INFORMATIONAL CONSTRAINTS IN PERCEPTION-ACTION COUPLING

by

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ABSTRACT

The present work sought to investigate informational constraints in perception-action coupling through the study of spatial constraints and to extend the study of perceptual-motor compatibility to coordination. A paradigm of person environment coordination was employed in which rhythmic forearm rotations were coupled to a periodic visual stimulus. Four experiments were performed. Experiment 1 examined basic spatial constraints through the study of the relation between information-action mappings and configurations and their impact on coordination dynamics. The intrinsic dynamics of the coordination mappings were influenced by the information-action configuration. Under orthogonal configurations, the mappings, up-right/down-left and up-left/down-right, were arbitrary compared to in-phase and anti-phase mappings. This was reflected in the general absence of stability differences between these orthogonal mappings. This equistability was attributed to a symmetry in the informational constraints imposed by the orthogonal mappings. Experiment 2 proceeded with an investigation of whether the information-action global spatial relation mediated the interaction between configuration and mapping. Response location was manipulated in order to change the global spatial relation. The preferred orthogonal mapping changed as a function of the global relation. Indications were of an up-right/down-left preference for movements performed in ipsilateral space and a trend toward an opposite preference for contralateral space. Experiment 3 extended the investigation of the influence of spatial configurations on coordination dynamics and finally, Experiment 4 studied the asymmetric dynamics of perception-action coupling under spatial parameter scaling. These experiments further confirmed the intrusion of spatial constraints in visual coordination. Moreover, compatibility effects were noted even when the coordination mappings were based on a mapping of an informational feature to action and not based on both the spatial dimensions of the information and action. In sum, the results suggested that spatial constraints impinged upon visual coordination dynamics.

DEDICATION

To Brenda, for her love

What a piece of work is man! how noble in reason! how infinite in faculty!
in form and moving how express and admirable! in action how like an angel!

Hamlet, Act II scene ii
William Shakespeare

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I have benefitted considerably from the contributions of many individuals over the last several years. To this collective, I wish to extend my sincere thanks. The cast of characters has been large and I will mention only a few by name. It has not been easy following the likes of my friends and predecessors, Richard Carson and Winston Byblow. Richard has been a mentor for much longer than he will ever admit and Winston provided fuel and guidance for my early forays into systems dynamical (and informational). David Goodman and Digby Elliott started me on my academic journey, and Daniel Weeks has been an invaluable force throughout this work. Dave provided support and freedom to explore and wander far from equilibrium. Digby and Dan have never failed to offer their guidance, encouragement, support, and friendship, often beyond the call of duty. I have always found their doors open. Finally, to my wife and family, I thank you always for your love.

TABLE OF CONTENTS

LIST OF FIGURES

INFORMATIONAL CONSTRAINTS IN PERCEPTION-ACTION COUPLING

1. Introduction

1.1 Motor Control: A Behavioural Emphasis

The puzzle of how action is effected has long intrigued scientists. The importance of movement as a probe into neural mechanisms and psychological functions has been championed by such scientists as Helmholtz, Sherrington, Woodworth, von Holst, Bernstein, Fitts and many others (Jeannerod, 1985, 1988). Central to the relation between brain and behaviour is the problem of how movements are organized and controlled. The scientific field of study concerned with this problem is generally known as Motor Control.

Students of motor control have available to them a variety of approaches with which to examine the nature movement organization and control. These approaches to the study of motor control occur at different levels of resolution, requiring different perspectives, and utilizing different concepts and tools. At a biomechanical level, the student seeks to understand the physical basis for movement and the mechanical factors, or rules, that govern human movement. At a neurophysiological level, the student seeks insights into the neuronal machinery and the functional neural interactions that underlie motor control. At a behavioural level, the student seeks to understand the structures and processes underlying movement without reference to their physical instantiation. The focus in the present work will be primarily at, though not exclusive to, a behavioural level of analysis. It is likely that a thorough understanding of motor control will require some integration of all of the above approaches; however, such integration is beyond the scope of the present inquiry. It is acknowledged that underlying human perception and action are the collective interactions of many biological mechanisms; however, of greatest concern here, are the emergent properties of the system as a whole, rather than its physical realization (e.g., Rosenbaum, 1991).

