target patterns, not as they are generated originally, but as they are affected by noise as a perfect reproduction of the subject would be. (Noise can be added, for example, in the analog lines and in the converters.) All the descriptive indices for the target patterns were obtained in this manner.

243
interaction between these two factors, $F(8, 176) = 8.4$, were significant, $ps < .01$.

The correlations of the time-scaled reproductions with the target pattern ($R$) are presented in the upper half of Figure 2. The harmonic target pattern was reproduced more accurately than the nonharmonic one ($r = .65$ vs. $.50$), $F(1, 22) = 7.2, p < .05$, and this difference remained stable throughout practice. The negative acceleration of the practice curve is reflected in the interaction between sessions and blocks, $F(8, 176) = 3.5$, in addition to the main effects of sessions, $F(1, 22) = 46.5$, and blocks, $F(8, 176) = 10.2$, all $ps < .01$. Corresponding results were found for integrated absolute error, except that the difference between groups—223 versus 243 in arbitrary units for the harmonic and nonharmonic target patterns respectively—fell short of significance.

The correlations with the target pattern not presented during practice ($R'$) are shown in the lower half of Figure 2. These are the correlations with the nonharmonic target pattern in the group having harmonic practice, and with the harmonic target pattern in the group having nonharmonic practice. Reproductions of the nonharmonic pattern were highly correlated with the harmonic target pattern ($r = .62$), while reproductions of the harmonic pattern had smaller correlations with the nonharmonic target pattern ($r = .36$), $F(1, 22) = 25.9, p < .01$. The difference between groups varied irregularly over the course of practice, causing a significant triple interaction, $F(8, 176) = 2.1, p < .05$. In addition, the main effects of sessions, $F(1, 22) = 17.9$, and blocks, $F(8, 176) = 3.4$, were significant ($ps < .01$), while the interaction between these two factors fell just short of significance, $F(8, 176) = 1.9, p < .10$.

The correlations revealed a remarkable asymmetry: Reproductions of the harmonic target pattern were highly similar to this pattern ($r = .65$) and only slightly similar to the nonharmonic target pattern ($r = .36$). Reproductions of the nonharmonic target pattern, in contrast, were intermediate to this pattern ($r = .50$), but their similarity to the harmonic target pattern was about the same size as found for reproductions of that pattern ($r = .62$). This asymmetry was still present at the end of practice. Thus, no matter which pattern was reproduced, deviations from the harmonic target pattern were about the same. But when the task was to reproduce the nonharmonic pattern, these deviations were "biased" in such a way that the deviations from the nonharmonic pattern became smaller.

Power of the first three spectral harmonics, expressed as a proportion of total power, is presented in Figure 3. Averages for the first three and last three blocks of each session are shown, as well as the spectra of the two target patterns. Relative power of the first harmonic was larger in the nonharmonic group than in the harmonic group, $F(1, 22) = 10.4, p < .01$, corresponding to the difference between the spectra of the target patterns. The change of this difference in the course of practice was not significant. Relative power of the second harmonic was larger in the harmonic group, $F(1, 22) = 26.2, p < .01$, again corresponding to the difference between the spectra of the target patterns. There was a tendency for this difference to increase during the course of practice; the interaction between groups and blocks was significant, $F(8, 176) = 2.2, p < .05$, and the interaction between groups and sessions approached significance, $F(1, 22) = 2.5, p < .20$. The differences between groups were .12 and .24 in Blocks 1–3 and 7–9 in the first session, and .23 and .28 in the corresponding blocks of the second session. These effects were significant only after six blocks of practice (i.e., for Blocks 7–9 and beyond). Finally, there were no significant differences between groups regarding relative power of the third harmonic; it tended, however, to decline in the harmonic group but to remain stable in the nonharmonic group.

In general, the spectra of the reproductions remained rather dissimilar from the spectra of the target patterns. The deviations, however, were simple and systematic, revealed in the comparison of the final spectra (Session 2, Blocks 7–9) with those of the target patterns (see Figure 3). In both groups, relative power of the first harmonic was too low by about .2, and relative power of the second harmonic was too high by about the same amount.

