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Structural constraints on bimanual movements

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Summary. A theoretical framework is outlined, according to which structural constraints on bimanual movements can at least in part be understood as coupling between parameters of generalized motor programs. This framework provides a conceptual link between reaction-time data from experiments with bimanual responses, successive unimanual responses, and choice between left-hand and right-hand responses on the one hand and performance data obtained with concurrently performed continuous movements or sequences of discrete responses on the other. On the basis of data obtained with different methods for the study of intermanual interactions, a distinction is drawn between steady-state and transient constraints, and the hypothesis that the tendency to coactivate homologous muscles originates from a transient coupling of program parameters is applied to a variety of observations on performance in different tasks. Finally, the notion of transient constraints is applied to other types of intermanual interdependencies and to interpersonal coordination; the possible emergence of transient constraints from steady-state constraints through progressive development of inhibitory pathways in childhood is discussed, as is the potential biological significance of transient constraints.

Introduction

Humans are able to activate selectively a single motor unit (e.g., Basmajian, 1978). At the other extreme, muscular activation can be quite unselective, as in a stubborn infant who kicks her feet, tosses around her arms, twists her trunk, throws her head, and contorts her face (own unpublished observations). In between these extremes one can find the range of normal motor activities. Most actions require that muscle activity at various joints is coordinated. Thus the problem of coordination figures highly in motor control.

Coordinated movements in general have to satisfy several constraints. The most important and most obvious constraints are imposed by the task. Although bathing a baby and washing dishes are similar in some way, they require different types of coordination of the two hands. The transformation of task requirements into coordinated motor activity is the first problem of coordination (cf. Saltzman, 1986; Saltzman & Kelso, 1987). The second problem is that of motor equivalence. Quite frequently the task constraints do not specify a unique motor pattern. Uniqueness is often thought to arise because additional constraints are added that are intrinsic to the performer (e.g., Cruse, 1986; Hogan, 1984; Nelson, 1983; Uno, Kawato, & Suzuki, 1989).

The first two problems are not specific for multijoint movements, but in principle they do also exist in uniarticular movements. However, there is a third problem that is unique for coordinated activity: the problem of structural constraints. The main characteristic of these constraints, which makes their presence obvious, is that they oppose the task constraints and impede performance. For example, it is almost impossible to draw a circle and a rectangle simultaneously or, according to Peters (1977, Exp. 3), to recite a nursery rhyme while tapping a 1–2–123 rhythm. In this paper I shall describe a conceptual framework for the analysis of structural constraints and, within the framework, draw a distinction between two types called *steady-state* and *transient* constraints.

A conceptual framework

The field of motor control and learning is currently characterized by a lack of consensus about a theoretical framework that serves to guide the design and interpretation of experiments. Sometimes the situation is described by a dichotomy between "motor" and "action perspectives"

Part of the work reported in this paper was done while I enjoyed the hospitality on the NIAS, Wassenaar (NL)

(Meijer & Roth, 1988) or between an information-processing and an ecological framework (e.g., von Hofsten, 1987). Sometimes one may even get the feeling of living in a period of scientific revolution as described by Kuhn (1970) and detailed for the field of motor behavior by Abernethy and Sparrow (1992). However, the situation can be conceived differently as a kind of competition between different groups or schools that span a much greater variety of thought than simple dichotomies suggest. And the existence of diverse approaches seems to be a natural consequence of the kind of system that is studied.

Complex systems and simple models

The neuromotor system is a complex system, and it is a rather trivial fact that complex systems such as computers can be described in different ways. There seems to be some consensus on how to describe the elementary units such as transistors or neurons. However, the understanding of these units falls short of understanding the system. Knowing about transistors is of little help in programming a computer, and knowing about synaptic changes or other memory-related processes on the neuronal level does not enable one to understand the disortions in memory of connected prose. Thus it is obvious, and at least for computers it is generally accepted, that more abstract descriptions are needed.

Attempts to understand the functions of the central nervous system have a long history of relying on the use of analogies (cf. Burns, 1968). Examples are hydraulic machines, switchboards, servomechanisms, communication channels, and computers. In all these instances, of course, the material substrate of the analogous devices differs from that of the nervous system. However, the function of these various devices is taken to be similar in some way to some function of the nervous system. Some characteristics of the unknown complex system are captured by the known simple models or analogies, while others, of course, are not.

In the second half of this century a new set of analogies and models has entered the scene with the rise of information theory, cybernetics, and systems theory. The new analogies differ from previous mechanical or electronic ones in that they are abstract by their very nature and independent of a particular material substrate. Apparently the tools offered by the theory of linear and nonlinear systems, by neural networks or expert system shells, are more powerful in mimicking certain aspects of human behaviour than the older analogies were. Nevertheless, the models constructed by means of such tools are not radically different from the older analogies: they are still analogies that in some ways are analogous to functions of the central nervous system, but not in other ways. It is probably trivial that this is true for every model of a complex system, except for a model that is identical with the system in all functional characteristics one can think of – and such a model would be almost useless because it would be as little understood as the real system.

It seems impossible to construct a perfect model of a complex system. Therefore one should expect some divergence of abstractions: the development of a multiplicity of models or analogies that serve to understand different aspects of the central nervous system. Of course, not only should this divergence be expected for models of a certain type that are formulated according to certain conceptual tools like those offered by the theory of linear systems or neural networks, but it will encompass different major conceptual frameworks as well. These may coexist even in the long run; light, for example, is described variously in terms of quanta, waves, or rays, and each type of conceptualization serves a certain purpose best.

Usefulness for a certain purpose seems to be the main criterion that is suited to evaluate different abstractions from an existing complex system and the conceptual frameworks that are involved; the criterion of usefulness can be seen to imply that of simplicity and that of scope. Turning from the general remarks to the specific topic of this paper, the purpose of the conceptual framework described below is to shed some light on the nature of structural constraints on coordination as they can be evidenced from kinematic characteristics of simultaneous movements as well as from different types of reaction-time data. The central concept is that of a generalized motor program. It may not be the most fashionable one currently, but it serves to link kinematic and reaction-time studies.

Structural constraints and generalized motor programs

Schmidt, Zelaznik, Hawkins, Frank, and Quinn (1979) drew a distinction between common and specific parameters of a generalized motor program. Studying bimanual aiming movements, they found a high correlation between the movement times of the two hands computed across a series of trials; thus they postulated that duration is determined by a common parameter. In contrast, the correlation between amplitudes was negligible, giving rise to the hypothesis that these are determined by specific parameters that vary independently for the two hands. These results are nicely supplemented by those of Kelso, Southard, and Goodman (1979), who found that durations of different aiming movements performed by the two hands simultaneously became quite similar, while the amplitudes differed only little from those in single-movement conditions (cf. Corcos, 1984; Fowler, Duck, Mosher, & Mathieson, 1991; Marteniuk & Mackenzie, 1980).

Generalized motor-program theory implies that movements are programmed before they are initiated. Thus it is quite natural to extend the hypothesis of Schmidt et al. (1979) to reaction-time studies. Heuer (1986a) observed a longer reaction time when subjects had to choose rapidly between left-hand and right-hand responses of different durations as compared with a control condition in which durations were the same. This finding suggests that preprogramming of different durations is impossible, which would be expected if duration were determined by a common parameter. In contrast, when the choice was between movements of different amplitude, the reaction time was not significantly longer than in the control condition with the same amplitudes, which was consistent with the hy-

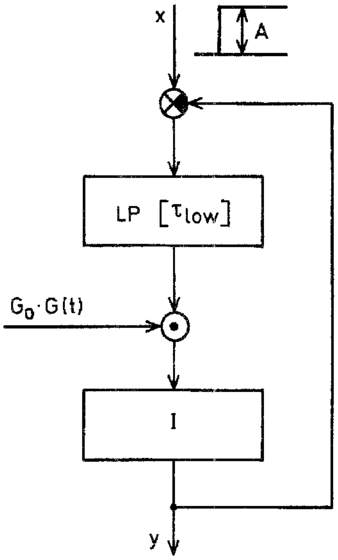

Fig. 1. A motor-program represented as a generative structure (LP: low-pass filter, I: integrator)

pothesis that amplitude is determined by specific parameters.

The link between simultaneous-movement studies and reaction-time studies is an important feature of generalized motor-program theory, not shared by other theoretical approaches to structural constraints on coordination (cf. Heuer, in press). Its prerequisite is the distinction between the programming and the execution of a movement. Structural constraints on coordination are attributed to program characteristics and should thus be observable during programming – as is indicated by their effects on reaction times – as well as during execution, as is evidenced in simultaneous-movement studies. In fact there seems to be considerable convergence of conclusions derived from both types of experiment (Heuer, 1990 a).

The strength of generalized motor-program theory in linking simultaneous-movement and reaction-time studies is accompanied by a certain rigidity and excessive simplicity of the distinction between common and specific parameters. The simple all-or-none distinction is unsuited to capture the graded and complex effects of structural constraints (cf. Heuer, in press). However, generalized motor-program theory offers more, and hitherto unexplored, possibilities to account for structural constraints. Toward that end it is useful to reconsider a fairly narrow conception of motor programs that seems to be quite widespread – explicitly or implicitly.