1.2 Information-Processing

After a lengthy and diverse history (e.g., see Schmidt, 1988 for a brief overview), the field of motor behaviour emerged as a distinct area of experimental psychology which inquired into such issues as the information capacity of the motor system (e.g., Fitts, 1954), the attentional demands of movements (e.g., Posner & Keele, 1969), motor memory (e.g., Adams & Dijkstra, 1966), processes of motor learning (e.g., Adams, 1971), and the nature of motor programs (e.g., Keele, 1968). The language of information-processing (e.g., Shannon & Weaver, 1949) provided the vehicle for discussions of mental and computational operations of the cognitive and perceptual-motor system (Posner, 1982). The information-processing approach has been central to the field of cognitive psychology (Neisser, 1967) and has comprised a major perspective in motor behaviour (Marteniuk, 1976).

Under the information-processing approach (e.g., Fitts, 1964; Marteniuk, 1976; Stelmach, 1982), the human is viewed as an active processor of information. The central nervous system is likened to a communications channel and perceptual-motor performance is viewed as involving processes such as information transmission, information translation, information reduction, collation, and storage (Fitts, 1964). The fundamental tenets of the information-processing approach are that mental operations take time, and that there exists a number of processing stages between stimulus input and a response (Donders, 1868-1869). Of interest in the study of movement is the nature of the cognitive processes which underlie and subserve action.

A key feature of the information-processing approach is its emphasis upon the cognitive activities that precede the movement (Marteniuk, 1976; Stelmach, 1982). From this perspective, the movement is viewed only as the end-result of a complex chain of information-processing activities, each of which takes some finite time (Marteniuk, 1976). Thus, chronometric measures such as reaction time, as well as other global outcome measures, are the predominant dependent measures of interest. More recently, however, investigators have also advocated a "movement process" approach (e.g., Kelso, 1982) to supplement chronometric explorations. The argument is that if researchers are to understand the nature of movement organization and control and the underlying processes, they should also examine the movement itself (e.g., Kelso, 1982; Marteniuk, MacKenzie, & Leavitt, 1988). Thus, investigators have begun to examine the kinematics of movements in attempts to further understand the underlying organization involved (e.g., Brooks, 1974; Chua & Elliott, 1993; Elliott, Carson, Goodman, & Chua, 1991; Kelso, Southard, & Goodman, 1979; MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987).

Evolving in parallel to the information-processing perspective in the past two decades has been an approach to understanding motor behaviour grounded in physical biology. Influenced by the views of Gibson (1966, 1979) and the work of Bernstein (1967), Turvey (1977; e.g., see also Turvey, Fitch, & Tuller, 1982) led the call for an "ecological approach" to the study of perception and action and brought to the forefront Bernstein's (1967) formulation of the "degrees of freedom" problem as one of the major problems in motor control.

2. Coordination Dynamics

2.1 Degrees of Freedom Problem

Bernstein (1967) defined the basic problem of coordination as that of the mastering of the body's many degrees of freedom involved in a particular movement. In the first round of theorizing relevant to Bernstein's "degrees of freedom" problem (e.g., see Kugler, Kelso, & Turvey, 1980; Turvey, 1977, 1990 for overview), one solution proposed was the assembly of coordinative structures, or equations of constraint, which serve to reduce the relevant degrees of freedom involved in a particular movement (Kelso et al., 1979)[1]. In the second round, a dynamical systems approach to movement coordination has evolved from the early investigations into Bernstein's (1967) degrees of freedom problem (e.g., Kugler et al., 1980). This approach seeks to explain movement regulation and coordination in terms of fundamental, physical laws and principles (Turvey, 1990; see Jeka & Kelso, 1989 for a tutorial). This theoretical perspective is characterized by the application of the tools and principles from physical biology, synergetics (self-organization), and nonlinear dynamics. Under the dynamics perspective, a coordinative structure may be regarded as an instantiation of a dynamical system (Kugler et al., 1980). One feature of dynamical systems is that the degrees of freedom of the system are usually larger than that of the observed behaviour. The evolution of the dynamical system over time itself may serve to constrain the relevant number of degrees of freedom (e.g., Kay, 1988). Thus, it is not necessary to have some higher order executive prescribe control over each degree of freedom of the system.

