Long-term consistencies in assembling coordinated rhythmic movements *

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Abstract


At the level of tasks the problem of coordination is relating families of potential circumstances to families of potential movement patterns. Major theoretical efforts to address this problem hypothesize that any task-specific coordination is a function which generates for any given circumstance a movement pattern satisfying the task criteria. In three experiments spanning approximately two years, the same three subjects were required to achieve a 1:1 frequency locking of rhythmic motions about the wrists under variable circumstances comprising different loadings of the two limb segments. Mappings between measures of the coordination problem and measures of the coordination solution were determined. Similar single-valued functions spanning the period of investigation were observed for each subject. The results are discussed in terms of the parameterization of an oscillatory control structure by the magnitude and asymmetry of the inertial loadings at the wrists.

Different environmental circumstances usually require different movements to be performed in order for the same movement goal to be attained. For example, bringing a cup to the mouth will require different movements for different sized cups (large, small), different

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liquids (hot, cool) and depending upon whether one is standing or sitting. There is a family of movements, an equivalence class of movements, that a person can perform that accomplish the same goal. This equivalence class has been called an action (Greene 1988). Depending upon the environmental circumstances, a particular movement from an action equivalence class will be executed to accomplish a goal.

Consider a robotic system engaged in the transferring of a tool from one hand to another, where the circumstances surrounding the action (the location of transfer, the size and/or weight of the tool, the method of grasping, the orientation of the trunk, the speed of transfer, and so on) can differ (Greene 1978). The trajectories of the receiving arm would be different functions of the position of the giving hand and of the specifications for the giving hand’s actuators. Consequently, variations in the aforementioned parameters will generate a very large family of functions comprising the context-conditioned variations (Turvey et al. 1978) of performing the action of ‘transferring the tool’. Any controlling subsystem must be able to generate any of these coordinating functions upon demand. Patently, to transfer a tool is an ability that goes beyond coordinating states that actually exist; it entails matching the entire family of movement patterns satisfying the task criteria with the entire family of circumstances in which the task is executed.

Greene (1975a, 1975b, 1978) assumes that, as a general principle, both the entire family of circumstances and the entire family of movement patterns comprise single state spaces under some (high-level, task) description, with the consequence that every coordination is potentially a single function that maps one total space into the other. Greene’s arguments are directed at the coordination of families of action variants (that is, at tasks) and not just at the coordination of single actions. For task-oriented systems, the key strategy is ‘...somehow to pack all the relevant information about possibilities and variants into something that looks and behaves, at the high level, like a function from one set to another’ (Greene 1978: 1–11). Two major implications follow from Greene’s arguments. First, the varied ‘creative’ solutions to an action problem should show a high degree of uniformity, that is, they should conform to a single functional mapping between the task circumstances and movement patterns. Second, given that there are probably few high-level ways of describing the
circumstances and the movement patterns as single state spaces, and hence, few ways of mapping between them, the single-valued functions underlying the assembly of task-specific movement patterns should be persistent (that is, they should be exhibited over long periods of observation). Intuitively, once a person (or species) has discovered a method to achieve constancy of coordination over variable contexts he or she (or it) adheres to that method. To a degree, observed solutions will be idiosyncratic to the individual system performing the action. That is, different individual systems (e.g., different people, different species) performing a given action under sufficiently varied circumstances may not show identical mappings from the set of potential circumstances to the set of movement patterns. Nonetheless, it is expected that these mappings should be characterizable as an equivalence class under an appropriate description. Accordingly, differences in the same single-valued functions observed for different individuals should capture what is intuitively meant by ‘individual style’.

**Generalized motor programs and schema theory**

Greene’s abstract ideas are implicitly embodied in theories of movement coordination. In R.A. Schmidt’s (1982a, 1982b) motor program theory, the rationalization for how a task is achieved in variable contexts is that the performer has represented in memory generalized motor programs that prescribe such properties as the order of muscular contractions involved in the activity and their relative timing or phasing. Other properties of effector systems with which these programs deal are not invariant features of a program but have to be parameterized for each different circumstance in which the action is to be performed. For example, for the motor program for throwing an object, the commands to the muscles will differ for throwing an object near versus far, or for throwing an object that is heavy versus light. In order for a single motor program to be used in a number of different circumstances, R.A. Schmidt (1982a, 1982b) has proposed that additional memory structures parameterize the motor programs. These additional structures are referred to as motor schemas. An actor has represented in memory a ‘family of functions’ that relate the variables operating in a given context to the desired outcome of the action (recall schema). Accomplishing the action is
maintained by a representation in memory of a family of functions that relate sensory consequences of the action to the desired outcome of the action (recognition schema). The smooth execution of the desired outcome is produced through a comparison of the actual sensory consequences and the represented sensory consequences in the recognition schema.

Underlying the capability of an action system to adapt to different environmental settings is a family of functions in a schema that relates different properties of the effector organs and the effects it has upon the environment to different environmental circumstances. For example, the amount of force to be used in throwing an object a desired distance is dependent upon the weight of the object. The relation between force and distance for a light object would have a number of siblings, for example, the relation between force and distance for a medium weight object and the relation between force and distance for a heavy object. Together, they constitute a family of functions that relate the force to be exerted with the distance to be thrown under different parameterizations due to object weight. In order for a particular movement to be executed from the functionally equivalent class of movements called the ‘action of throwing an object’, an intentional and environmental tuning of the action system must occur: a goal must be chosen (the desired distance), and the environment must be perceived (the weight of the ball, the distance to be thrown). An intentional agent needs only to look up the appropriate magnitude of motor program parameters of timing, force, and so on, from the schema and implement them within the program.