The narrow perspective on generalized motor programs conceives of them as a set of stored commands or as a data structure read out during the execution of a movement. From this perspective it is quite natural to postulate the existence of three parameters (Schmidt, 1980, 1985): total duration, as determined by the rate of reading (cf. Rosenbaum, 1985); overall amplitude, as determined by a gain factor; and muscle group, as determined by the selected output channel. Variation of these parameters leaves the relative timing and the relative amplitudes within the pattern unaffected.

Although the description of generalized motor programs as data structures may be appropriate for some tasks, such as sequences of discrete movements, it is certainly not appropriate for others. In particular, there is no reason to suppose that invariant relative timing is a mandatory characteristic of a generalized motor program (Heuer, 1991 a). Moreover, the evidence that gave rise to the motor-program concept (for reviews see Heuer, 1990 b; Rosenbaum, 1985; Summers, 1989) does not enforce the particular conception as a data structure. There is nothing against replacing the stored data by a structure that generates such data (cf. Cruse, Dean, Heuer, & Schmidt, 1990). As an example, consider the structure shown in Figure 1, which corresponds to two lumped antagonistic channels of Bullock and Grossberg's (1988, 1991 a) VITE model (Bullock & Grossberg, 1991 b; Heuer, 1991 b).

The structure of Figure 1 produces an output that corresponds to the position-time curve of an aimed movement. It consists of a low-pass filter with a variable gain, τ_{low}, an integrator, an amplification (or GO signal) of the form $G_0 \cdot G(t)$, and a feedback branch. The input is a step function with amplitude A. Thus, the structure generates a certain position-time curve with characteristics determined by the structure itself and its parameters τ_{low}, G_0, and A. It is a motor program, just as the wired integrators and other components of an analogue computer are a program, although some people may find it hard to see the VITE model in this way. Programming – from this broader perspective on motor programs – consists of, first, the assemblage of the structure and, second, the adjustment of its parameters.

The idea that the generative structure of Figure 1 or any other generative structure is a description of a motor program has several implications (Heuer, 1991 a). For example, when a motor program specifies the kinematics of an end effector, its output has to be channeled through inverse-kinematics and inverse-dynamics networks to produce an adequate movement (e.g., Kalveram, 1991 a, b). More important for the present purpose, however, is that different generative structures will generally be parameterized in different ways and that there is not necessarily a simple relation between the program parameters and the surface characteristics of the resulting movement.

The potentially complex relation between the surface characteristics of a movement and the program parameters complicates the inferences that can be drawn from behavioral data. Although occasionally there may be a direct mapping between an observable characteristic such as the amplitude of a movement and a program parameter (like A in Figure 1), it will be more typical that a surface characteristic has to be expressed in terms of several parameters. (Appendix A illustrates such a reparameterization of the system of Figure 1, which was used for simulations described below). Therefore interlimb interactions on the level of parameters can produce interdependencies on the level of kinematic characteristics that are quite complex and that will not allow a straightforward mapping of observables on parameters. This is less than satisfactory, because it is likely to complicate the description of structural constraints in terms of surface variables. However, it does not invalidate this type of description.

When generalized motor programs are conceived of as generative structures, rather than as data structures, structural constraints can be modeled in various ways. First, signals can be coupled: these can be output signals of the generative structures, signals within the structures, or signals within the lower networks that compute the inverse kinematics and inverse dynamics. Common to these varieties of coupling is that they should show up only during movement execution, but not during preparation or programming. Second, there may be constraints on assembling different generative structures for the two hands or for other pairs of limbs. Finally, the parameters of the generative structures can be coupled so that they cannot be set independently for the two limbs. The latter two kinds of constraint should produce equivalent effects in simultaneous-movement and reaction-time studies, and these are what I shall explore in more detail. In particular, parametric coupling seems to exist in two variants, the one related to the steady-state values of parameters and the other to the transient states of parameter change. On the behavioral level, these variants give rise to steady-state and transient constraints on bimanual movements.

Steady-state constraints

Many people find certain bimanual tasks hard or impossible to perform: drawing a circle and a rectangle simultaneously or clapping one's forehead with the one hand while rubbing one's stomach with the other hand are popular examples. Less popular is tapping simultaneously with the index finger of the one hand and performing lateral to-and-fro movements with the other index finger. These movements have been studied in a series of choice-reaction time experiments (see Heuer, 1990a, for a review). When different movements were assigned to the two hands, reaction time was consistently longer than in control conditions with identical movements. In addition to the longer mean reaction time, the intraindividual variability was increased and the proportion of responses with the incorrect hand reduced. These results were obtained although the subjects in the experiments knew about the movements that were assigned to both hands well in advance of the response signal. The data thus suggest that the different responses cannot be programmed simultaneously, no matter how much time is available. Casual observations also suggest that longer preparation time is not of much help in performing these and other movements of the same kind concurrently. Thus it is a steady-state constraint on programming what does not vanish with the passage of time.

For the choice situation steady-state constraints have been modeled in terms of an accumulator model (Heuer, 1987). More specifically, a two-choice model proposed by Vickers (1979) was modified by the addition of cross-accumulation: each value added to the one accumulator is subtracted from the other one after multiplication with a coupling constant c ($0 \leq c \leq 1$). This addition generates a continuous transition between an accumulator model ($c = 0$) and a random-walk model ($c = 1$). A larger coupling constant produces a longer mean RT, a larger RT variability, and a higher choice accuracy, corresponding to the results of the choice experiments.

There can be little doubt that steady-state constraints do exist, but it is not altogether clear which movement characteristics are affected by them. The finger movements in the initial choice experiments (Heuer, 1982a, b) differed in spatial, as well as in temporal, characteristics. Later experiments showed that the effect of the relation between the responses assigned to the two hands remained the same when only tapping movements were used that differed in total duration or when tapping and lateral movements were used that had the same total duration (Heuer, 1984). It is conspicuous that not only tapping and lateral movements differed in their temporal pattern (e.g., the relative timing of segments before and after reversal of direction), but also tapping movements of different durations (longer durations are mainly achieved by the introduction of a hold component at the directional reversal). Thus it is possible that differences in the temporal structure are critical. This view finds support in observations on the production of polyrhythms. These suggest that polyrhythms are produced by an integrated control structure that governs the taps of both hands (see Heuer, in press, for review).

The statement that steady-state constraints on bimanual movements are related to temporal structure is not really satisfactory for a variety of reasons. First, it neglects a potentially important difference between the production of polyrhythms on the one hand and the concurrent production of circles and rectangles or vertical and lateral finger movements on the other. In the former task a particular temporal structure is defined as a goal to be achieved, and timing appears as the main performance variable that is likely to be explicitly controlled; in the latter kind of task, however, there are no explicit timing requirements, and temporal structure is more likely to be an emergent property related to the required spatial characteristics (cf. Viviani, 1986). Thus it is not very plausible that steady-state constraints should affect temporal structure in both types of task in the same way. Second, temporal structures are ill defined operationally – in particular for continuous movements. And finally, there is a lack of simultaneous-movement studies in which different spatiotemporal patterns have to be produced. Such tasks are either impossible to perform, or else subjects tend to cope with the task demands in a highly variable manner, so that it becomes hard to obtain any meaningful results (the data of Swinnen, Walter, & Shapiro, 1988, illustrate such variability).

Transient constraints

While steady-state constraints can be seen to originate from common parameters of a generalized motor program or from one's inability to set up different programs concurrently, transient constraints are different. It is likely that they exist for a variety of movement characteristics. However, I shall discuss them only with respect to homologous coupling (the tendency to coactivate the homologous muscle groups of the two sides of the body). This structural constraint on bimanual movements seems to be the one that has been studied most extensively.