2.2 A Dynamical Systems Approach

The study of the dynamics of action shows great promise with respect to the understanding of coordination and control of action. The dynamical systems approach seeks to understand movement in terms of lawful (holonomic constraints) processes and principles, rather than in terms of some higher order executive prescribing instructions for control (non-holonomic constraints). Proponents of dynamics argue that the study of movement must address firstly the laws, the dynamics, the holonomic constraints, and secondarily the non-holonomic constraints (Turvey, 1994).

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[1] The characterization of research into Bernstein's "degrees of freedom" problem into a first and second round is borrowed from Turvey (1990).

Dynamical systems theorists approach the degrees of freedom problem from a lawful, perspective and seek to view movement coordination as continuous with the physical problem of pattern formation in open systems (e.g., Kugler et al., 1980; Schöner & Kelso, 1988). In the language of dynamics, movement systems are thought of as self-organizing systems, whereby patterns emerge from the interaction of the many degrees of freedom inherent in the system. Thus, the theoretical and analytical tools and principles of synergetics and nonlinear dynamics become relevant to the study of movement systems (e.g., see Beek, 1989; Schöner & Kelso, 1988). Furthermore, with the application of these tools, the set of observables (or measurable, dependent variables) are extended to capture the richness of movement dynamics more adequately.

Kelso and Schöner (1988; Schöner & Kelso, 1988) have outlined what they refer to as a synergetics strategy for a dynamic pattern approach to understanding movement behaviour. The main features of this strategy, some of which comprise the basic issues in dynamics, are:

a) the identification of collective variables or order parameters which characterize the movement patterns;
b) the mapping of the observed stable patterns onto attractors of the collective variable dynamics;
c) the identification of control parameters which lead the system through its collective states;
d) the study of stability and loss of stability of the movement patterns, which allows a determination of the dynamics of the collective variable; and
e) the establishment of a relation amongst levels of observation by deriving collective variable dynamics from the coupling amongst components.

As the name dynamic pattern implies, a key element of the approach is the identification of patterns (in the present context, behavioural patterns) relevant to the system under study. The primary strategy for identifying these patterns is to find phase transitions or bifurcations, situations in which one observes qualitative changes in the system's behaviour. The phase transition demarcates one pattern from another, and the qualitative change allows one not only to distinguish between the patterns but also to identify the relevant dimension of the pattern (Jeka & Kelso, 1989; Kelso, 1994). It is also the change about the phase transition that helps to identify the relevant collective variable, or order parameter, that characterizes the pattern itself. The parameter or dimension which is manipulated to lead the system through the transition is designated as the control parameter. Thus, the order parameter is the dimension which characterizes the patterns, whereas the control parameter which leads the system through its collective states remains unspecific and carries no information about the pattern that emerges. A second important element of the synergetics strategy is the study of stability and loss of stability of the patterns. The study of the system's stability or instability allows a determination of the system's dynamics. It is the stability of a given pattern that distinguishes it from others, characterizing the state in which the system resides. Moreover, dynamical instabilities, or the loss of stability, is hypothesized to be a mechanism that effects a change in pattern (Jeka & Kelso, 1989; Kelso, 1994). Thus, it is the loss of stability of a pattern that may lead to a bifurcation to a new pattern, one distinguished by its greater stability.

The determination of a system's dynamics can be done at two levels, related to the kinds of changes that occur. If a system exhibits qualitative changes between equilibria, that is, a phase transition, the dynamics can be described as global. If a system exhibits change without a change in equilibria, then the dynamics can be described as local (Schmidt & Turvey, 1995). It is not always the case that a coordinative system will exhibit bifurcations given the boundary conditions present in a natural or experimental context. Thus, additional techniques for the study of steady state behaviour and local dynamics have also been employed to complement the phase transition methodology (e.g., Kugler &

Turvey, 1987; Schmidt, Shaw, & Turvey, 1993; Schmidt, Treffner, Shaw & Turvey, 1992; see Schmidt & Turvey, 1995 for review). This approach is characterized by the observation of the system dynamics in regions in which transitions are less likely to occur.