Dynamical systems approach

From the perspective of an account that interprets movement patterns in dynamical terms, the assembly of task-specific movement patterns is governed by a dynamical control structure embracing variables of the person’s action system and variables of the environment (Fowler and Turvey, 1978; Kugler et al. 1980; Kugler and Turvey 1987; Saltzman and Kelso 1987; Schöner and Kelso 1988; Turvey 1990). Following Bernstein (1967), a major assumption is that functional linkages or constraints are formed between the many degrees of freedom of an action system so that fewer degrees of freedom need be controlled. Research has suggested that these functional synergies or
coordinative structures are dynamical systems. The many degrees of freedom of the action system that are opaque to the actor are not only constrained but are constrained dynamically – by the ‘free interplay of forces and mutual influences among the components tending toward equilibrium or steady states’ (Kugler et al. 1980: 6) and, hence, self-organizing. In the dynamical perspective, a dynamical system or control structure plays the same role in the organization of an action system as the program in the motor program perspective.

If a set of goal-equivalent movements (e.g., those movements that allow one to throw a light, medium-weighted, and a heavy object) all fall into the same action class because the same dynamical control structure gives rise to those movements, then how is the dynamical control structure reparameterized to effect the same goal in different circumstances? In other words, what plays the role of the motor schema in the dynamical theory? The short answer is that properties of the environment parameterize dynamical control structures directly, and the environment itself takes the place of the motor schema. Properties of the environment that are relevant to the performance of a given task are specified by low-energy (geometric, kinematic or spectral) patterns that the different perceptual systems pick up. The notion of a dynamical control structure refers not only to the effectors to be constrained, but also to the perceptual systems and to the action-relevant environmental properties that those systems are attuned to (Turvey et al. 1990).

Fowler and Turvey (1978) hypothesize that for each degree of freedom of the action system left unconstrained by muscle linkages, there is an environmental variable specified by information that constrains its magnitude. These environmental variables can include the distal segments of the actor's own body that are perceived haptically. In assembling a task-specific movement pattern, there are many degrees of freedom left unconstrained in the coordinative structure. Becoming proficient in the task is tantamount to (a) finding the appropriate functional linkages between muscle groups in the effector system producing the action, and (b) becoming attuned to the information about the environmental properties that can constrain the errant degrees of freedom. Accomplishing an act proficiently involves producing the appropriate magnitude of an action system parameter for a given magnitude of the environmental property that is informationally-specified and perceptually-registered. Such relationships be-
tween action system variables and environmental variables are the basis for mappings or functions between environmental circumstances and movement patterns that underly the ability to perform a task in a number of different circumstances.

In sum, the solution to the problem of task-equivalent movements from the dynamical perspective is similar to the solution of the motor programming theory in that both suggest that a family of single-valued functions is involved in mapping environmental variables to action system variables. The differences in the solutions are in terms of what each perspective posits as the origin of action organization (motor program vs. dynamical control structure), and how the family of functions that parameterizes the organization of action is instantiated (representational vs. direct perceptual mapping, respectively). From either perspective, learning to perform a task requires exploring the functional space defined by the family of circumstance-to-movement pattern mappings that define how environmental properties constrain degrees of freedom of the action system.

An empirical evaluation

The focus in the present article is an evaluation of the functional relationships between environmental circumstances and aspects of simple, bimanual, rhythmic actions. The questions are whether or not the solutions for assembling a task-specific coordination in varied circumstances can be specified as single-valued functions, and whether or not these solutions are uniform, persistent in time, and parameterized by the individual subject. If solving an action problem depends on well-defined mappings from environmental variables to action system variables, then the foregoing properties should be observed.

Addressing the assembling problem experimentally in a way that bears on the single function hypothesis is difficult. The minimal requirements for an appropriate method are that (a) the same coordination problem can be posed in many different forms, (b) the different forms of the problem can be quantified, and (c) the solutions to these different forms of the problem can be quantified. To satisfy the preceding requirements, we can use a task in which a person holds a pendulum in each hand and swings the two pendulums together through motions at the wrists (Kugler and Turvey 1987). The person is required to produce a coordinated state in which the two pendulums
oscillate at a single common frequency, the one that feels most comfortable, and at a phase relation of 180° (alternate phase mode). By varying the relation between the dimensions of the pendulums (such that their rotational inertias are identical, moderately different, or markedly different), we can vary the details of the coordination problem to be solved while keeping the basic nature of the problem constant.

In the present study, the different versions of the problem will be quantified by two ‘problem measures’: the inertial loading of the wrists and the difference between the inertial loadings at the two wrists. The various solutions to these problem measures can be quantified by ‘solution measures’ such as (i) the period of oscillation (cycle duration) at which isochronous coordination of the two wrist-pendulums (1:1 frequency locking) is observed, and (ii) the power spectral analysis of the relative phasing of the two wrist-pendulums. The two solution measures refer to different aspects of the coordination. The particular period of the 1:1 frequency locking represents the temporal preference of the organization assembled to execute the 1:1 frequency locking of the two pendulums (Kugler and Turvey 1987; Turvey et al. 1988). The power spectrum of the continuous relative phase (Φ) captures the rhythmic patterning of the relative lagging and leading of the two wrist-pendulums within a cycle and, hence, can help identify the cyclic activities of involved neuromuscular processes at different time scales (Schmidt et al. 1991). The total power of the spectrum is a simple quantification of the variability of cyclic component processes.