The most conspicuous evidence for homologous coupling can be seen in associated movements of children

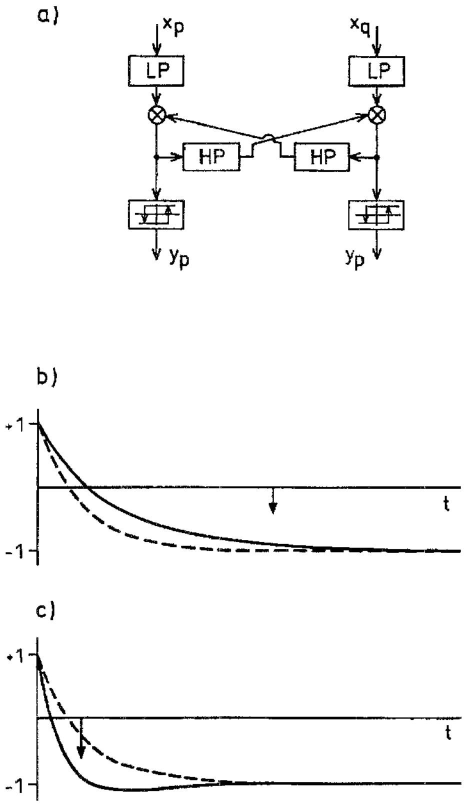

Fig. 2. **a** A model for transient constraints during motor programming (LP: low-pass filter, HP: high-pass filter); **b** time course of the state of programming unaffected by transient coupling (dashed line) and under inhibiting transient influences from the other channel (continuous line); **c** same as **b**, but the continuous line shows the facilitatory influence of the other channel. Time constants of the low-pass filters were 0.05 s, and those of the high-pass filters 0.07 s. Gains of high-pass filters were 0.5

below the age of 7 or 8 years (Wolff, Gunnoe, & Cohen, 1983) and of adults with lesions of the central nervous system. Associated movements accompany voluntary movements without serving any apparent purpose. For certain voluntary movements they are typical, and frequently they are mirror movements of the contralateral limb. Although in healthy adults mirror movements can no longer be observed, evidence for homologous coupling can be found in other tasks that are not strictly unilateral. According to this evidence, which will be presented below, homologous coupling is transient. I shall first give a more formal description of transient homologous coupling during motor programming and thereafter review the evidence from reaction-time studies and simultaneous-movement studies.

Formal representation of transient constraints

Figure 2 presents a model that mimics transient constraints during programming. It will be used for illustrations as well as for simulations. Basically, two identical channels are shown with inputs x_p, x_q and outputs y_p, y_q. Each channel consists of a low-pass filter and a threshold element with hysteresis; the channels are cross-coupled via high-pass filters. The output of each channel represents the state of programming a certain movement characteristic (or of setting a certain parameter of a generative structure).

The low-pass filters serve to mimic the time-course of programming. The dashed lines in Figure 2b and c show the output when the input changes stepwise from +1 to −1 (and the cross-coupling has gain zero). The general characteristics of this curve (which is the same in Figure 2b and c) are consistent with the results on the time-course of programming reported by Ghez, Hening, and Favilla (1990) as well as with the time-course of response strength as determined by applications of variable criterion theory (e.g., Grice, Nullmeyer, & Spiker, 1977). The most important feature of the scheme, of course, is the cross-coupling. The continuous line in Figure 2b shows the time-course as affected by cross-coupling when the input signal to the other channel steps from −1 to +1, and in Figure 2c the facilitating effect of the other channel is shown when its input steps from +1 to −1 as well. In both cases the rate of programming is reduced or speeded up, but the final steady state of programming is not affected.

The curves in Figure 2b and c could correspond to the gradual shift of the programmed amplitude of a movement from a default setting to a target setting, as has been observed by Ghez et al. (1990). However, the selection of a particular muscle group to be activated or the specification of flexion, rather than extension, of a joint refers to a categorical variable which, in the scheme of Figure 2a, is binary. The target value is given by the input (±1), and the continuous output is transformed again to ±1 by a threshold element. In Figure 2b and c the arrows mark the time at which an absolute threshold of 0.9 is reached and at which the new output $y = -1$ would indicate that programming is sufficiently advanced so that the new muscle group is actually specified. The binary input and output variables are thus not essential ingredients of the scheme, but are needed only to deal with categorical, specifically binary, movement characteristics rather than with continuous ones.

A step function as input to the programming level may be too much of a simplification, at least for rapid responses to external signals, as in reaction-time experiments. It would be appropriate only for a stage model, but not for a continuous-flow model. (These types of model have been discussed in detail by Miller, 1988, and Sanders, 1990.) For the latter case the input could be replaced by a ramp function or by a negatively accelerated function. This would reduce the slopes of the curves in Figure 2b and c, but would not change the essential characteristics of transient constraints – that is, the effects on the rate of programming, but not the final steady states.

Reaction-time studies

The hypothesis of transient homologous coupling has been derived from reaction-time experiments (Heuer, 1986b). The evidence from this type of experiment will therefore be reviewed first. Basically, the hypothesis implies different effects of the relation between left-hand and right-hand responses, depending on whether programming occurs before or after the response signal. With advance specification of muscle groups (e.g., for certain fingers or movement directions), programming should be in a steady state at the time of the response signal and reaction times should not depend on whether homologous or nonhomologous muscle groups of the two sides of the body have been programmed; without advance specification, however, the transient coupling during programming should affect reaction time. I shall examine this basic prediction for three different situations: simultaneous responses of the two hands or arms, successive responses, and choice responses.

As to simultaneous responses, Rabbit, Vyas, and Fearnley (1975, Exp. 3) studied reaction times for various finger chords in a sequential task. When the chords involved one finger of each hand, they found shorter reaction times for homologous than for nonhomologous fingers. In this experiment it was the response signal that informed the subjects about which finger of each hand to use so that programming necessarily occurred during the reaction-time interval. I am not aware of an equivalent experiment in which subjects were informed well in advance of the response signal about which finger of each hand to use.

However, relevant data have been reported for simultaneous aiming movements of small amplitude (4 in.), directed to targets located to the left, to the right, distal, or proximal from the start position; all 16 two-handed combinations of these movements were studied by Peterson (1965). The mean reaction times for movements in the same and different directions were 225 and 225 ms, respectively (computed from the means for the various conditions given by Peterson, 1965, Table 1). Contrasted with these findings are those of Taniguchi, Nakamura, and Oshima (1977), who reported faster simple reaction times for symmetric elbow movements than for asymmetric ones. This result, however, may possibly have been caused by a confounding factor: gross movements such as elbow flexions and extensions are preceded by postural responses, and the delay between initiation of postural and voluntary responses is longer with unilateral arm movements than with bilaterally symmetric ones (Zattara & Bouisset, 1986); a similar difference in the time needed for preceding postural responses may have caused the reaction-time difference in the comparison of symmetric and asymmetric arm movements in the experiment of Taniguchi et al. (1977).

Predictions for successive responses can be derived from the scheme of Figure 2 when a delay between the input signals is introduced. As long as programming occurs within the reaction-time interval and the transient phases of programming have temporal overlap, reaction times of both successive responses should be affected by whether they involve homologous or nonhomologous muscle groups.

In an experiment in which the first response required a choice between the index and the middle finger of the left hand, and the second response a choice between the index and the middle finger of the right hand, Wakelin (1976) actually observed faster first and second reaction times when homologous fingers of the two hands were used. From the scheme of Figure 2 additional predictions can be derived for variable delays between the input signals. Unfortunately the data given by Wakelin (1976) do not allow recovery of the effect of the delay between response signals on the differences between homologous and nonhomologous finger sequences. When subjects were informed about which finger of each hand to use well in advance of the two successive response signals, no difference between response sequences performed by homologous or nonhomologous fingers could be found (Heuer, 1985).

Turning to the choice between the two hands, the initial evidence gave no indication of homologous coupling. Across a series of experiments no difference was found between conditions in which homologous or nonhomologous fingers were assigned to the two hands (Heuer, 1982a, b, c; Rosenbaum & Kornblum, 1982). In all these experiments finger assignments were constant for blocks of trials, so that advance specification was possible. Only when advance specification was at least partly prevented, when subjects were given the relevant information only briefly before the response signal or when catch trials that should discourage preprogramming were introduced, did reaction time become longer in nonhomologous conditions than in homologous ones (Heuer, 1986b).

Taken together, the notion of transient homologous coupling finds considerable support in the results of reaction-time experiments, although several of the experiments mentioned above were not designed for the purpose of examining differences between conditions involving homologous and nonhomologous muscle groups. I shall next examine the predictions of the hypothesis for some simultaneous-movement tasks.

Simultaneous-movement studies

Several results obtained in simultaneous-movement studies suggest that performance is constrained by homologous coupling – more specifically, by transient homologous coupling. However, the relation between the kind of coupling illustrated in Figure 2 and the observed phenomena is not always as straightforward as in the reaction-time studies. So I shall explore three tasks in greater depth and compare the experimental findings with the results from simulations based on an implementation of the scheme of Figure 2. The three tasks are sequential bimanual tapping, bimanual oscillation, and bimanual out-of-phase tapping.

Sequential tapping. MacKay and Soderberg (1971) introduced a task in which subjects had to tap sequentially with pairs of fingers, one on the left hand and one on the right hand each time, using the fingers in sequence from left to right or right to left. If the task is performed correctly, the fingers of each pair are never homologous. However, MacKay and Soderberg found that the pairing of homologous fingers, rather than of nonhomologous ones, is a frequent error when the task is performed as rapidly as possible.

Figure 3 presents some pilot recordings from this task.[1] In Figure 3a tapping was performed in the symmetric,

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[1] The data were recorded and analyzed by Jörg Sangals, Marburg.