2.3 Interlimb Coordination

Impetus for employing dynamical analyses in motor control came from the seminal work of Kelso (1981, 1984) on interlimb coordination. Examples of phase transitions had often been cited in the form of the abrupt transitions that occur in quadruped gaits as speeds of locomotion increase. Interested in bimanual coordination, Kelso designed an experiment to examine whether a similar transition could occur in human movement. In his study (Kelso, 1981), subjects were required to perform rhythmic, bimanual oscillations of the two index fingers in either of two modes of coordination: a) in-phase, in which homologous muscles contracted simultaneously and b) out-of-phase or anti-phase, in which homologous muscles contracted in alternating fashion. Subjects were also asked to perform their movements at a frequency specified by a metronome. Frequency was scaled upwards as a trial progressed. The phase difference between the individual phases of the fingers (in terms of their position within a cycle) was identified as a candidate order parameter, or collective variable, in that it adequately captured the coordination pattern between the fingers. The frequency of movement oscillation was identified as a relevant control parameter, in that scaling of frequency led the system through its collective states.

The findings showed that subjects were able to maintain an in-phase pattern as the frequency of oscillation was scaled upward. However, when subjects initially began cycling in an anti-phase pattern, a change of pattern, that is, a phase transition, occurred as frequency was increased. The anti-phase pattern became difficult to maintain and a bifurcation to an in-phase pattern ensued. Stability of the pattern, measured as variability in the phase relation, decreased and was lost as the coordinative system reached the critical bifurcation point. However, when frequency was decreased, there was no return to the original anti-phase pattern, demonstrating the phenomenon of hysteresis.

Similar phenomena have been observed in earlier studies of bimanual coordination. For example, Yamanishi, Kawato, and Suzuki (1980) found in a study of bimanual finger tapping that synchronous and alternate tapping (in-phase and anti-phase, respectively) patterns were more stable and accurate than other relative phase patterns. Cohen (1971) in a study of bimanual wrist rotations, found that anti-phase coordination, in which non-homologous muscles were active simultaneously, exhibited greater variability and difficulty than in-phase coordination, in which homologous muscles were active simultaneously. Moreover, Cohen (1971) also observed occasional transitions to occur from the anti-phase to the in-phase pattern. Kelso's (1981, 1982) findings were therefore consistent with and supported by earlier studies. What followed was a rigorous pursuit, in both theory and experiment, of the principles underlying coordination.

2.4 A Model of Coordination Dynamics

Haken, Kelso, and Bunz (1985) introduced a mathematical model (hereafter referred to as the HKB model) to describe the empirical findings of Kelso (1981, 1984). A key idea, as alluded to in the previous section, was to map the observed coordination patterns onto attractors of a dynamical model. The model was motivated by the observations that (a) in-phase and anti-phase were the predominant patterns, (b) anti-phase coordination became unstable as movement frequency was scaled and a transition to in-phase coordination ensued, and (c) decreasing frequency did not result in transitions from an in-phase to an anti-phase pattern. Haken et al. (1985) captured the dynamics of the collective variable, relative phase, with the following dynamical model:

$$V = - a \cos(\phi) - b \cos(2\phi) \qquad (1)$$

in which V is a potential function, and a and b are parameters. The dynamics of the system described by Equation (1) can be visualized with a portrait of the potential. Relative phase, ϕ, can be represented by a ball on the potential landscape. Stable attractors are represented by local wells within this landscape. Figure 2.1 displays the potential landscape described by the HKB equation. When the ratio of the parameters a and b, specifically b/a, is equal to 1, an attractor exists at $\phi = 0$ (0° - in-phase) and $\phi = +/- \pi$ (180° - anti-phase). When the ratio of the parameters is decreased (corresponding empirically to an increase in movement frequency), the anti-phase attractor basin becomes shallower and eventually is annihilated. This corresponds to the empirically observed transition from an anti-phase pattern to an in-phase pattern (depicted by the ball in Figure 2.1). Further apparent in Figure 2.1 is that there would be no transition from in-phase to anti-phase if the parameter ratio was either increased or decreased, thereby characterizing the empirically observed phenomena of hysteresis (see also Jeka & Kelso, 1989).