A highly systematic relation of a ‘solution measure’ to a ‘problem measure’ over a number of sessions would suggest that the coordination is assembled in much the same way every time, indifferent to the variations in the problem and would comport with Greene’s (1975b, 1978) notion that tasks are expressible by single functions between circumstance and movement pattern state spaces. The data that will be used to evaluate the single function interpretation of the assembling problem were provided by three experiments. The three experiments were part of a larger study totaling six experiments with the same three subjects, and directed at a number of aspects of coordinated rhythmic movement. The data on some of these aspects have been reported previously (Rosenblum and Turvey 1988; Schmidt et al. 1991; Turvey et al. 1988; 1989). In the present paper, we are inter-
ested in aspects that have not heretofore been reported, namely, the subject’s long-term consistencies in solving the problems involved in this simple coordination task. The three experiments of the series providing the data for the present article were those for which a single scaling relation held consistently between pendulum mass and pendulum length (Turvey et al. 1988). Such consistency is needed for determining the function relating the ‘solution’ of coupled period of oscillation to the ‘problem’ of inertial loading (see below). For present purposes, the most important feature of the three experiments satisfying the consistent mass-to-length scaling was that they were separated by long periods of time. The first two experiments were separated by 6 months, and the second and third experiments were separated by 15 months. They permit, therefore, an evaluation of persistent, uniform methods of assembly in different circumstances and the opportunity to pinpoint the nature of individual variations.

Method

Subjects

The same three male subjects participated in all three experiments. Two of the subjects were graduate students and the other was a faculty member. Each subject was right handed. The subjects weighed as follows: subject 1, 73.5 kg; subject 2, 74.9 kg; subject 3, 78.0 kg.

Materials and apparatus

The method of constructing the pendulums is reported in Kugler and Turvey (1987). In each of the three experiments the right wrist pendulum was of fixed magnitude. Different conditions of interlimb coordination were produced by varying the magnitude of the left wrist pendulum. The characteristic frequencies of the wrist pendulums considered as strictly gravitational pendulums for experiments 1–3 are the same as reported for experiments 1, 5, and 6 in Schmidt et al. (1991).

The displacement of each subject’s wrist-pendulum system was measured by a Teka PN-4 Polgon goniometer. Polarized light sensors were attached to a metal plate on the pendulum’s shaft (≈ 13 cm from
the handle end) and on the subject's forearm ($\approx 7$ cm from the wrist joint). The data were recorded onto FM tape and later digitized at 200 samples/s using a Datel ST-PDP 12 bit analogue-to-digital converter. For further details, see Rosenblum and Turvey (1988).

Procedure

Each subject was instructed to hold his forearms parallel to the ground-plane and to gaze straight-ahead without looking at either wrist-pendulum system. He was asked to oscillate the pendulums forward and backward smoothly in the sagittal plane using only the wrist joints while gripping each pendulum's handle so as to have complete control over the entire swing. The subject was told to swing the pendulums in alternate fashion (one pendulum moving forward simultaneously with the other pendulum moving backward) with a single, most comfortable common period. Importantly, before the recording of each trial, the subject was given as long as needed to settle on a tempo that he felt was comfortable and stable. Each recorded trial lasted for 15 s, except in experiment 3 in which the trials were of 10 s duration.

In experiments 1 and 3, there were eleven interlimb coordination conditions and one single right wrist-pendulum condition. In experiment 2, there were eight interlimb coordination conditions and one single right wrist-pendulum condition. (The single right wrist-pendulum condition in each session permitted the determination of the right system's characteristic period which was needed to address certain issues of coordination but not those of concern to the present article.) In experiment 1, there were eight trials per condition; in experiment 2, there were eight trials per condition; and in experiment 3, there were six trials per condition. For each experiment, the total trials were divided into a number of blocks each of which involved one trial of every condition type. Trials within each block were given a random ordering and this ordering was different for each subject. Again, experiments 1 and 2 were separated by 6 months, and experiments 2 and 3 were separated by 15 months.

Analyses

The effective mass and length of a single wrist-pendulum system were calculated as the equivalent simple pendulum mass and length of
the compound pendulum consisting of the attached mass, the dowel and the hand of the subject (see the algorithm in Kugler and Turvey (1987)). Because of the rotational nature of the movements, the effective length of a wrist-pendulum system will be considered as the index of a single hand's inertial loading \( (l_i) \). The amount of competition that is involved in achieving a 1:1 frequency locking state will be measured by the difference in the individual pendulums inertial loadings \( (l_r - l_l = \Delta L) \). To estimate the inertial loadings of a given interlimb wrist-pendulum pair, the distance to the center of oscillation of the two wrist-pendulums was calculated using the equivalent simple pendulum quantities,

\[
distance \text{ to center of oscillation} = \frac{(m_l l_l^2 + m_r l_r^2)}{(m_l l_l + m_r l_r)}, \quad (1)
\]

where \( m_l, l_l \) refer to the effective mass and length, respectively, of the left wrist-pendulum system and \( m_r, l_r \) refer to the effective mass and length, respectively, of the right wrist-pendulum system. The distance to the center of oscillation is the simple pendulum equivalent length of the compound pendulum consisting of the two wrist-pendulum systems. Because of this fact, the distance to the center of oscillation will be referred to as the virtual length \( (L_v) \).

The digitized displacement time series of the wrist-pendulum systems were smoothed using a moving average procedure with a window size of 35 ms. Each trial was subjected to a software analysis to determine the coordination period of oscillation, the time series of the continuous relative phase \( (\Phi) \), the power spectra of \( \Phi \), and the total power associated with each of these spectra.

A peak picking algorithm was employed to determine the time of peak flexion and extension of the wrist-pendulum trajectories. From the peak extension times, the period of oscillation for the \( n \)th cycle was calculated as

\[
\tau_n = (\text{time of peak extension}_n + \text{time of peak extension}_{n+1}). \quad (2)
\]

The mean of these cycle periods was calculated to produce the mean period of oscillation for each system (right and left) for each trial.