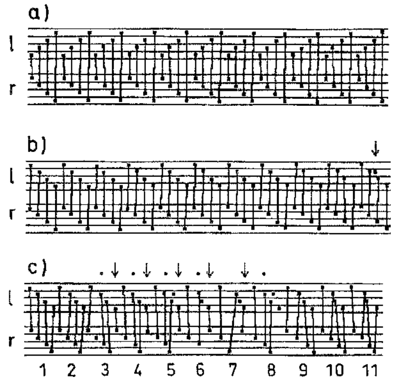

Fig. 3 a–c. Pilot recordings from sequential bimanual tapping (l: left hand, r: right hand) in the symmetric mode **a**, asymmetric mode **b** and asymmetric mode at a higher speed **c**. In **b** the *arrow* marks a homologous intrusion, in **c** *arrows* and *dots* mark homologous pairs of taps of index and ring fingers, respectively

rather than in the asymmetric, mode, beginning with the two index fingers, followed by the two middle fingers, etc. The figure presents a recording of 100 taps in total, neglecting the first run of 4 bimanual taps and the taps after the last complete run. The mean intertap interval was 186 ms for each hand, and the standard deviation of the time interval between paired taps of the two hands was 16 ms. Figure 3b shows performance in the asymmetric mode at about the same speed (intertap intervals of 177 ms for right hand and 174 ms for left hand). The arrow marks a single additional tap from the left hand; this was a repetition shortly before the correct tap with the homologous finger of the other hand. The standard deviation of the interval between paired taps was 12 ms.

When speeded up (Fig. 3c), performance becomes irregular (mean intertap intervals were 109 ms for the right and 104 ms for the left hand). It becomes hard to determine which taps of the two hands belong together; the algorithm that generated the connecting lines in the figure was based primarily on temporal adjacency. The first two runs are correct, but with the transition to the third run there is a phase shift: the right hand becomes advanced in relation to the left, which results in simultaneous taps of the two index fingers (arrows) and the two ring fingers (dots). This pattern continues with an additional tap from the left hand in run 5 and two omitted taps from the right hand in runs 6 and 7. With run 9 there is something like a re-start to bring the two sequences into the proper phase again. During the last three runs the right hand taps fairly regularly, while in the left hand the taps of the ring and middle fingers are temporally close together and separated from their neighbors, which has the effect of bringing them into temporal adjacency of the taps of the homologous fingers of the right hand. The standard deviation of the intervals between taps of correct pairs was 29 ms, while for taps of homologous pairs it was only 15 ms.

Figure 3 illustrates the tendency toward the coactivation of the homologous finger. However, it also reveals the difficulties in analyzing the performance in more detail. When the task is simplified by the use of only two fingers of each hand, some more clearcut observations can be made. Tapping the fingers of both hands in nonhomologous pairs is simple, as long as the rate is slow. When the speed is increased, there is no well-defined upper limit for bimanual asymmetric tapping that is lower than the speed limit for symmetric tapping, but the asymmetric mode (nonhomologous fingers being used simultaneously) is switched to the symmetric mode (homologous fingers used simultaneously). Introspection seems to give no clear indication of when the switch occurs; it is only some time thereafter that one notices that it has occurred.

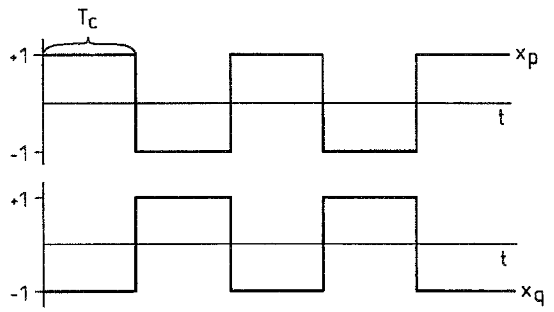

Fig. 4. Functions that could be used as inputs to the structure of Fig. 2a

Supposing that in each intertap interval nonhomologous or homologous fingers have to be specified for the two hands, the hypothesis of transient homologous coupling would predict that the maximal rate should be slower in the asymmetric than in the symmetric mode. But this does not quite correspond to the observations. Instead of reaching an upper speed limit, the asymmetric mode is involuntarily switched to the symmetric one. This switch, however, is consistent with the notion of transient coupling when two additional assumptions about repetitive tapping are made.

To apply the scheme of Figure 2a to bimanual sequential tapping, the values ±1 of the input and output variables of the two channels can be taken to represent the two alternative fingers of each hand. Suppose that the inputs are rectangular functions with period $2T_c$ which are out of phase, as shown in Figure 4. Then, within each half-period T_c, programming of the proper fingers can or cannot reach threshold. When the thresholds are not reached, the input values during that half-period will have no effect on the output. When there is independent variability in the two channels, either in the rates of programming or in the threshold, it may happen that only one channel reaches threshold. In the asymmetric mode this random event will tend to occur at longer periods of the input function, and it will produce a homologous error in that the outputs of the two channels become identical. Random variation was introduced by independent normally (μ, σ) distributed thresholds in the two channels, corresponding to variable criterion theory (e.g., Grice, Nullmeyer, & Spiker, 1977). However, to prevent absolute threshold values above 1, the range between $|\mu|$ and $|\mu| + 3\sigma$ was compressed or expanded to fit into the range between $|\mu|$ and 0.99.

Independent variable thresholds will produce homologous errors, but no switch from the asymmetric to the symmetric mode. The input functions will remain out of phase and will drive the system back into the asymmetric mode. To produce a switch that is not automatically corrected at some later time, the homologous output that oc-

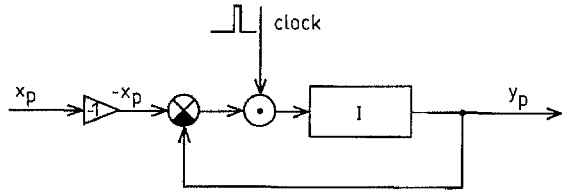

Fig. 5. A structure that generates functions like those in Fig. 4 when y_p is fed back as the input x_p; when the output of a channel of the structure of Fig. 2a is used as input x_p, switches of relative phase for functions generated by two such structures can be produced

curs by chance when only one channel reaches threshold in the time period T_c must affect the input functions. Figure 5 presents a structure that serves this purpose. To distinguish it from the structure shown in Figure 2a, it will be called the *cognitive level* and the latter will be designated as the *programming level.* Basically the cognitive level is a sample-hold element that upon each clock pulse samples the negative value of its input; thus, at each clock pulse its output becomes its negative current input and remains so until the next clock pulse. If the output of this structure is fed back as its input, it will generate a rectangular curve like the one shown in Figure 4; this is not affected by the output of lower levels, and in particular not by whether programming reached threshold within the clock period T_c or not. However, when the output of the programming level is fed back as input to the cognitive level, a homologous state of the outputs of the two channels of the programming level at the time of the clock pulse will switch the relative phase of the rectangular functions generated by the cognitive level.[2]

Figure 6 illustrates the joint operation of the cognitive and programming levels. The marks between the traces for the two channels represent the clock pulses (every 0.15 s), and the rectangular curves the outputs of the programming level. These could be transformed to a sequence of peripheral events if one assumes the existence of a random delay between a change of finger specification and the corresponding key press. The big waves indicate the time-course of the state of programming as affected by transient coupling. The system was started in the asymmetric mode so that the state of programming changed relatively slowly at first. The critical event that causes the switch from the asymmetric to the symmetric mode – the outputs of the programming level are identical at the occurrence of a clock pulse – is clearly visible: the inhibitory effect of transient coupling switches to a facilitatory effect, so that the state of programming changes rapidly. Thus, one of the fundamental observations in repetitive asymmetric movements – the switch to symmetric movements – can be produced by transient homologous coupling when two additional plausible assumptions are made: first, independent random variability in both channels on the programming level, and second, feedback of the output of the programming level to a structure that generates the programming level's input by way of switching between states.

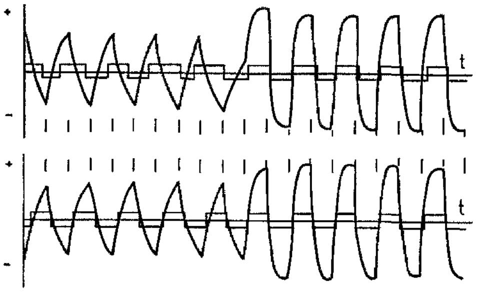

Fig. 6. Joint operation of the cognitive level (Fig. 5) and the programming level (Fig. 2 a). Marks in the middle represent clock pulses, rectangular functions represent outputs of the programming level, the big waves represent the state of programming as affected by transient constraints, first in an inhibitory way and, after a shift of relative phase, in a facilitatory way

Wrist and finger oscillations

The bimanual tapping task that I have discussed so far has never been studied formally. This is different for the bimanual-oscillation task introduced by Cohen (1971). Cohen had his subjects oscillate their hands symmetrically or asymmetrically (in later studies the fingers were used as well). He observed that for asymmetric oscillations the cross-correlation between the position-time curves of the two hands was smaller than for symmetric movements. In addition he found that at frequencies between 2 Hz and 4 Hz subjects sometimes switched involuntarily from the asymmetric to the symmetric mode, but never in the reverse direction. Later it was shown by Kelso (1984) that the switch occurred systematically when the frequency of asymmetric oscillations was increased.