The two groups differed in how the final spectra (Session 2, Blocks 7–9) developed during practice. As can be seen in Figure 3, there was little change in the harmonic group. In particular, the power of the second harmonic was larger than that of the first harmonic from the start of practice on. Only
during the first session did the difference slightly increase. In the nonharmonic group, by contrast, the final spectrum (Session 2, Blocks 7–9) looked quite different from the initial one (Session 1, Blocks 1–3). Initially, the power of the second harmonic was larger than that of the first harmonic—similar to the spectrum of the harmonic group—and this was reversed only gradually during the course of practice. Thus, the final spectrum of the group having nonharmonic practice developed out of an initial spectrum similar to that of the harmonic group, while the spectrum of the harmonic group remained rather stable during practice. This suggests that the spectrum of the harmonic group might be characteristic of an "easy" relative timing that also served as a start in the nonharmonic group, but here it had to be developed toward a more "difficult" temporal pattern.

Test trials. In the test trials, subjects had to reproduce the harmonic target pattern with a 4-s duration. One block of test trials preceded the practice period, and two blocks followed it. The two groups of subjects were treated identically until after the initial test block, and so no differences were expected in this block of trials. In the final two blocks of test trials, however, subjects in the harmonic group had to change only the duration of the pattern practiced, while subjects in the nonharmonic group also had to change its relative timing. Therefore, if the practiced pattern is indeed controlled by a generalized motor program with (mandatory) invariant relative timing and duration as a parameter, performance of the harmonic group on the final test trials should be superior to that of the nonharmonic group.

The dependent variables were subjected to two-way fixed-effects ANOVAs, with groups and blocks as factors. Durations and correlations are presented in Table 1, and the relative powers of the first three harmonics are given in Figure 4. There were no significant effects involving groups; a significant main effect of blocks indicates nothing more than an improvement from the initial test period to the final one. The mean absolute deviations were 297 versus 290 in the initial test period, and 200 versus 218, and 219 versus 224 in the final test period (the values for harmonic practice are given first). The ANOVA again revealed no significant effect involving groups.

Although there were no reliable effects, some indications of a short-term persistence of relative timing can be seen. From Table 1, the correlation with the harmonic test pattern (R) in the first block of the final test period was slightly larger after practice of the harmonic pattern (.69) than after practice of the nonharmonic pattern (.64)—also true for the mean absolute deviations—while the correlation with the nonharmonic pattern (R') was slightly larger after nonharmonic practice (.46) than after harmonic practice (.42). Also, in the first block of the final test period, the spectrum of the nonharmonic group, shown in Figure 4, was shifted slightly to resemble that at the end of practice (see Figure 3), seen mainly with respect to the relative power of the first two harmonics. In the nonharmonic group, relative power of the first harmonic was larger than after harmonic practice, whereas relative power of the second harmonic was smaller. In the second block of the final test period, this effect of previous practice with different patterns had vanished (see Figure 4). Thus, at best there was a slight persistence of the previously learned relative timing in the final test trials, with relative timing

Table 1

<table>
<thead>
<tr>
<th>Test period</th>
<th>Harmonic practice</th>
<th>Nonharmonic practice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duration</td>
<td>R</td>
</tr>
<tr>
<td>Initial</td>
<td>4,670</td>
<td>.39</td>
</tr>
<tr>
<td>Final</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block 1</td>
<td>3,730</td>
<td>.69</td>
</tr>
<tr>
<td>Block 2</td>
<td>3,802</td>
<td>.70</td>
</tr>
</tbody>
</table>
being changed relatively quickly. These results do not support the notion that during practice, a generalized motor program is established with invariant relative timing. Whatever was learned seemed not to be a particular temporal pattern. Thus, when tested on a pattern with a particular relative timing, performance was the same whether a different or the same relative timing had been practiced earlier.

There is some ambiguity with respect to whether the present results provide evidence against the notion that a generalized motor program is established during practice. A major reason is statistical, in that it can be easily argued that more powerful procedures could have revealed a difference between the groups in test trials. Providing a replication of these effects, or lack of them, is a traditional way to solve such ambiguities, and this was the major rationale for the second experiment. In addition, the possibility of asymmetric transfer between the two target patterns, as well as the potential influence of the amount of training, was explored.

Experiment 2

In the first experiment only the harmonic target pattern had been used in test trials. In the second experiment, both target patterns were used so that any asymmetries in transfer among the patterns could be revealed. Although transfer from the nonharmonic target pattern to the harmonic target pattern might be nearly perfect, there is reason to hypothesize that transfer to the nonharmonic pattern after practice on the harmonic one might be considerably lower.