The HKB model has subsequently been elaborated with the addition of a stochastic force to describe non-deterministic aspects of the dynamics (Schöner, Haken, & Kelso, 1986) and a symmetry breaking term to characterize oscillating components which differ in nature (e.g., Kelso, DelColle, & Schöner, 1990). The extensions to the HKB model (e.g., Schöner et al., 1986) predict other hallmark features of physical bifurcations and dynamical instabilities, namely, the enhancement of phase fluctuations (critical fluctuations) and increased relaxation times in response to perturbations (critical slowing down) that occur as a system approaches criticality. Subsequent experimental observations of these features in interlimb coordination (e.g., Kelso, Scholz, & Schöner, 1986; Scholz, Kelso, & Schöner, 1987) lend credence to a dynamical interpretation of the transitions observed in interlimb coordination.

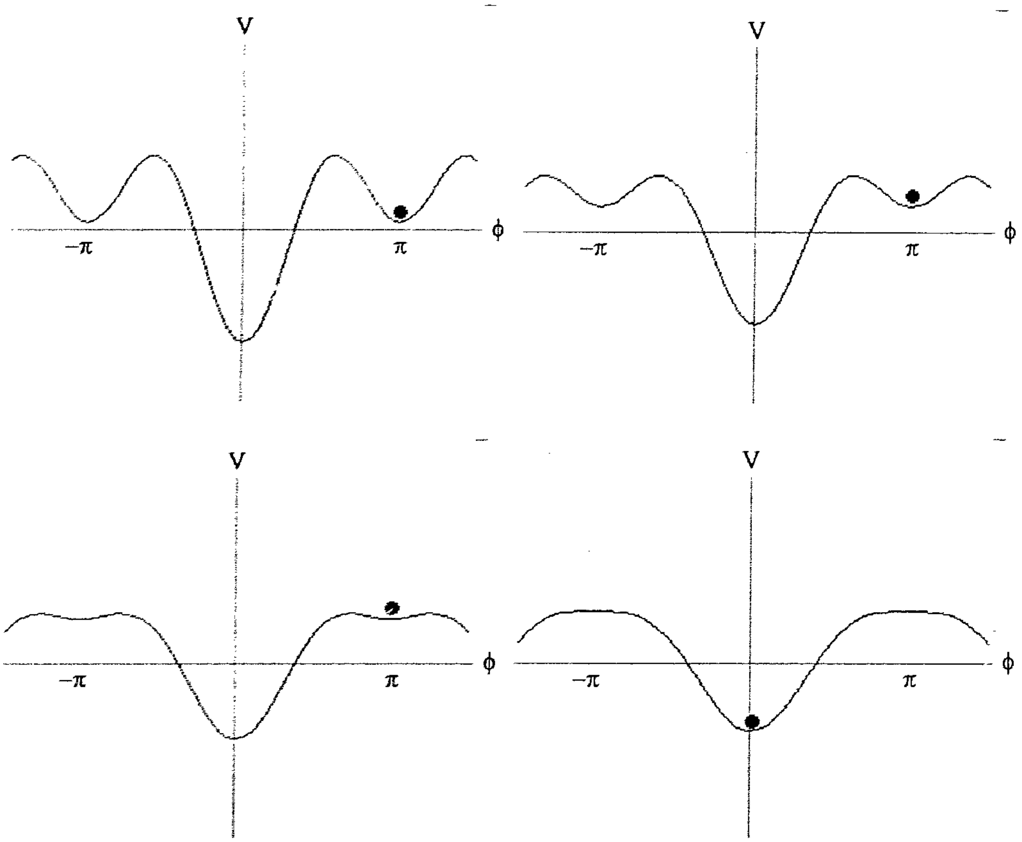

Figure 2.1 HKB potential (V = - a cos (ϕ) - b cos (2ϕ)). As ratio of parameters *b/a* is decreased (top left to bottom right of figure), the attractor at ϕ = 180° disappears and *relative phase* (represented by ball) settles into the attractor at ϕ = 0°. The potential shifts from a *bistable* to *unistable* landscape as critical ratio of *b/a* is reached.