The analysis of performance in the bimanual-oscillation task was based on kinematic variables. Therefore, to explore the role of transient homologous coupling in this task, the cognitive and programming level used so far has had to be supplemented by a structure that transformed the programmed parameters into movement trajectories. So the structure shown in Figure 1 was added to each channel as the *trajectory-formation level.* The amplitude parameter A was set to a fixed value, and its sign was given by the output of the programming level. The function G(t) was set equal to 1, and the parameters τ_{low} and G_o were set to produce a critically damped step response that reached about 80% of its steady-state output within the clock period (see Appendix A). Finally, at a *peripheral level* the output of the trajectory-formation level was channeled through two low-pass filters in series (gains = 1; time constants = 0.02 s; cutoff-frequencies *c.* 8 cycles/s).

Figure 7a presents an example output of the system. The arrow marks the switch from the asymmetric to the symmetric mode. The upper traces show the outputs of the programming levels of both channels p and q. The lower

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[2] The fundamental function of the cognitive level is to provide the input for the programming level. Therefore it has to be modeled differently for different tasks (or intentions of the performer). Using a more anthropomorphic description, for the particular task considered it realizes the intention to switch the current finger at a certain rate, and as information about which is the currently active finger the output of the programming level is used.

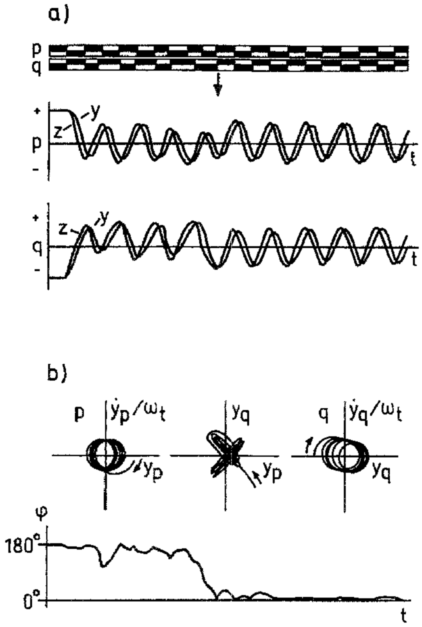

Fig. 7 a, b. Joint operation of the cognitive level (Fig. 5), the programming level (Fig. 2a), the trajectory formation level (Fig. 1), and the peripheral level, **a** upper traces: outputs of the programming level, channels p and q; lower traces: output of the trajectory formation (z) and the peripheral level (y), channels p and q; **b** upper row, center graph: both output signals plotted against each other; left and right graph: phase-plane plots for both output signals; lower graph: time course of relative phase

traces present the outputs of the trajectory-formation levels (z) and the peripheral levels (y). From inspection of the outputs of the two channels it is apparent that variability is higher in the asymmetric mode before the switch than in the symmetric mode thereafter. This impression is corroborated by the results of more formal analyses presented in Figure 7b. The center graph in the upper row shows the outputs of the two channels plotted against each other and compares well with examples from real data reported by Kelso (1984). The left and right graph are the phase-plane plots of the two output signals ($\dot{y}$ was scaled by the inverse angular frequency computed from the clock period T_c). From these phase-plane plots the relative phase was estimated (Appendix B), the time-course of which is shown in the bottom graph. Corresponding data from actual recordings have been reported by Kelso and Schöner (1988), for example, and there seems to be a fairly good correspondence.

To study the effects of homologous coupling in the bimanual-oscillation task in more detail, a simulation was run. Period durations were 1.0, 0.8, 0.6, 0.4, and 0.2 s. For each period the system was started 10 times in the asymmetric and 10 times in the symmetric mode, and each run (trial) lasted for 15 periods. Parameters of the normal threshold distribution were $\mu = 0.6$, $\sigma = 0.075$ (the actual distribution was a transformation of the normal distribution as described above). The qualitative features of the results of the simulation were rather insensitive to particular parameter settings.

Table 1 presents the mean period durations and peak-to-peak amplitudes as well as the mean intratrial variabilities of these measures. For the three longest periods no switches from asymmetric to symmetric oscillations were observed. When the period decreased, its variability tended to decrease, as did the mean amplitude, while the amplitude variability increased. For the two fastest periods the asymmetric mode was maintained in only 1 out of 10 trials at each period duration. With the period duration of 0.4 s there were only 7 trials in which there were at least two periods before the switch so that means and variabilities could be computed; the procedure used to determine the occurrence of a switch is described in Appendix C. When the target period was set to 0.2 s, the system was unable to follow it in the asymmetric mode. It therefore operated with only half the target frequency, and in one trial this was continued through all 15 cycles; in 6 trials as well-defined switch to the symmetric mode occurred, while three other trials produced ambiguous data and were omitted in the further analysis.

Figure 8a presents the mean cross-correlation between the outputs of the two channels. Corresponding to Cohen's (1971) results, cross-correlations were smaller in the asymmetric than in the symmetric mode. For the two shortest periods the data are shown separately for intervals before and after the switch; again the differences between symmetric and asymmetric oscillations can be seen. When the target period was 0.2 s, the cross-correlation before the switch was quite high, caused by the irregular functioning of the model, which produced only half the target frequency with very large amplitudes (cf. Table 1). The

Table 1. Means (standard deviations) of periods and peak-to-peak amplitudes

Target period	Symmetric		Asymmetric (before switch)		Asymmetric (after switch)	
	Mean (*SD*) of period	Mean (*SD*) of amplitude	Mean (*SD*) of period	Mean (*SD*) of amplitude	Mean (*SD*) of period	Mean (*SD*) of amplitude
1.0	1.00 (0.017)	64 (0.64)	1.00 (0.043)	63 (3.36)		
0.8	0.80 (0.017)	63 (0.74)	0.80 (0.044)	62 (4.32)		
0.6	0.60 (0.015)	61 (1.00)	0.60 (0.041)	60 (5.65)		
0.4	0.40 (0.014)	58 (1.36)	0.40[1] (0.033)	56[1] (7.28)	0.40[3] (0.031)	57 (6.77)
0.2	0.20 (0.012)	45 (3.28)	0.39[2] (0.030)	89[2] (3.69)	0.23[4] (0.054)	53 (12.13)

[1] 1 trial without switch, 7 trials before switch

[2] 1 trial without switch, 1 trial before switch

[3] 9 trials

[4] 6 trials

periods are in s, amplitudes in arbitrary units

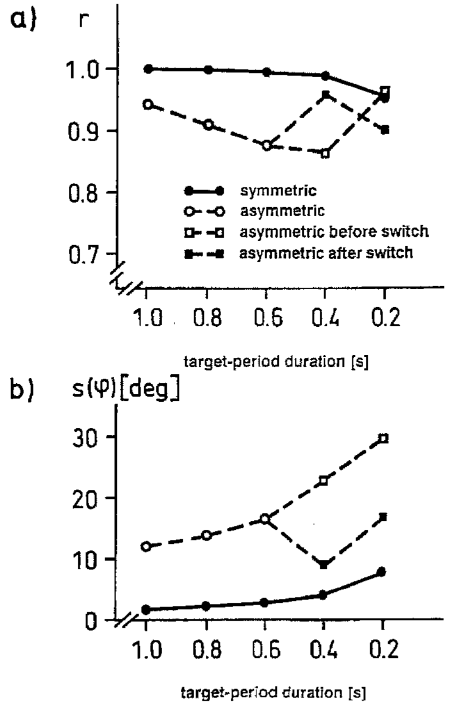

Fig. 8 a, b. Results of simulations with different target-period durations. **a** Cross-correlations between output signals, for short target-periods computed separately before and after the switch; **b** standard deviation of relative phase, for short target-periods computed separately before and after the switch

fact that after the switch cross-correlations were not quite as high as in symmetric trials results from the procedure used to determine the occurrence of a switch (see Appendix C): The interval after a switch tends to include part of the transition period from asymmetric to symmetric movements.

Figure 8 b shows the estimates of relative-phase variability. These correspond to the cross-correlation data. A comparison with published experimental results (e.g., Kelso & Scholz, 1985; Kelso & Schöner, 1988) reveals some apparent discrepancies in that the published data show a clear peak in the region of those frequencies at which transitions occur. This apparent discrepancy, however, is caused mainly by procedural factors. The simulation data are from discrete trials, each of which was started with a particular phase relation. The experimental data were obtained from trials in which the pacing-signal frequency was increased every 4 s by 0.25 Hz, and relative-phase variability was computed across the last 3 s of each frequency plateau. Thus, for those plateaus at which switches occurred, variability is inflated by the mixing of relative phases close to 0° and 180°, while for frequency plateaus after the switch, movements were symmetric from the very start. When the procedure of computing variability across full trial durations – with the combination of asymmetric and symmetric movements – is applied to the simulation data, the apparently dramatic increase in variability at the frequencies at which switches occur can also be seen: variability at the target period of 0.4 s becomes 55.9°, and for higher frequencies the small variabilities for symmetric trials would enter into the plot.