The concept of a generalized motor program imposes no constraints on the particular relative timing used in the production of a motor pattern. Such real-world constraints, however, do appear to exist. This is most clearly seen in two-dimensional figural patterns, in which Derwort (1938) noted that the relative timing in drawing figures is not arbitrary (see Viviani, 1986, for a review). The results concerning the relation between trajectory and relative timing in two-dimensional movements certainly cannot be taken to mean that relative timing is completely determined by trajectory or vice versa. But given a certain trajectory, there seems to be a preferred relative timing, and attempting to use a different one may be more difficult or even impossible. Such a preferred and presumably easy relative timing will be called “natural.”

Generalizing the results from two-dimensional movements to any motor pattern, we can hypothesize that different timing patterns differ with regard to this naturalness. There are at least three different criteria to determine the degree of naturalness. First, if subjects have a choice, they will prefer more natural patterns over less natural ones. Second, when distracted or no longer forced to maintain a particular relative timing, subjects will maintain natural patterns and attempt to change less natural ones toward more natural ones. Finally, more natural patterns will probably be more accurately reproduced than less natural ones.

Thinking in terms of more or less natural patterns provides a basis for conceiving of the often observed invariant timing as a strategic phenomenon associated with the minimization of some, yet undefined, “cost” associated with the use of a less natural relative timing. Invariant relative timing might therefore be restricted to temporal patterns of the more natural variety and would, perhaps, not be found indiscriminately for all temporal patterns. There is some evidence in support of this view.

First, several studies showing invariant relative timing used motor patterns with self-selected relative timing, where the patterns actually produced could be assumed to be more natural. Second, when the relative timing was experimenter imposed, it may have been natural in some cases by chance. In other cases, subjects tend to deviate from the prescribed relative timing (e.g., Carter & Shapiro, 1984; Shapiro, 1977), indicating that they used a more natural relative timing even if a less natural pattern was requested. It also suggests that establishing a less natural temporal pattern may be difficult or sometimes even impossible. Finally, support for a strategic invariant relative timing comes from the finding that some temporal patterns are maintained when relative timing is no longer prescribed, whereas others tend to be changed (e.g., Summers, 1975, for finger tapping, and Langley & Zelaznik, 1984, for aimed hand movements). In addition, Summers, Sargent, and Hawkins (1984) showed that whereas some temporal patterns of series of finger taps were maintained when a secondary task was introduced, other patterns were not.

Returning to the harmonic and nonharmonic target patterns of the first experiment, these patterns were constructed in an attempt to generate a more natural prototype and a less natural variant of it. The general intuition, of course, was that oscillator mechanisms play an important role in motor control (e.g., Craske & Craske, 1985, 1986; von Holst, 1937). The harmonic pattern can be generated by a single oscillator controlling the antagonistic forces acting at a joint, together with a modulation of its amplitude. The nonharmonic pattern, on the other hand, required modulation of the oscillator’s frequency and amplitude and should, as a result, be considerably less natural to produce.

The results of the first experiment gave some support to the hypothesis that the two target patterns indeed are more and less natural. First, the harmonic pattern was easier to
reproduce than the nonharmonic one. The difference between the two patterns was also reflected in subjects' spontaneous comments on how the movements felt, sometimes even with the expression of annoyance directed against the nonharmonic pattern. Second, no matter which pattern was reproduced, reproductions were always more similar to the harmonic pattern than to the nonharmonic one. And finally, although the spectral composition of the reproductions was similar at the start of practice, this spectrum was essentially maintained when the harmonic pattern was practiced but gradually changed during practice of the nonharmonic pattern. If the harmonic pattern was indeed the more natural one, and the nonharmonic pattern the less natural one, then there is reason to expect asymmetric transfer.

A second issue explored in Experiment 2 concerned the amount of transfer as a function of different amounts of training. A generalized motor program representing the whole pattern should develop over the course of practice and not yet be available in the early stages. Thus, different amounts of transfer, depending on whether relative timing is maintained or changed, would be expected only after a sufficient amount of practice.

Method

Subjects. Forty-eight subjects, from 16 to 37 years old at the University of Bielefeld, who were not involved in Experiment 1, took part in four sessions on successive days. Three males and 3 females were assigned to each of the eight experimental groups. All subjects were right-handed (Edinburgh Handedness Inventory, Oldfield, 1971) and were paid 25 DM (approximately $14) independent of their performance.