Recent empirical demonstrations that the predictions from the HKB model may generalize to other instances of within-person interlimb coordination, between-person coordination, and person-environment coordination (these are described in the following section) speak to the generality of the HKB model as a model of coordination dynamics (see Fuchs & Kelso, 1994; Schmidt & Turvey, 1995, for a review and discussion). The HKB model has been regarded as a phenomenological law of interlimb rhythmic coordination; that is, it expresses invariant relations among observable quantities, but it does so without (as yet) elaborating upon the neural, physiological, or biomechanical mechanisms that underlie these invariants (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1994; Schmidt & Turvey, 1995).

2.5 Dynamics of Perception-Action Coupling

In human motor activities, it is often the case that, not only do we have to master our body's degrees of freedom to bring about coordinated movement, but we must also coordinate our actions with some environmental event. This event may be in the form of some external, visual or auditory stimulus. In these cases, our actions must be coupled with the environmental information. A question that arises, therefore, is whether perceptual information specific to the external event entrains our actions (e.g., Kelso et al., 1990; Schmidt, Turvey, & Carello, 1990), and whether similar dynamical principles as those observed in interlimb coordination apply. Indeed, empirical work suggests that the dynamics observed in interlimb coordination is not unique to a system in which some material linkage (e.g., a neuromuscular system) exists between the components in coordination. Similar dynamic patterns have also been observed in systems formed by a coupling of action and perception. As in the study of interlimb coordination, the theoretical strategy has been to study perception-action coordination as a pattern formation process, that is, to characterize perception-action patterns in terms of their dynamics (Kelso et al., 1990).

Schmidt et al. (1990) have examined whether the dynamics observed in within-person coordination also applies to between-person coordination. They asked a pair of subjects to each oscillate a leg, with the goal of coordinating the legs in either an in-phase or anti-phase pattern, as the frequency of oscillation was increased. As with within-person interlimb coordination, a phase transition from an anti-phase pattern to an in-phase pattern was observed as oscillation frequency increased. Moreover, the dynamics were dependent upon the presence of an optical linkage between the two persons. That is, no phase transitions occurred if the subjects were asked to coordinate their legs without watching each other (see also Schmidt & Turvey, 1994).

In both examples of within-person and between-person coordination, there exists a bilateral linkage, or coupling, between the components in coordination: neuromuscular in the former and optical in the latter. The coupling is bilateral in that the events in each component (i.e., one oscillator) may affect the other. Perception-action systems can also be formed over a unilateral coupling, in which, for example, action is entrained to some external stimulus that is unaffected by the action (e.g., tapping to a beat). For example, Kelso et al. (1990) have shown that in a situation in which a rhythmic finger movement is coordinated with a rhythmic auditory stimulus, similar coordinative patterns and dynamics emerge as in the case of bimanual coordination. When subjects were asked to coordinate a finger flexion "off the beat" of a metronome (defined as an "anti-phase pattern"), a transition to an "in-phase" pattern, in which flexion was "on the beat" of the metronome, occurred as metronome frequency increased. In the study of Kelso et al. (1990), the linkage between perception and action was through auditory information. The same dynamical constraints also seem to operate when action is unilaterally coupled with visual information. Wimmers, Beek, and van Wierengen (1992), and Byblow, Chua, and Goodman (1995) asked subjects to perform rhythmic arm movements in coordination with a sinusoidal visual signal. Consistent with the results for the bilateral, optically coupled, between-person system, anti-phase patterns were found to be less stable than in-phase patterns. Bifurcations from anti-phase to in-phase, preceded by increasing instability of the anti-phase pattern, were also noted as oscillation frequency increased (Wimmers et al., 1992).