Scholz and Kelso (1989) reported another characteristic of the bimanual-oscillation task, the increase of the relaxation time in the frequency range at which switches tend to occur. Relaxation time is the time needed to return to a stable phase relation after a peripheral perturbation. The effects of such perturbations have not been studied with the present model. Even without a formal study, however, it is obvious that the present model would not produce a phase shift as a result of a perturbation. To produce such an effect, it would be necessary to use more peripheral signals than the output of the programming level as feedback to the cognitive level, or probably a mixture of some signals that indicate the current state at different levels.

Formal models for the phenomena observed in the simultaneous-oscillation task have been proposed before. Haken, Kelso, and Bunz (1985) developed a model that qualitatively accounts for the major phenomena, has a broad synergetic background, and has been generalized to other tasks (Schöner & Kelso, 1988 a, b; Schöner, 1990). However, it seems not to account for reaction-time data. While in this paper I have followed a synthetic approach, beginning with a simple hypothesis to account for reaction-time results, Haken et al. (1985) adopted an analytic approach. They started with a definition of a relation between relative phase and its first derivative with respect to time, and from this they developed expressions for two oscillators and their coupling. Given the different approaches to modeling, it is hard to compare the models directly. One way to do so, however, is to examine the relation between the relative phase and its first derivative.

Haken et al. (1985) defined this relation – with the addition of random noise (Schöner & Kelso, 1988 a) – as

$$(1)\ \dot{\varphi} = -\frac{dV}{d\varphi} + \sqrt{Q}\,\xi_t$$

with

$$(2)\ V = -a\cos\varphi - b\cos 2\varphi$$

and ζ_t as Gaussian noise with (0,1). For the expected value of $\dot{\varphi}$ (φ) one thus obtains

$$(3)\ E(\dot{\varphi}) = \alpha_1 \sin\varphi + \alpha_2 \sin 2\varphi$$

which are the first two terms of a Fourier series. This expression can be compared with the results of simulations with the present model. A new set of simulations was run with target periods of 0.3, 0.4, 0.5, and 0.6 s; the model parameters were the same as before. For the two shortest periods 250 runs each were started in the asymmetric mode, for the target period of 0.5 s 150 runs were started in the asymmetric and 100 in the symmetric mode, and for the target period of 0.6 s 125 runs were started in each of the two modes. The computation of relative phase was modified to cover a range between −180° and 540° (see Appendix B).

For each degree step of relative phase the estimated first derivatives observed for relative phases within that interval were averaged across all runs. Figure 9 a shows the means as a function of relative phase in the range between 0° and 360° for the target period of 0.3 s. A Fourier analysis was

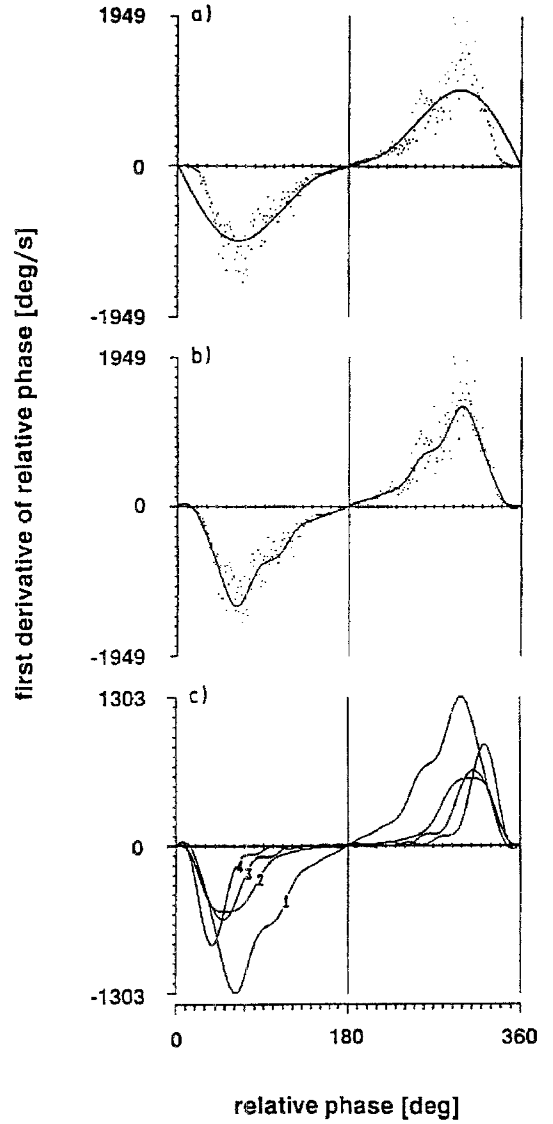

Fig. 9 a–c. Results of simulations, first derivative of relative phase as a function of relative phase; **a** bad fit by sum of first 2 harmonics (continuous line); **b** better fit by sum of first 10 harmonics; **c** fitted curves for target periods of 0.3 s (1), 0.4 s (2), 0.5 s (3), and 0.6 s (4)

performed on these data (Newland, 1984, ch. 10), and the sum of the first two harmonics is shown by the continuous line in Figure 9 a. Obviously the fit is bad, and this turned out to be true for the other target periods as well. Deviations can be found in the flat regions of the relation $\dot{\varphi} = f(\varphi)$ close to 0° and 180° in particular. Figure 9 b shows that a reasonable fit can be achieved using the first 10 harmonics (sine waves only, with 10 as a rather arbitrary number). In Figure 9 c the smoothed curves are shown for all four target periods (the zero crossings close to 0° and 360° are only in the smoothed curves, but not in the original data points).

From Figure 9 c it is apparent that the first derivative of relative phase expected according to the model is close to zero in the region around relative phases of 0° and 180°. With increasing oscillation frequency this region shrinks for the asymmetric movements (180°). Thus, there is no bias on the first derivatives of relative phase close to the target values of 0° and 180°; that is, there is no faster

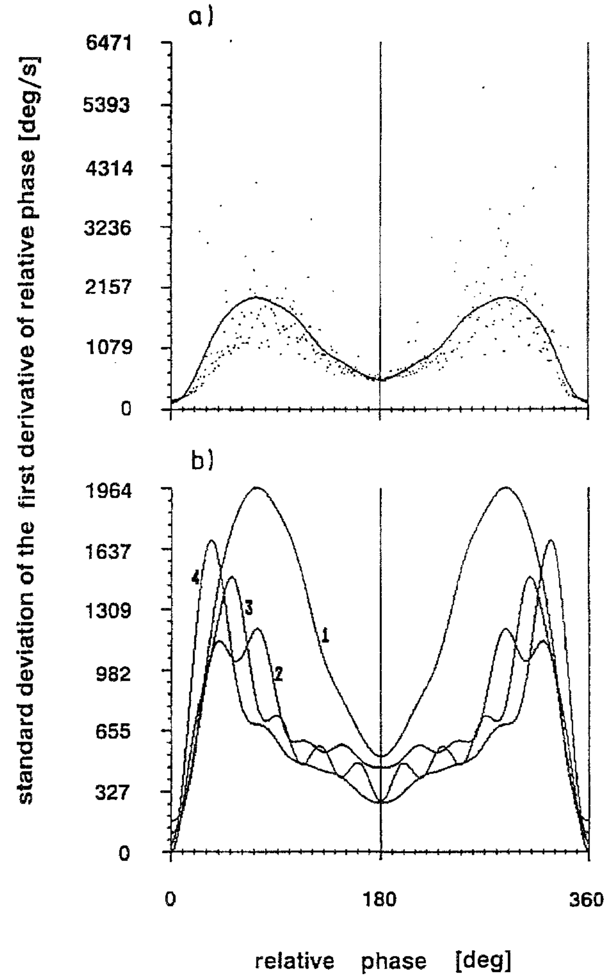

Fig. 10 a, b. Results of simulations, *SD* of the first derivative of target period of 0.3 s and fit by the sum of the first 10 harmonics; **b** fitted curves for target periods of 0.3 s (1), 0.4 s (2), 0.5 s (3), and 0.6 s (4)

change in approaching these values than in deviating from them. Only when a certain range of variability in relative phase is exceeded in the asymmetric mode does relative phase move faster toward symmetry than eventually back to 180° (if at all).

Figure 10 a shows the estimated standard deviations of the first derivative of relative phase for the target period of 0.3 s, smoothed by the sum of the first 10 harmonics (cosine functions only). Figure 10 b presents the smoothed curves for all four target periods. Variability tends to be larger for asymmetric oscillations (180°) than for symmetric ones (0°, 360°); that is, the relative phase tends to change with more variable speed in the former case than in the latter, corresponding to its larger variability (cf. Figure 8 b). The transition from asymmetric to symmetric oscillations is accompanied by highly variable relative-phase changes, but part of this increase might be an artifact of the rapidly changing means of the first derivative of relative phase in these regions (standard deviations of first derivatives were computed for intervals of relative phase; a steep slope of the function relating the mean first derivative to the relative phase within each interval will thus inflate variability).