Experimental conditions. The eight experimental groups were obtained by crossing three factors: (a) practice of the harmonic versus nonharmonic target pattern, (b) the target duration of 3 s versus 4 s during practice, and (c) the sequence of target patterns performed during the test (harmonic/nonharmonic vs. nonharmonic/harmonic). Two blocks of test trials, one block for each target pattern, were presented in the first session, at the end of the second session, and at the end of the fourth session. Target duration in test trials was always 4 s.

Apparatus. The apparatus was essentially identical to that used in the first experiment. The exception was that a second monitor was placed to the right of the main display to be used for summary KR.

Design and procedure. After familiarization with the apparatus as in the first experiment, two blocks of test trials were presented in the first session on the first day. The mean correlation with the two target patterns presented was used to assign subjects to the different practice conditions. This measure was recognized as being necessary only after about 30 subjects had been run. At that time it became apparent that the various groups, although treated in the same manner in the first session, would show highly different performance just by chance. Therefore, an attempt was made to obtain comparable initial correlations. This included replacement of a few subjects with extreme values. Care was taken, however, that selection was based only on first-session scores.

The second session on the second day consisted of 6 blocks of 12 practice trials each, followed by another 2 test blocks. In the third session on the third day only 8 practice blocks were presented, and the fourth session on the last day was identical to the second one. In total, there were 20 practice blocks (240 trials); test blocks were presented before practice, after 6 blocks (72 trials), and after practice was completed.

A single trial was basically the same as in the first experiment. However in test trials, KR about movement time was given, and in practice trials KR about movement time, mean absolute deviation, and maximal deviation was added to presentation of the actual reproduction. The new KR was displayed on the additional monitor immediately after the reproduction phase. KR about movement time was presented graphically. If movement time was within ±1% of the target, only an upward pointing arrow was displayed in the middle of the screen. For each additional 1% deviation, a star was added, up to a maximum of 15 stars to the left or right of the arrow for too-short and too-long movement times, respectively. Below this line, two numbers were displayed, giving the mean absolute deviation and the maximal absolute deviation in millimeters on the screen.

The second change from the first experiment was that all vertical motions of the rectangles on the screen were omitted. Rather, motion of the rectangles was confined to a horizontal path in the middle of the screen. We felt that the additional representation of time by vertical motion was more confusing than helpful.

Data analysis. In addition to the analyses performed in the first experiment, the acceleration-time curves were obtained from the position-time curves by double differentiation. The filter was adjusted so that the acceleration-time curve used for constructing the target patterns could be recovered from the re-played target patterns with as high accuracy as possible (cutoff frequency ωc = 50.0 rad). Each acceleration-time curve was divided into acceleration phases, defined as the intervals from one zero crossing to the next. The difference between the two target patterns was reflected in the mean durations of the acceleration phases computed separately for each third of the pattern's total duration. (Acceleration phases that crossed the boundaries between thirds were neglected.) Mean durations were 222, 224, and 218 ms for the three segments of the harmonic pattern (averaged across its two durations of 3 s and 4 s). For the nonharmonic pattern, the corresponding mean durations were 164, 493, and 165 ms. Thus, the ratios were about 1:1:1 for the harmonic target pattern and 1:3:1 for the nonharmonic pattern.

Results and Discussion

The results were analyzed separately for practice and test trials. Because of the complex experimental design, there were several significant effects that were not relevant for the problem under study. For the benefit of a clearer presentation, only the major results will be reported. The results of the spectral analysis were omitted because they tend to replicate those in the first experiment.

Practice trials. Dependent variables were subjected to four-way fixed-effects ANOVAs, with the three between-group factors and with blocks as the fourth factor; additional factors were included as described below. The duration of the reproductions, of course, was longer when the target duration was 4 s than when it was 3 s. It was also longer in groups practicing the nonharmonic pattern than in groups having harmonic practice, F(1, 40) = 12.5, p < .01. This finding was obtained in the first experiment as well (although not significant there) and was due to a technical detail (see Appendix B). Finally, duration was initially too long and declined over the course of practice, F(19, 760) = 10.1, p < .01. After a few blocks, the duration was close to the target duration.