The difference between the phase angles of each wrist-pendulum system was calculated for each sample (200/s) of the displacement
time series to produce a time series of the relative phase angle. The phase angles at sample \( i \) (\( \Phi_i \)) were calculated as

\[
\Phi_i = \arctan(\dot{x}_i^*/\Delta x_i),
\]

(3)

where \( x_i^* \) is the velocity of the time series at sample \( i \) divided by the mean angular frequency for the trial, and \( \Delta x_i \) is the displacement of the time series at sample \( i \) minus the average displacement for the trial. The relative phase angle that the subject intended to produce was 180°. The continuous time series of \( \Phi \) would allow an evaluation of how the subject satisfied this task demand. In order to see the magnitude and patterning of the variability of this time series, a power spectral analysis was performed on the time series of \( \Phi \). The data were windowed using a Welch filter to reduce spectral leakage, and all of the trial spectra from a given condition were averaged to reduce the error of the spectral estimate (Press et al. 1988). The total power of \( \Phi \) was calculated for each condition by summing the power at each frequency of the averaged spectra. This measure was used as a general index of the variability of the relative phasing of the left and right wrist-pendulum systems.

Results

Achievement of 1:1 frequency locking

There were 212 instances of interlimb coordination for subject 1 and 218 instances of interlimb coordination for subjects 2 and 3 across the 21 months. Regressing the left system periods on the right system periods revealed that each subject achieved consistently the goal of 1:1 frequency locking. For subjects 1–3, the \( r^2 \)'s were all 0.99 with slopes near unity (1.01, 1.00 and 0.99) and intercepts near zero (0.014, 0.002 and 0.009). Table 1 demonstrates each subject's consistency of achieving this frequency-locking goal across the three experiments. None of the slopes or intercepts for the analyses were significantly different from 1 and 0 (\( p > 0.05 \)), respectively.

Inertial loadings and cycle duration

Fig. 1 plots the relation between the interlimb coordination period (computed as the mean of the almost identical right and left periods)
Table 1
Regressions of the left wrist-pendulum system periods on the right wrist-pendulum system periods used to evaluate the achievement of 1:1 frequency locking for each subject and experiment separately.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.99x + 0.003, r^2 = 0.98$</td>
<td>$0.99x + 0.006, r^2 = 0.99$</td>
<td>$1.00x - 0.003, r^2 = 0.99$</td>
</tr>
<tr>
<td>1</td>
<td>$1.02x - 0.022, r^2 = 0.99$</td>
<td>$1.01x - 0.006, r^2 = 0.99$</td>
<td>$0.99x + 0.006, r^2 = 0.99$</td>
</tr>
<tr>
<td>2</td>
<td>$1.01x - 0.010, r^2 = 0.99$</td>
<td>$1.00x + 0.003, r^2 = 0.99$</td>
<td>$0.98x + 0.020, r^2 = 0.99$</td>
</tr>
</tbody>
</table>

and virtual length ($L_v$) across the three experiments for each subject. Given that $L_v$ is the ratio of the summed moments of inertia of the component wrist-pendulum systems to the sum of their static moments (see above), it provides a systematic measure of the conditions under which the designated interlimb coordination is to be achieved— the coordination problem instantiated by the inertial loading of the wrists. As can be seen, as the coordination problem varied, the coordination solution defined by periodic timing varied. For any given value of the $L_v$, one can observe a range of periodic timing solutions chosen by the subject on different trials. In spite of this variability, the covariation between the $L_v$ and cycle duration was systematic. Although the data are from observations spanning nearly two years, it is evident that for each subject the mapping of problem to solution was largely invariant over that interval.

A 2-way ANOVA with the continuous variable of $L_v$ and the categorical variable of subjects (Pedhazur 1982) revealed a main effect of $L_v$ ($F(1, 642) = 7655.83, MSe = 0.004, p < 0.001$) and a main effect of subjects (i.e., difference in the intercepts of the individual subjects regression equations) ($F(2, 642) = 65.81, MSe = 0.004, p < 0.001$). Post-hoc analyses indicate that the latter main effect was due to the difference between the intercepts of subject 1 and 2 ($F(1, 426) = 103.70, MSe = 0.003, p < 0.001$) and subject 1 and 3 ($F(1, 426) = 118.45, MSe = 0.004, p < 0.001$). Experiments could not be included in this analysis as a variable because the magnitudes of the $L_v$ did not span the same range for the three experiments (i.e., experiment 1 had a small range with low values). But the regression lines of the individual subjects can be compared for the three experiments separately to determine whether or not the subject differences are constant across the long term. Table 2 displays the regression equations
Fig. 1. The cycle duration solution of the three subjects to the coordination problem determined by the center of oscillation of the two wrist-pendulum systems ($L_v$) reveals a consistent mapping between periodic timing exhibited and $L_v$ for data of the three experiments collected over a two year period.
Table 2
Regressions of coordination period on $L_v$ for each subject and experiment separately.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1.84x + 0.58, r^2 = 0.74$</td>
<td>$1.32x + 0.55, r^2 = 0.80$</td>
<td>$2.13x + 0.29, r^2 = 0.74$</td>
</tr>
<tr>
<td>2</td>
<td>$1.62x + 0.62, r^2 = 0.97$</td>
<td>$1.45x + 0.59, r^2 = 0.93$</td>
<td>$1.43x + 0.54, r^2 = 0.93$</td>
</tr>
<tr>
<td>3</td>
<td>$1.50x + 0.69, r^2 = 0.97$</td>
<td>$1.55x + 0.57, r^2 = 0.94$</td>
<td>$1.51x + 0.57, r^2 = 0.97$</td>
</tr>
</tbody>
</table>