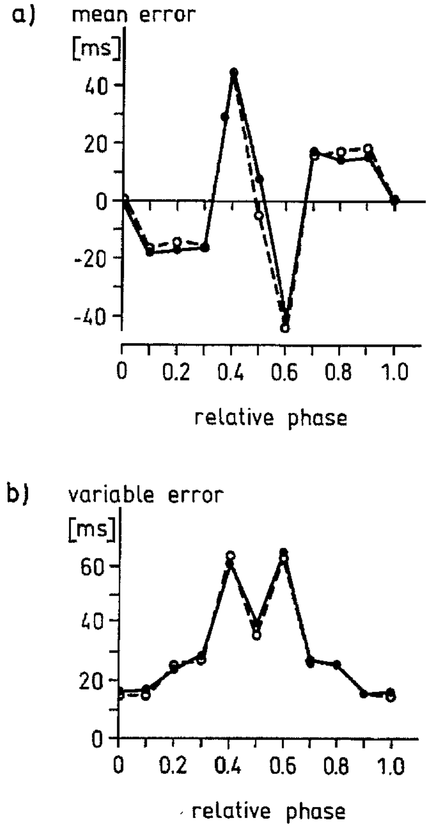

Fig. 11 a, b. Results of simulations of bimanual tapping with different relative phases; **a** mean error as a function of relative phase; **b** variable error as a function of relative phase; broken and continuous lines give the results for each channel when the other is taken as the reference

It is not clear how the simulated data of Figures 9 and 10 compare with experimental ones. In addition, although they characterize the model as simulated, they may be partly determined by ancillary assumptions rather than by essential ones. For example, the introduction of sequential dependencies in the thresholds of the programming level is likely to affect the relation between the relative phase and its first derivative, but such dependencies do not belong to the essentials, as there are (1) transient coupling at the programming level, (2) independent (or at least not fully dependent) variability of thresholds across both channels (not necessarily across time), and (3) feedback of lower-level output to the cognitive level.

Out-of-phase tapping. The model of Haken et al. (1985) has been generalized to account for the results of Yamanishi, Kawato, and Suzuki (1980) on producing bimanual sequences of taps with a certain phase shift (Schöner & Kelso, 1988a, b). Designating the relative phase by the proportional delay of the second hand in relation to the period duration of the first hand, Yamanishi et al. (1980) found the lowest phase variability at relative phase 0, somewhat higher variability at relative phase 0.5, and the highest variability in between. In addition, at all target phases other than 0 and 0.5 there were systematic biases toward one of these two distinct phases, whichever was nearer. In spite of the attention that these data have attracted, attempts at replication have not always been successful (e.g., Summers, Bell, & Burns, 1989). The available data can be taken to suggest the hypothesis that there are different ways of performing this task (cf. Heuer, in press).

The experimental task of Yamanishi et al. (1980) was simulated with the present model, omitting the trajectory-formation level and the peripheral level, as in the other simulations of discrete-response tasks reported above. The outcome of the simulation does not depend only on the parameterization of the model, but also on the relative phase of the upward movement within the time interval between two key presses, that is, the timing of the clock pulses. I am not aware of experimental data on the relative temporal position of the up-stroke between two successive down-strokes and the way it is affected by the relative phase. Therefore, for simulations equal temporal spacing has been used.

Figure 11 shows the results of a simulation with 12 runs per relative phase and 20 periods per run. The mean errors and the variable errors show only a remote resemblance to the data reported by Yamanishi et al. (1980). For example, at relative phases of 0.3 and 0.7 the mean error should be of the opposite sign than the one shown, and the variable error should be second-smallest at the relative phase 0.5. In addition, some search for proper parameter values was necessary to generate these data (time constants of low-pass filters of the programming level were 0.075 s; time constants and gains of high-pass filters were 0.1 s and 0.3 s, respectively; threshold parameters were as in the other simulations except that the upper limit was 0.9 rather than 1.0). In general, the results of simulations will strongly depend on the timing of successive programming phases in the two channels (as in successive discrete responses), and too little is known about the relative timing of up-strokes and down-strokes in this task to allow a more realistic simulation.

Discussion

The basic premise of the preceding analysis of structural constraints on bimanual and probably other multilimb movements has been that these constraints originate largely from coupling on a central level of programming. On the basis of this premise it becomes possible to relate results of kinematic studies of concurrent movements to results of reaction-time studies, and these two sets of data seem in fact to converge. In providing a link between the two sets of experiments that are kept fairly separate otherwise, a motor-program approach appears to be rather unique. Of course, the focus on programming constraints does not imply that interactions do not exist on other levels of motor control (cf. Marteniuk & MacKenzie, 1980), but these are – somewhat arbitrarily – neglected.

The available data on structural constraints do strongly suggest that they are of two different kinds: steady-state constraints and transient constraints. Steady-state constraints will impede performance, no matter how much time for programming is available. The existence of such constraints is apparent from various examples, but their formal study presents a challenge. A major problem is that subjects, when faced with the request to do what appears impossible, may find quite variable strategies to approximate the required motor patterns.

Transient constraints will impede performance only when the time available for programming is not sufficiently long for a steady state to be reached before movement initiation. At least as far as homologous coupling is concerned, the notion of transient constraints serves to account for a variety of data from reaction-time studies as well as from simultaneous-movement studies, requiring only very few additional assumptions.

At first glance, steady-state and transient constraints appear to exhaust the logical alternatives. Nevertheless, there might be something else that cannot easily be classified. For example, Heuer (1986 a) found that choice-reaction time was longer when aiming movements of different, rather than same, durations were assigned to the two hands. This result seems to indicate a steady-state constraint because the durations were known well in advance of each response signal and there was plenty of time for advance specification. However, the increase of mean reaction time was not accompanied by an increase of reaction-time variability and choice accuracy as in other experiments in which movements with different and same temporal patterns were assigned to the two hands (e.g., Heuer, 1982 a, b, c; 1984) and as would be predicted by a simple model of steady-state constraints during programming (Heuer, 1987). Thus the present distinction between two types of constraint is less exhaustive than it might appear.

Transient constraints have been discussed in relation to homologous coupling. Only little is known about other varieties of coupling that would allow one to decide whether or not they are transient. There are some hints, however, that several constraints on bimanual performance – or multilimb performance in general – might be of the transient variety; indications of transient interactions can even be found in the little-studied field of interpersonal coordination.

Evidence of transient coupling exists with respect to force or amplitude coupling, for example. (Given a certain duration, the amplitude of a movement depends on the overall force level, at least when the movement is approximately isotonic.) As was mentioned above, amplitudes of bimanual aiming movements are essentially uncorrelated across a series of trials (Schmidt et al., 1979), and the mean amplitudes of simultaneously performed different aiming movements deviate only a little from those of corresponding unimanual movements (Corcos, 1984; Kelso et al., 1979; Marteniuk & MacKenzie, 1980). With respect to reaction-time data for simultaneous aiming movements, Norrie (1964, 1967) found no reaction-time increase when the amplitudes were different as compared to same amplitudes, and Heuer (1986 a) found no reliable difference between corresponding conditions in a choice task. In all these experiments the required amplitudes were known well in advance of the actual execution of the movements so that programming was in a steady state at movement initiation.

The findings obtained under such conditions contrast with the results observed under conditions in which programming and initiation were probably not well separated in time. Kelso, Tuller, and Harris (1983) had their subjects oscillate a finger while repeating the syllable "stock." When every second syllable was stressed, the amplitude of every second finger movement was increased, contrary to instructions; when the amplitude of every second finger movement was increased, every second syllable was stressed – again contrary to instructions. This result was replicated by Chang and Hammond (1987). Although a lot of the required evidence is missing, the available pattern of results on amplitude coupling does suggest that it might be transient – showing its effects when programming is not yet finished at movement initiation, but not after a steady state of programming has been reached.

One of the early studies of interpersonal coordination was conducted by Drill (1933) on hammering. (Although the paper is well hidden in a German journal, a photograph was reproduced by Drillis (1959) – who is most likely identical with the original author – and this reproduction has found its way into at least one of the several editions of the popular Human Factors book by McCormick, 1970, p. 291.) Regarding interpersonal coordination, Drill's report does not go far beyond stating that it exists: the hammering characteristics of a particular person depended on his co-worker. For two persons using the same anvil, of course, the hammering cycles must be phase-shifted.