The correlations with the target pattern (R) are presented in the upper half of Figure 5. As in the first experiment, the harmonic pattern was reproduced more accurately than the nonharmonic one (r = .68 vs. .60), F(1, 40) = 4.2, p < .05.
the number for the target patterns. In the second session, the mean number was 15.0, and in the fourth session it was 13.6. The decline during the course of practice was significant, $F(19, 760) = 7.9, p < .01$. In addition, there were more acceleration phases in reproductions of the harmonic pattern than in reproductions of the nonharmonic pattern (14.6 vs. 13.6), $F(1, 40) = 5.6, p < .05$, and in reproductions with 4-s target duration than in those with 3-s target duration (15.5 vs. 12.7), $F(1, 40) = 38.7, p < .01$. There were no other significant effects for this variable.

Inspection of the target patterns in Figure 1 reveals some of the potential causes for the differences in the number of acceleration phases between target patterns. In particular, small velocity changes should be more difficult to discover when the whole pattern is presented in 3 s rather than in 4 s, because the average velocity is higher, which perhaps explains the effect of duration of the target pattern. Also, when the middle part of the pattern was compressed, the delicate velocity changes in this part would be more difficult to detect for the same reason. Thus, the number of acceleration phases indicates that certain difficult-to-detect features of the pattern were not accurately reproduced; only perfect reproduction would require exactly 16 acceleration phases.

The mean durations of the three thirds of the acceleration phases were subjected to a five-way fixed-effects ANOVA, with the three segments added as the fifth factor. Of major interest were the interactions between segments and any other factor, that is, any dependencies of the profile of the three mean values. Figure 6 presents these profiles for the first and last practice block in each session, separately for subjects who practiced the harmonic target pattern and for those who practiced the nonharmonic one.

The most conspicuous feature of the data in Figure 6 is that the means of the acceleration phases were always longer for reproductions of the nonharmonic target pattern than for reproductions of the harmonic pattern, $F(1, 40) = 10.7, p < .01$. This finding corresponds to the larger number of acceleration phases in reproductions of the harmonic pattern. A second feature is that the mean durations of the acceleration phases in the three segments of the reproductions were different, $F(2, 80) = 23.2, p < .01$, but were smallest in the last segment, perhaps because one or two rather brief acceleration phases occurred when the arm was brought to rest.

From Figure 6, in the reproductions of the harmonic pattern, acceleration phases were longest in the first segment, while in reproductions of the nonharmonic pattern they were longest in the middle segment. In evaluating these apparent differences, however, one should bear in mind that for the target patterns themselves, the ratios of the mean durations in the three segments were 1:3:1 for the harmonic pattern and 1:3:1 for the nonharmonic pattern. It is obvious that the ratio of 1:3:1 was not even approached by the mean durations observed for the reproductions of the nonharmonic pattern. Moreover, the statistical analysis revealed that the apparent differences between profiles were not reliable. The interaction between harmonic versus nonharmonic practice and segments was nonsignificant, $F(2, 80) = 1.4, p > .20$, as were all higher order interactions involving these two factors. Only the inter-

In contrast to the first experiment, the difference declined over the course of practice, $F(19, 760) = 2.8, p < .01$. Except for the general improvement across blocks, $F(19, 760) = 35.7, p < .01$, there were no other significant effects. The advantage of the harmonic target pattern in terms of mean absolute deviation turned out to be significant in this experiment, 191 $p < .01$. Except $F(19, 760) = 2.8$, over the course of practice, $F(19, 760) = 2.8$, the difference declined for the general improvement across blocks, $F(19, 760) = 2.8$, the difference declined for the general improvement across blocks, $F(19, 760) = 2.8$. The advantage versus 225 arbitrary units. The advantage versus 225 arbitrary units.
action between harmonic versus nonharmonic practice, blocks, and segments approached significance, $F(38, 1520) = 1.4, p < .10$. The initially very similar profiles tended to diverge over the course of practice; this divergence, however, was, at best, only marginally significant and was extremely small compared with the difference between the profiles of the two target patterns.

From these findings it appeared that a major characteristic of the nonharmonic target pattern was missing in its reproductions—the systematic modulation of the duration of the acceleration phases. Although reproductions of the nonharmonic target pattern approached the correct relative timing (indicated by the correlations and spectral analysis), they did so by means other than a modulation of duration of acceleration phases, probably involving a strategy of force modulation.\(^2\)

**Test trials.** Two blocks of 12 test trials each had been presented before practice in Session 1, after six blocks of practice in Session 2, and after the end of practice in Session 4. In each block one of the two target patterns had been used in the order harmonic/nonharmonic for half of the subjects and in the reverse order for the other half. Depending on the target patterns used during test and practice, no change, a change of duration or relative timing, or a change of both duration and relative timing was requested in test trials.