for the individual experiments while table 3 displays the results of the pairwise comparisons of the subject regression lines for each experiment. In general the pairwise comparisons corroborate for the three separate experiments the results of the ANOVA above which are exhibited in the omnibus regressions of fig. 1: the cycle durations of subject 1 are generally greater than those of subjects 2 and 3 across the range of $L_v$. In experiment 1, subject 1's idiosyncratic solution to the coordination problem is indicated by a greater slope than subject 2 and a greater intercept than subject 3. In experiment 2, his difference is indicated by a greater slope than subject 2 and a greater slope and intercept than subject 3. And in experiment 3, subject 1's idiosyncratic solution is indicated by a greater intercept than those of both subjects 2 and 3. Although in first two experiments the regressions of subjects 1 and 2 differ in their slopes rather than in their intercepts (as is the case in the omnibus regression), inspection of fig. 1 suggests that this slope difference indicates the same kind of difference in the two solutions of these subjects: The cycle durations of subject 1 are generally greater than those of subjects 2 and 3.

Table 3
Paired comparisons of subjects' regressions of coordination period on $L_v$ for the three experiments.

<table>
<thead>
<tr>
<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>S2</td>
<td>S3</td>
</tr>
<tr>
<td>S1</td>
<td>×</td>
<td>a</td>
</tr>
<tr>
<td>S2</td>
<td>ns</td>
<td>×</td>
</tr>
<tr>
<td>S3</td>
<td>a</td>
<td>×</td>
</tr>
</tbody>
</table>

Note: The comparisons above the diagonal are for the slopes of the two regression lines while the comparisons below the diagonal are for their intercepts.

$^a p < 0.01$. 


Fig. 2. The dependency of the total power of relative phase on the coordination problem determined by the difference in the simple equivalent pendulum lengths, $\Delta L_i$, for data of the three experiments.
In sum, these results indicate a common mapping of coordination circumstances to cycle duration because each subject's solution to the increased inertial loadings was to increase systematically the preferred cycle duration. Aspects of this mapping, however, are open to individual variation. Across the three experiments, subject 1 preferred periods of coupled oscillation that were greater on the average for each experiment than those preferred by subjects 2 and 3.

Achieving antiphase (180° interlimb phase relation)

In addition to producing a 1:1 frequency locking of the two wrist-pendulum systems, the subjects were also required to oscillate the wrist-pendulums in antiphase. The mean $\Phi$'s produced by the three subjects in the three experiments were 196.74°, 196.04°, and 192.24° with standard deviations of 12.67°, 16.55°, and 10.24° for subject 1, subject 2, and subject 3, respectively. These magnitudes reveal that the subjects approximated the task goal (achieving antiphase coordination) on a coarse-grain level of analysis. However, as pointed out in Schmidt et al. (1991), the $\Phi$s attained by the subjects were not held statically at this constant mean value. To the contrary, they were time-varying, with significant periodicities. Spectral analysis revealed distinct spectral peaks that occurred at integer multiples of the coordination frequency of the wrist-pendulums. In order to summarize how this variability of the moment-to-moment lagging and leading of $\Phi$ changed with the difference between the inertial loading at the two wrists, the difference in the simple pendulum equivalent lengths of the two wrist-pendulum systems ($\Delta L_1$) was employed as a 'problem measure' and the total power of $\Phi$ was employed as the 'solution measure'.

Total power of $\Phi$ and difference in inertial loadings

Fig. 2 shows the total power dependency on the problem measure ($\Delta L_1$) across the three experiments for each subject. In each case the dependency is linear. As the inertial loadings of the two wrists differed more and more, the degree to which a given rhythmic unit lagged or led fluctuated more and more. Although the data spanned two years in collection, the solutions of the coordination problems
Table 4
Regressions of total power of $\Phi$ on $\Delta L_i$ for each subject and experiment separately.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-0.87x + 2.31$, $r^2 = 0.80$</td>
<td>$-0.96x + 1.95$, $r^2 = 0.49$</td>
<td>$-1.60x + 2.01$, $r^2 = 0.88$</td>
</tr>
<tr>
<td>2</td>
<td>$-0.74x + 2.16$, $r^2 = 0.83$</td>
<td>$-1.24x + 2.04$, $r^2 = 0.98$</td>
<td>$-1.33x + 1.95$, $r^2 = 0.87$</td>
</tr>
<tr>
<td>3</td>
<td>$-1.13x + 2.14$, $r^2 = 0.78$</td>
<td>$-1.34x + 2.03$, $r^2 = 0.90$</td>
<td>$-1.58x + 2.01$, $r^2 = 0.96$</td>
</tr>
</tbody>
</table>

revealed in the power spectra are highly suggestive of a single-valued function common to the three subjects.

As with the scaling of $L_v$ to preferred periodic timing, the coefficients of the linear mapping are not identical for the three subjects. A 2-way ANOVA with a continuous variable of $\Delta L_i$ and and a categorical variable of subjects revealed a significant main effect (i.e., slope) of $\Delta L_i$ ($F(1, 84) = 729.06$, $MSe = 0.008$, $p < 0.001$) and a significant interaction between $\Delta L_i$ and subjects ($F(2, 84) = 32.41$, $MSe = 0.008$, $p < 0.001$). The latter result indicates that the slopes of the individual subjects' regression equations are different; specifically, subject 1 is distinguished from subject 2 ($F(1, 55) = 37.17$, $MSe = 0.009$, $p < 0.001$), and subject 3 ($F(2, 55) = 47.65$, $MSe = 0.010$, $p < 0.001$). As with the analysis above, experiment could not be included in the present analysis as a variable because the magnitudes of $\Delta L_i$ did not span the same range for the three experiments. But the regression lines of the individual subjects can be compared for the three experiments separately. Table 4 displays the regression equations for the individual experiments while table 5 displays the results of the pairwise comparisons of the subject regression lines for each experiment.