A less natural task has been studied by Schmidt, Carello, and Turvey (1990) in some detail: instead of one person oscillating both hands, there were two people watching each other, each one oscillating one leg (sitting on a stool 1 m in height). The results were similar to those with the bimanual-oscillation task, revealing a tendency to switch from opposite-phase to in-phase oscillations. Schmidt et al. (1990) interpreted their results in terms of Haken et al.'s (1985) model; as an abstract formalism, the model outlined above could be applied as well replacing the intraorganismic cross-coupling by some visual cross-coupling. Alternatively, an intermediate step of programming the movement seen could be postulated, corresponding to the hypothesis that movement imagery is associated with programming the imagined movements (Decety & Ingvar, 1990; Heuer, 1989).

In one respect the results of Schmidt et al. (1990) appear implausible at first glance. Pairs of subjects sat in a distance of about 1.5 m, facing the same direction, and turned only slightly toward each other; one subject oscillated his or her left lower leg and the other his or her right lower leg. For a single person the preferred relative phase between the two legs is 180°, as in walking, rather than 0°. Although this statement is mainly based on casual observations of my own legs, it is correct for oscillations of the arms parallel to the median plane (Gunkel, 1962). Therefore, why is the preferred relative phase – von Holst's (1939) *Koaktionslage* – 0° in the two-person situation? The model of Haken et al. (1985) appears to be silent on this problem.

The distinction between programming and execution, which is an essential aspect of the motor-program perspective, may offer a solution. The phase reversal in the two-person situation as compared to the single-person situation

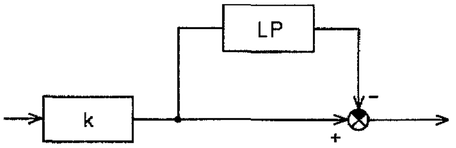

Fig. 12 High-pass filter implemented as forward inhibition of a signal (K: gain factor; LP: low-pass filter)

could result from the phase shift between programming and execution. Suppose that a flexion is programmed while the knee is extending. In opposite-phase movements of a single person the programming of flexion for the one leg would be facilitated by programming extension for the other leg (there is no homologous coupling in this situation, but antagonistic coupling instead; cf. Heuer, in press). However, in opposite-phase movements of two different people, the one programming a flexion (while performing an extension) would see a flexion of the other person; if the visual signal were processed with only a slight delay, possibly triggering some programming for the other leg, it would inhibit, rather than facilitate, programming. The opposite relations would hold for in-phase movements. Thus the phase shift between programming and execution might serve to explain why the preferred phase relation is different in interpersonal and intrapersonal coordination.

The occurrence of associated movements in children, but not in healthy adults, suggests that the strength of coupling in general declines in the course of development and that movements of different limbs achieve a higher degree of independence (cf. Heuer, in press). The disappearence of associated movements can be viewed as a particular instance of an increased efficiency of inhibitory processes. As stated by Basmajian (1977, p. 39): "During maturation, motor learning consists of a steady inhibition of motoneurons whose activation is superfluous to the best performance of the peripheral musculature." A generalization of the idea of increasing inhibitory control to coupling during motor programming suggests that in the course of development transient constraints might evolve from steady-state constraints. In Figure 12 the high-pass filters of Figure 2a are implemented as a proportional element with gain K, the output of which is low-pass filtered and subtracted from itself. Increasing the gain of the inhibitory (subtractive) branch from 0 to 1, or developing stronger inhibitory pathways, would carry the system from steady-state coupling through mixtures to transient coupling.

Finally, the hypothesis that some structural constraints on coordination are transient suggests the consideration of the advantages that organisms might gain from this type of constraint. In the first case, of course, it is not evident that structural constraints are of any advantage at all – they are usually experienced as impeding performance. Nevertheless it is likely that they represent some kind of evolutionary inheritance and support basic motor patterns (Heuer, in press). Motor skills that are facilitated by structural constraints, rather than impeded, seem in fact to exist. Homologous coupling, for example, supports mirror writing with the left hand during concurrent normal writing with the right hand (in right-handers). Biologically more important, homologous coupling supports the maintenance of balance, at least as far as it serves to produce symmetric movements or mirror movements (for swinging the arms forward and backward, for example, coupling is not of the homologous kind; Gunkel, 1962). Symmetric movements tend to stabilize the lateral position of the center of mass. Although finger movements do not represent a threat to balance, they might be coupled according to a more general principle.

If homologous coupling does in fact assist the maintenance of equilibrium, transient coupling can be viewed as a compromise between this desideratum and that of an independent use of the limbs. When rapid actions are required and the time available for programming is short, transient coupling will produce a bias toward symmetric movements and thus assist the maintenance of balance. However, when there is enough time for postural responses to develop fully before the initiation of the voluntary movement, transient coupling will have lost its power, and its function in assisting the maintenance of balance is no longer needed because it has been taken over by the postural activity.

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Appendix

A *Adjustment of the parameters of the trajectory-formation level to target period*

The trajectory-formation level is described by

$$\ddot{y}_t + \frac{1}{\tau_{low}} \dot{y}_t + \frac{G_o}{\tau_{low}} (y_t - x_t) = 0$$

where τ_{low} is the time constant of the low-pass filter and G_o the amplitude of the constant GO signal (the gain of the low-pass filter was set to 1 and the time constant of the integrator to 1 s). Critical damping is obtained with $G_o = 1/(4\tau_{low})$. The parameter τ_{low} was set such that within the time interval between two successive clock pulses (T_c) the step response of the system reached a certain proportion of its full amplitude.

Consider an initial steady state with $x_t = y_t = +1$. At time zero x_t steps from 1 to 0. The step response of the system with critical damping is:

$$y(t) = e^{-t/(2\tau_{low})} + [t/(2\tau_{low})]\, e^{-t/(2\tau_{low})}$$

The second term of this equation was neglected and the parameter τ_{low} was determined such that the first term equalled 0.05 (corresponding to 95% of a full step response):

$$0.05 = e^{-T_c/(2\tau_{low})}$$

$$\tau_{low} = -T_c/(2 \text{ In } 0.05)$$

Inserting this expression for τ_{low} in the equation for y(t) yields:

$$y(T_c) = 0.05\ (1 - \text{In } 0.05) = .20$$

Thus the step response of the trajectory-formation level reached 80% of its full amplitude in the time interval between successive clock pulses.

B *Estimation of relative phase*

The outputs y_p and y_q of the two channels of the system were analyzed as if they were harmonic functions. At time t they can be characterized by two vectors in their respective phase planes that were obtained after scaling the velocities by $1/\varpi = 1/2\pi f$ as estimated from the clock period $2T_c$. The angle φ between the two vectors is their scalar product after normalization:

$$\varphi = \text{arc cos} \frac{y_p y_q + \dot{y}_p \dot{y}_q}{\sqrt{(y_p^2 + \dot{y}_p^2) \cdot (y_q^2 + \dot{y}_q^2)}}$$

These estimates range between 0° and 180° (it is always the smaller angle between the two vectors that is taken), and they were used for the first set of simulations.

For the second set of simulations that served to estimate $\dot{\varphi} = f(\varphi)$, estimates outside the range from 0° to 180° were obtained by taking $\dot{\varphi}$ into account. For each point in time, $n\Delta t$, the predicted phase was computed as $\hat{\varphi}.\ (n\,\Delta\,t) = 2\varphi\ [(n-1)\,\Delta t] - \varphi\ [(n-2)\,\Delta t]$, and from four values, φ_1, φ_2, φ_3, φ_4 that one was chosen that had the smallest deviation from $\hat{\varphi}$. In particular φ_1 was equal to φ as defined above (0°–180°), $\varphi_2 = 360 - \varphi_1$, $\varphi_3 = 0 - \varphi_1$, and $\varphi_4 = 360 + \varphi_1$. Thus a range from –180° to 540° was covered.

C *Determination of switches from asymmetric to symmetric oscillations*

The mean relative phase was computed for time windows of half the target-period duration. Initially the windows were placed at the start (after velocity was unequal zero in both channels) and at the end of a trial. When both means were above 120° (asymmetric) or below 60° (symmetric), the trial was classified as a no-switch trial. When the first mean was above 120° and the second below 60°, it was classified as a switch trial (the opposite never occurred).

All other trials were preliminarily classified as irregular. There was one such trial among those with target period of 0.4 s; although it had been started in the asymmetric mode, both mean relative phases were below 60° and the variability of the relative phase – computed across the full trial – was in the range characteristic of trials without a switch of relative phase (<30° rather than >50°). In this trial the switch thus occurred very early, and it was classified as a switch trial. With the target period of 0.2 s, three trials were preliminarily classified as irregular. In all three of them the initial mean relative phase was just below 120° and the final one close to zero; so they were classified as switch trials. However, they were neglected in the computation of the means of the dependent variables because for two of them it appeared that the low initial mean was not caused by an early switch (the variability of relative phase computed over the full trial was >50°, indicating that the asymmetric mode was maintained for a while).

For switch trials the windows were moved forward and backward as long as the means stayed above 120° and below 60°, respectively. This procedure served to determine the intervals before and after the switch (which include part of the transition periods because of the arbitrarily chosen threshold values of 120° and 60°). Occasionally the interval before a switch was not long enough to determine the statistics shown in Table 1.