Dependent variables were analyzed by way of five-way fixed-effects ANOVAs, with the three between-group factors, plus target pattern during test and sessions. For duration, the major interest was whether it was different for target durations during practice of 3 s or 4 s. (Target duration in test trials was 4 s.) There was, in fact, a significant main effect of target duration during practice, $F(1, 40) = 10.5, p < .01$. This difference, however, did not develop during practice, but rather was present at the start of the experiment; it was even larger in the first session than in the second, and in the second than in the fourth, although the decline was not significant. Thus there was no clear indication of a difficulty in shifting from a duration of 3 s to one of 4 s.

Correlations are presented in Table 2. For each of the two target patterns during test, these correlations were highly similar for subjects who practiced the one or the other target pattern. For the correlations with the target pattern presented (R), there was no significant interaction between target pattern during practice and target pattern during test, $F(1, 40) = 1.0, p > .20$. Also, the triple interaction with session as the third factor fell short of significance, $F(2, 80) < 1.0$, as did all higher order interactions involving these three factors. The same was true for the correlations with the target pattern not presented (R'), except for a significant four-way interaction between target pattern during test, target pattern during practice, sessions, and target duration during practice, $F(2, 80) = 6.2, p < .01$. This interaction, however, appeared irregular. There was no indication that the proper interaction between target patterns during test and practice—indicative of a diffi-

\(^2\) There is a possibility that the too-flat profiles of mean durations observed for reproductions of the nonharmonic pattern were caused by artifacts. A "real" profile with 1:3:1 ratios can be made flat if artifacts occur preferably in the middle segment. Such a distribution of artifacts, which would occur in reproductions of nonharmonic movements but not in reproductions of harmonic movements, seems unlikely. If modulations were indeed present and only obscured by artifacts, the mean duration in the first and third segments should be particularly small (165 ms as compared with 220 ms for the nonharmonic and harmonic target patterns). On the contrary, the observed values for reproductions of the nonharmonic pattern were always larger than the corresponding values for reproductions of the harmonic target pattern. These too-large mean durations cannot be due to artifacts. Therefore, it seems safe to conclude that reproductions of nonharmonic patterns indeed lacked the systematic modulation of the acceleration phases.
ulty in changing the practiced pattern—developed during practice with one target duration but not with the other.

For the mean absolute deviation, a pattern of results was found that deviated somewhat from that for the correlations; the interaction between target patterns during test and during practice was significant, $F(1, 40) = 5.1, p < .05$. With the harmonic test pattern, performance was better after harmonic practice (222 vs. 235), but it was worse with the nonharmonic test pattern (262 vs. 253). This kind of interaction indicates a difficulty in shifting to a new relative timing. Two aspects of this interaction, however, are noteworthy. First, it was restricted to groups practicing the pattern of 4-s duration and was not found in groups practicing the 3-s pattern, the three-way interaction between target patterns during practice and during test and duration of practice pattern being significant, $F(1, 40) = 5.1, p < .05$. Second, the interaction did not develop over the course of practice, but rather was present already in the very first session without any previous practice. Thus it cannot really be attributed to different amounts of transfer and is more likely a chance result. Moreover, as follows from the findings on the correlations, even if it indicated a difference in transfer, this would not be due to the greater or lesser accuracy of the relative timing.

The results obtained in test trials replicated those of the first experiment: There was no evidence for a particular difficulty in reproducing the harmonic target pattern after practice on the nonharmonic one. (There may have been a weak short-term persistence of relative timing, however, indicated by the spectral analysis of the first experiment and also by the spectral analysis of the second experiment, which was not reported.) In addition, there was also no evidence for a particular difficulty in reproducing the nonharmonic pattern after practice on the harmonic one. Thus, the hypothesis of asymmetric transfer between these two patterns of relative timing cannot be substantiated. Rather, relative timing was changed quickly after short, as well as extended, practice.

### General Discussion

The conclusions that can be drawn from the present results are mainly negative, but some more positive suggestions are possible. The negative conclusion is that relative timing did not constitute a "boundary for transfer," in the sense that transfer to patterns with the same relative timing as during practice is essentially perfect, whereas transfer to patterns with a different relative timing is essentially lacking or at least much smaller. The concept of the generalized motor program with invariant relative timing makes this prediction for any two motor patterns that differ with respect to relative timing.