Table 5
Paired comparisons of subjects' regressions of total power of $\Phi$ on $\Delta L_i$ for the three experiments.

<table>
<thead>
<tr>
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<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
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<tbody>
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<tr>
<td>S1</td>
<td>$\times$</td>
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<td>S2</td>
<td>$^{b}$</td>
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<tr>
<td>S3</td>
<td>$ns$</td>
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<td>$a$</td>
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</tbody>
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Note: The comparisons above the diagonal are for the slopes of the two regression lines while the comparisons below the diagonal are for their intercepts.

* $p < 0.05$; $^{b} p < 0.01$. 

These comparisons corroborate the differences between the subjects indicated in the omnibus regression above and displayed in fig. 2. In general, the total power of $\Phi$ is scaled by $\Delta L_i$ differently for subject 1 than subjects 2 and 3 in that (a) in the $\Delta L_i$ range around 0, subject 1's fluctuations are greater than those of subjects 2 and 3 but (b) in the $\Delta L_i$ range past $-0.3$, subject 1's fluctuations are about equal to those of subjects 2 and 3. This is what the significant slope difference in the ANOVA above indicates. In experiment 1, subject 1's regression differs from subject 2's in intercept and from subject 3's in slope and intercept. In experiment 2, subject 1's regression differs from subject 2 and 3's in both slope and intercept. Lastly in experiment 3, because the different scalings of the total power of $\Phi$ by problem measure $\Delta L_i$ have brought the total power of the subjects into the same part of the parameter space, none of the subject's regressions are different from one another. Although somewhat counterintuitive, the lack of difference in the subject regressions in experiment 3 is just what would be expected from the significant interaction in the above ANOVA and from the regressions displayed in fig. 2. In those omnibus analyses, the regressions of subject 1 and subjects 2 and 3 intersect in the range of $\Delta L_i = -0.3$ to $-0.4$.

In sum, the ANOVA and subsequent regressions corroborate the conclusion that, over the approximately two years of observation, a single function linked $\Delta L_i$ and total power of $\Phi$. As with the mapping between preferred period and $L_v$, it can be argued that each subject abides the same universal function (total power of $\Phi$ linearly increases with $\Delta L_i$) and that the individual differences between subjects are understandable as differences in how this function is parameterized or scaled.

Discussion

In the present article we have focussed on Greene's (1978) claim that at the level of tasks the problem of coordination is relating families of potential circumstances to families of potential movement patterns that accomplish a given goal. The hypothesis is that any task-specific coordination is a function that, given a circumstance, generates a movement pattern satisfying the task criteria.
The hypothesis was evaluated through a simple, bimanual, rhythmic coordination task using hand-held pendulums. Subjects were given two task goals: oscillate the two pendulums (a) at the same comfortable frequency and (b) in antiphase coordination. These goals were to be accomplished in spite of changing circumstances that redefined the coordination problem. The changing circumstances in this task were the total inertial loadings of the two hands (captured by $L_v$) and the difference in the inertial loading of the two hands (captured by $\Delta L_i$). The aspects of the movement patterns that were the indices of the solution of the coordination problem were the preferred cycle duration and the total power of the relative phasing of the two wrist pendulums. Figs. 1 and 2 demonstrate that the mappings of the circumstances to the movement pattern properties were uniform, and further, were uniform in the long term since the same functional form summarizes the data across the 21 months of the three experiments.

What underlies the uniformity observed in these mappings? From either the motor programming or the dynamical perspectives, it is assumed that the subjects exploit a control structure (a motor program or a dynamical system, respectively) in order to accomplish the task. Given this, the uniformity of the mapping in question is a result of the processes by which the control structure is parameterized by the occurring circumstances. From the motor programming perspective, these processes are schema processes that look up stored rules based upon the perceptual analysis of the circumstance. From the dynamical perspective, these are direct, perceptual tuning processes that specify which parameters are required to have which values. The result in either case is a parameterization of the control mechanism which instantiates the function that brings about the mapping of circumstances to movement pattern.

Kugler and Turvey (1987; see also Schmidt and Turvey 1989; Turvey et al. 1988) have proposed that the control structure governing the periodic behavior of wrist-pendulum systems appropriates a very general oscillatory regime. The rationale is as follows. When a person performs a rhythmic movement, a nonrhythmic energy source – the chemical fuel contained within the muscles – is converted into rhythmic excitation. Systems that function in this manner, producing rhythmicity from nonrhythmicity, are usually referred to as self-induced or self-sustained oscillators. They consist essentially of four components: (a) an oscillatory component, made up of an elastic property (the
system's stiffness or spring) that guarantees a return to equilibrium and an inertial property that guarantees overshoot; (b) an energy source that makes up for the loss of energy through friction; (c) a gate that admits energy to the oscillatory component in the right amounts and at the right instants. The challenge of producing a rhythmic movement of a single limb or limb segment is that of assembling neural, muscular, and cardiovascular processes, with their voluntary and autonomous controls, into the functional equivalents of the preceding components. The challenge is further compounded when two or more limbs or limb segments must be moved rhythmically together. Now the functional equivalent of a coupling component (d) that links self-sustained oscillatory mechanisms at disparate bodily locations must be assembled.