Two arguments can be raised against this conclusion. First, the negative findings of the present experiments may have occurred because the two patterns of relative timing were too similar to each other to produce observable differences in transfer. If relative timing is changed only a little in test trials as compared with practice trials, transfer performance would be good even if the relative timing established during practice had been maintained. For example, at the end of nonharmonic practice, reproductions of the nonharmonic target pattern correlated to .65–.70 with the harmonic target pattern.

This was essentially the size of the correlations in test trials between the harmonic target pattern and its reproductions. In principle, this correlation would have been obtained if subjects had just continued to do what they had done during practice. However, the correlations with the target pattern not presented for reproduction, as well as the spectral analysis, clearly showed that the relative timing established during practice was not maintained, but rather was changed quickly with a small amount of subsequent practice. Also, the two target patterns used in these experiments were clearly different, and subjects often said that the reproductions of them had a distinctly different feel. For these reasons, the failure to find differential transfer depending on maintained versus changed relative timing should probably not be attributed to this kind of methodological problem.

The second argument is a familiar one against any conclusion that is based on nonsignificant results. The expected differences may have been present, but they may have escaped the power of the statistical tests. However, the present negative results are relatively strong. They have been replicated with a reasonably large number of subjects and with reasonable statistical power. For example, a difference between correlations of only .08 was significant here. Moreover, in both experiments the means did not indicate a difference in transfer that just failed to reach significance. Rather, at best, they tended to indicate a short-term persistence of the relative timing that was practiced. Furthermore, there seems to be no study with results contrary to the present ones; in fact, there are data which support the present conclusion that a change in relative timing is accomplished easily (Langley & Zelaznik, 1984). The consistency of results argues against the hypothesis that our negative findings are a product of low statistical power. Rather, the data are consistent with the view that a change in relative timing does not produce a "breakdown" of performance, or even reduced transfer, as compared with a change in duration only.

If this conclusion is accepted, it constitutes evidence against the notion that relative timing is one of the invariant charac-

### Table 2

**Correlations of Reproductions With the Target Presented (R) and the Target Not Presented (R') in Test Blocks**

<table>
<thead>
<tr>
<th>Measure and session</th>
<th>Harmonic test</th>
<th>Nonharmonic test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HP</td>
<td>NHP</td>
</tr>
<tr>
<td>R</td>
<td>.46</td>
<td>.45</td>
</tr>
<tr>
<td>1</td>
<td>.64</td>
<td>.64</td>
</tr>
<tr>
<td>2</td>
<td>.72</td>
<td>.70</td>
</tr>
<tr>
<td>4</td>
<td>.23</td>
<td>.21</td>
</tr>
<tr>
<td>R'</td>
<td>.42</td>
<td>.43</td>
</tr>
<tr>
<td>1</td>
<td>.49</td>
<td>.58</td>
</tr>
</tbody>
</table>

Note. HP = harmonic practice; NHP = nonharmonic practice. When the harmonic pattern was used in test blocks (harmonic test), R was the correlation with the harmonic target pattern, and R' was the correlation with the nonharmonic target pattern; when the nonharmonic pattern was used in test blocks (nonharmonic test), R was the correlation with the nonharmonic target pattern, and R' was the correlation with the harmonic pattern.
characteristics of a generalized motor program. The expectation that transfer to a new movement pattern is high as long as only a parameter change is required, but is considerably lower as soon as the established program can no longer be used, is an integral component of the concept (e.g., Schmidt, 1982, p. 508). Alternatively, one interpretation of the frequently observed invariant relative timing is that it is a strategic phenomenon rather than a mandatory one. In this view, relative timing would not be imposed by a generalized motor program capable of generating only one particular temporal pattern. Rather, invariant relative timing could be due to other strategic factors having to do with patterns of timing that are in some way preferred as compared with others.

Suppose that motor programs are parameterized in a more complex way than has been considered previously, so that (contrary to the earlier views of this invariance) changes in relative timing can be achieved by way of changing certain parameters. Further, assume that spatial and temporal characteristics are not independently controlled. A generalized motor program conceived in this way would no longer be unconstrained with respect to relative timing.