Either of the current theoretical perspectives could use this oscillatory hypothesis to explain the present results. From the motor programming perspective, the functioning of the oscillator components and their relation to one another are what needs to be represented in the motor program while the schema contains rules for parameterizing them depending upon the present circumstances. From the dynamical perspective, the task constraints set up a particular task-specific device or coordinative structure in the effector organs that is relatively segregated from mental processes, dynamically governed (in this case by the laws of oscillatory dynamics), and directly tuned by perceptual information. The latter perspective, however, does not require the functional form of the mechanism to be explicitly mentally represented, the perceptual tuning information to be cognitively processed, nor the parameterizations of the control structure to be found in a look-up table.

_Addressing the uniformity and individual variation in the mapping of L_v to \( \tau_c \) (coupled period)_

In view of the preceding comments, we consider the proposal that the long-term, consistent mapping found in fig. 1, and the subject differences evident in that figure and in subsequent analyses, can be explained as the parameterization of the oscillatory regime appropriated to produce the interlimb coordination of rhythmic pendular movements. A variety of considerations (e.g., Kugler and Turvey 1987; Turvey et al. 1988) identify this regime, at resonance, as the regular,
periodic displacement of a point mass about a fixed axis of rotation relative to two conservative forces provided by gravity and a spring. By definition, the work done in overcoming the two conservative forces during periodic displacement is recoverable and stored as potential energy. In biological instances of this regime, the regular periodic displacement is achieved and sustained by contractile, muscular forces; and the spring potential force is provided by the animal's tissues, primarily muscular and tendinous tissues, and adjustable (within limits and depending on species) by neural processes (Turvey et al. 1988). For this regime the resonance equation for the period \( \tau \) of small amplitude oscillations is:

\[
\tau = 2\pi \left[ \frac{ml^2}{(kb^2 + mlg)} \right]^{1/2},
\]

where \( m \) is the mass, \( l \) is the length of the equivalent simple pendulum, \( k \) is the restorative potential (stiffness) provided by biological tissues, \( mlg \) is the restoring torque due to gravity, and \( b \) is a mechanical advantage term (Schmidt and Turvey 1989; Turvey et al. 1988). Eq. (4) can express the eigenperiod \( \tau_c \) of the 1:1 coordination if the two coupled wrist-pendulum systems are regarded as a virtual single system (Kugler and Turvey 1987) with a mass of \( M_\nu = m_1 + m_\nu \), a length of \( L_\nu \) and a virtual elastic potential \( k_\nu \) that indexes the elastic potential at the two wrists:

\[
\tau_c = 2\pi \left[ \frac{M_\nu L^2_\nu}{(k_\nu b^2 + M_\nu L_\nu g)} \right]^{1/2}.
\]

If the subject assembles this oscillatory regime, then both the long-term consistency and subject variations of the mapping between \( \tau_c \) and \( L_\nu \) evident in fig. 1 should be understandable through eq. (5). The double logarithmic regression equations for the data presented in linear coordinates in fig. 1 were \( \log \tau_c = -0.50 \log L_\nu + 0.31 \) \( (r^2 = 0.99) \) for subject 1, \( \log \tau_c = -0.57 \log L_\nu + 0.29 \) \( (r^2 = 0.94) \) for subject 2, and \( \log \tau_c = -0.58 \log L_\nu + 0.29 \) \( (r^2 = 0.94) \) for subject 3, yielding scaling relations of \( \tau_c \propto L_\nu^{0.50} \), \( \tau_c \propto L_\nu^{0.57} \), and \( \tau_c \propto L_\nu^{0.58} \), respectively. By hypothesis, the similarity of the scaling relations across the three subjects (all exponents in the range 0.5 to 0.6) is due to the resonance dynamics expressed by eq. (5) and the common experimenter controlled magnitudes entering into that equation, for example, \( L_\nu \). By
the same token, the dissimilarity of the scaling relations (the difference in the exponents) across the three subjects must be due to the resonance dynamics expressed by eq. (5) and differences in the subject controlled magnitude entering into that equation, viz., $k_v$. Simple calculations using eq. (5) show that $k_v$ for subject 1 was consistently negative (fig. 3), decreasing the total restorative potential of the interlimb system given by the elastic potential of the musculature and the gravitational potential. Hence, the resulting periods for this subject were consistently greater than those due to a purely gravitational pendulum. In contrast, these calculations revealed that subjects 2 and 3 produced consistently positive $k_v$ values (fig. 3), resulting in periods that were consistently less than those of a purely gravitational pendulum.

Eqs. (4) and (5) have been used to provide a uniform interpretation of apparently disparate locomotory time scales that relate the mass ($m$) and length ($l$) of locomotory effectors to the duration of the cycle period. For insects, wing cycle duration scales approximately as $l^{1.0}$ and $m^{0.3}$. For quadrupeds, limb cycle duration scales approximately as $l^{0.5}$ and $m^{0.125}$. For large birds, wing cycle duration scales approxi-
mately as \( l^{0.5} \); but for small birds, like the insects, it scales approximately as \( l^{1.0} \). The traditional explanation of the variance of these scaling relations emphasizes differences in biological design (Calder 1984; Peters 1983). Turvey et al. (1988) found that the oscillatory dynamic captured equivalently in eqs. (4) and (5) underlies all of these various scaling relations. The differences in time scales arise straightforwardly from operating this regime at different ranges of mass and length (e.g., the large magnitudes of the largest terrestrial mammals vs. the small magnitudes of the smallest insects). These results speak to the generality of the identified dynamical regime and its appropriateness as a basis for interpreting the mapping of inertial loading to preferred cycle duration observed in fig. 1. As an additional point, Turvey et al. (1988) presented evidence (primarily from Greenewalt 1962) that the elastic potential contributed by an animal at resonance is proportional to the animal's body weight. In the present experiments, the mean rigidities calculated with the aid of eq. (5) increased with the size of the subject: for the three body weights of 73.5 kg, 74.9 kg, and 78.0 kg, the mean \( k_s \)s were 0.30, 1.38 and 1.75, respectively.