For the particular features of the target patterns used in the present experiments, the preferred temporal characteristics appear to be harmonic force oscillations that are not frequency modulated in a systematic way, even if this was required for exact reproduction of the target pattern. In the particular case where spatial aspects appear to favor force oscillations without a systematic frequency modulation, patterns of relative timing would be easily varied as long as this is possible by way of modulating force amplitudes. Such patterns, it appears, constitute a set of natural temporal patterns as defined above. Other patterns of a less natural variety could, in principle, be possible to the extent that the interdependence between spatial and temporal characteristics could be "stretched."

According to such a view, a generalized motor program would be able to control movements with different relative timings, but with given spatial characteristics the relative timing produced would not be arbitrary. Rather there could be larger or smaller ranges of natural (i.e., harmonic) temporal patterns that could be stretched to some extent to produce (moderately) unnatural patterns. Here, invariant relative timing would be viewed as a strategic phenomenon due mainly to the existence of these ranges of natural temporal patterns.

The implications of a modified concept of a motor program for transfer to patterns of different relative timing are less strict than those of a concept with invariant relative timing. The latter concept implies a breakdown of performance subsequent to any change in relative timing—a kind of "boundary condition" for transfer to new motor patterns. Thus, although in the present experiments only one such change was studied (another change was used by Langley & Zelaznik, 1984), this is—by strict criteria—relatively strong grounds for rejecting the earlier program concept. The modified concept of a generalized motor program, in contrast, leads one to expect essentially perfect transfer to a new relative timing as long as this belongs to the range of the more natural temporal patterns; this was probably the case in the present experiments—not actually for the nonharmonic target pattern, but for the subjects' reproductions of it. However, one would also expect reduced transfer to a new relative timing if this does not belong to the range of natural patterns. In addition, asymmetric transfer would be expected between more and less natural patterns, provided that the subjects actually produce the less natural patterns.

References


Appendix A

Target Patterns

The position-time curve of the harmonic target pattern is given by the following equation:

\[ h(t) = K \cdot \int_0^\alpha A(\beta) \sin(\beta \, d\beta) \, d\beta, \quad \alpha = t/T - 16 \pi, \]

\[ 0 < t < T. \quad (A1) \]

with \( A(\beta) = \)

\[ a_i, \quad \text{for } 0 < \beta \leq \pi \]

\[ \vdots \]

\[ a_i, \quad \text{for } (i - 1) \pi < \beta \leq i\pi \]

\[ \vdots \]

\[ a_{16}, \quad \text{for } 15\pi < \beta \leq 16\pi, \]

where \( T \) is total duration of the movement, and \( K \) is a scaling factor set to achieve a certain maximal amplitude. The values of \( a_i \) were 20, 25, 10, 35, 25, 5, 35, 45, 70, 65, 30, 25, 5, 10, 20, and 5.

The position-time curve of the nonharmonic target pattern, \( g(t) \), was derived from \( h(t) \), by way of the following transformation:

\[ g(t) = \sin(\omega(t/T) + \varphi) \, t, \quad 0 < t < T, \quad (A2) \]

with \( s = 0.6, \omega = 2\pi, \varphi = 0.5\pi \). Note that this transformation left the total duration unchanged, because the integral is zero for \( i = T \).

Appendix B

Definition of Start and End of a Movement

A tolerance range corresponding to ±1 mm (approximately ±0.65° at the elbow joint) was defined around the start position. When the range was exceeded for the first time, this was taken as the start of the movement. Then during the movement, whenever the range was exceeded, it was defined again around the current position. The end of the movement was detected on-line when the tolerance range had not been exceeded for 1 s. The preliminary end was defined by the time at which the final tolerance range had been defined. Redefinition of the end (corresponding to the definition of the start) was done thereafter as follows: The average position in the time period 200–800 ms after the preliminary end was computed. Moving backward, the end was redefined by the first position that lay outside the tolerance range around the final position.

Before any comparisons between reproductions and target patterns were made, the latter were truncated at both ends in the same way. These truncated target patterns correspond to perfect reproductions as they would have been recorded. Truncation affects the harmonic pattern more strongly than the nonharmonic one because of the difference in "steepness" at the beginning and end. Thus the 3,000-ms pattern was reduced to 2,836 and 2,898 ms for the harmonic and nonharmonic pattern, respectively; and the 4,000-ms pattern was reduced to 3,782 and 3,862 ms.