Given the identified oscillatory regime, what precisely must the subject discover in order to perform a 1:1 frequency lock? If the right wrist-pendulum system's period is \( \tau_r = 2\pi[m_r l_r^2/(k_r l_r g)]^{1/2} \) and the left system's period is \( \tau_l = 2\pi[m_l l_l^2/(k_l + m_l l_l g)]^{1/2} \) then, when the two periods are equal (frequency locked),

\[
k_r + m_r l_r g/k_1 + m_1 l_1 g = m_r l_r^2/m_l l_1^2.
\]

That is, to achieve frequency locking, the subject must 'discover' that the ratio of the summed harmonic coefficients, elastic and gravitational, must equal the ratio of the rotational inertias (Bingham et al. 1991). By selecting the stiffness value of one hand, the other is determined by the frequency-locking nature of the task. Given a value for one of the two \( k_s \)s, the constraint defined by eq. (6) sets the value of the remaining \( k \). Bingham et al. (1991), using the two equations of motions of the individual wrist-pendulum systems, derived an equation that demonstrates the dependency of \( \tau \) on \( k_r \) and \( k_l \):

\[
\tau = 2\pi[(m_r l_r^2 + m_l l_l^2)/(k_r + k_1 + gm_r l_r + gm_l l_l)]^{1/2}.
\]
Fig. 4. The relationship between the stiffness assembled by the oscillatory regime in the right hand, $k_r$, and the total power of $\phi$ for (a) the three subjects combined and for (b–d) each subject separately.
Note that eq. (7) contains a nonanalytic form of $L_v$, namely, \((m_r l_r^2 + m_t l_t^2)/(m_r l_r + m_t l_t)\) and demonstrates that $k_v$ is the sum of the two local stiffnesses. Hence, eq. (7) is equivalent to eq. (5). Since all three subjects met the requirement of 1:1 frequency locking across the varied conditions, but did so with different ranges of frequency, it can be concluded that the three subjects (a) satisfied consistently eq. (6), and (b) differed consistently in the selection of the $k$ value ($k_r$ or $k_t$) comprising the one degree of freedom that is set intentionally.

*Addressing the uniformity and individual variation in the mapping of $\Delta L_i$ to fluctuations in $\Phi$*

Some insight into the mechanisms underlying the dependence of fluctuations on $\Delta L_i$ are provided by further consideration of eqs. (6) and (7). Regression analyses reveal that $k_r$ is affected by $\Delta L_i$ while $k_t$ is not. For all three subjects, analyses reveal a highly significant nonlinear decrease in $k_r$ as the magnitude of $\Delta L_i$ moves from positive to negative (S1: \(y = -0.13 + 2.15x + 2.53x^2\), $r^2 = 0.74$; S2: \(y = 0.90 + 6.89x + 7.55x^2\), $r^2 = 0.94$; S3: \(y = 1.11 + 8.92x + 10.57x^2\), $r^2 = 0.92$). These results suggest that the circumstances indexed by the ‘problem measure’, $\Delta L_i$, modulated only the stiffness of one of the hands, namely, the right. How $k_r$ directly scaled the coordination ‘solution measure’, the total power of $\Phi$, can be seen in fig. 4. The data for the three subjects define a continuous nonlinear function (fig. 4a) that indicates that the variability of $\Phi$ decreases as stiffness of the right hand increases. This plot demonstrates the uniformity by which the control structure property of $k_r$ scales the laboratory-observed magnitude of the variability in $\Phi$ across the three subjects. Figs. 4b–d show the relation of $k_r$ to total power of $\Phi$ for each subject separately. The analyses collected in fig. 4 suggest an explanation of the individual differences observed in fig. 2. Subject 1’s mean total power was higher because his mean $k_r$ was smaller than subjects 2 and 3. Further, subject 1’s slope in fig. 2 was more shallow because the rate of change of $k_r$ with $\Delta L_i$ (see regression equations above) was smaller for subject 1 than for either subject 2 or subject 3. Finally, because subject 1’s $k_r$ does not decrease as quickly with $\Delta L_i$ as do the $k_r$ magnitudes of subjects 2 and 3, subject 1’s total power does not increase as quickly.
Concluding remarks

A remarkable feature of a well-practiced coordination is that one can perform it reliably and repeatedly in the face of highly variable contexts (e.g., Fowler and Turvey 1978; Higgins and Spaeth 1972; Kelso et al. 1985; Schmidt 1975). Because the contexts are mostly novel, the ability to assemble the same coordination each time can be said to express ‘generativity’ or ‘productivity’, a quality that is frequently highlighted in discussions of language, and in the phrasing of arguments for a language-like representational medium (e.g., Fodor 1975). Although this characteristic quality of the movement system is well respected (e.g., Bartlett 1932; MacNeiilage 1970), it is rarely the subject of rigorous theorizing and direct experimental analysis. One proposal is that this characteristic quality expresses a general principle in which both variable circumstances and variable movement patterns constitute single state spaces such that every task is potentially a single-valued function mapping one total space into the other (e.g., Greene 1975a, 1975b, 1978). Support for the foregoing proposal is provided in the present article by the demonstration of functions governing a simple rhythmic interlimb coordination task that are invariant over an extended time scale and over different individuals.

References