Results from examinations of perception-action coupling (e.g., Byblow et al., 1995; Kelso et al., 1990; Schmidt et al., 1990; Wimmers et al., 1992) demonstrate that the dynamics of these coupled systems exhibit the same dynamical properties as that observed in within-person interlimb coordination. The above examples of perception-action coupling do, however, differ from within-person coordination in many ways. For example, in the case of between-person coordination, notable differences are that in the two-person case, two cognitive/neural systems are involved as opposed to one, and the linkage is formed over the visual perceptual system as opposed to the haptic perceptual system. Nonetheless, it appears that, in the language of dynamics, anatomical and informational (optical) connectives between rhythmic actions are similar (Turvey, 1990). Phase information may be communicated via visual, auditory, or kinesthetic information within the individual, between individuals, or between the individual and the environment (Kelso, 1994). The dynamical principles by which these systems abide appear to be indifferent to the nature of the coupling (Schmidt & Turvey, 1994). What is observed is that dynamical descriptions and principles transcend levels of observation. Similar dynamics emerge in coupled systems with different interacting components. As intimated in the studies described above, inherent in the dynamical systems approach to perception-action coordination is a departure from the material substrate producing the coordinative patterns, and a focus upon the dynamical laws governing the patterns (Kelso, 1994; Kelso et al., 1990).

2.6 Informational Constraints

The consideration of information and its interaction with action opens the door for further investigation into the dynamics of perception-action coordination. A consideration of informational interactions in coordination may allow the elucidation of the role of informational constraints in the coupling of perception and action. That is, how do informational constraints impinge upon patterns which emerge in perception-action coupling?

For example, in perception-action coordination (e.g., Schmidt et al., 1990; Wimmers et al., 1992), the influence of the dynamics underlying the control parameter - that which drives the system - on coordination dynamics may be examined. That is, it may be of interest to determine in what manner might information which defines perception-action dynamics, influence the dynamics of coordination? In a recent study of visual coordination briefly described earlier, Byblow et al. (1995) varied the informational dynamics of the control parameter (i.e., the visual stimulus) and examined its impact on the coordination dynamics. In a unimanual coordination task, subjects were required to coordinate rhythmic forearm movement with a periodic visual stimulus. The stimulus changed position either discretely, denoting two endpoints of a cycle , or pseudo-continuously across a display. Results showed that the perception-action couple, of which the pseudo-continuous visual stimulus was a component, was inherently more stable than the system composed of the discrete visual stimulus. The continuous visual information-action system enjoyed an advantage in relative phase variability, as well as the duration for which stable coordination was maintained. Thus, the dynamics underlying the information driving the system impinged upon the coordination dynamics.

In visual coordination tasks (e.g., Byblow et al., 1995; Schmidt et al., 1990; Wimmers et al., 1992), another important informational constraint is the spatial correspondence between the visual information and the movement. Indeed, in contrast to interlimb coordination (e.g., Carson, Byblow, & Goodman, 1994; Kelso, 1981, 1984) in which coordination patterns are defined at the level of muscle activation, coordination patterns in visual coordination are defined according to spatial relations.[2] For example, in between-person coordination (Schmidt et al., 1990), or person-environment coordination (Byblow et al., 1995; Wimmers et al., 1992), anti-phase and in-phase patterns are defined respectively as movement in the opposite or same direction as the driving visual information. The differential stability of these patterns correspond to their counterparts in interlimb coordination. What these studies of visual perception-action coupling (e.g.,

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[2] Interestingly, the muscular dependency of the phase patterns (e.g., Riek, Carson, & Byblow, 1992) in bimanual coordination does not seem to extend to multijoint coordination (e.g., Buchanan & Kelso, 1993; Kelso & Jeka, 1992). In multijoint coordination, it is easier to coordinate joints of the same or different limbs when these joints are rotated in the same direction (e.g., Kelso, Buchanan, & Wallace, 1991).

Schmidt et al., 1990) bring to light is the spatial dependence of the visual coordination dynamics.

The intrusion of spatial constraints into action is certainly not without precedent. The spatial dependence of response selection in choice reaction time situations is well established and forms a cornerstone of the study of *stimulus-response (S-R) compatibility* (e.g., Fitts & Seeger, 1953; see Proctor & Reeve, 1990 for review). However, the consideration of spatial constraints in coordination has received relatively less attention. The examination of spatial, informational, constraints in perception-action coupling holds the promise that S-R compatibility, an aspect of perceptual-motor behaviour that has predominantly existed within the purview of cognitive science, might be empirically and theoretically broadened by a dynamical framework. Empirically, this can be accomplished by considering how the spatial relation between the perceptual (visual) event and the action with which it forms a coupled system, affects the stability of perceptual-motor coordination. Further, the examination of compatibility constraints in coordination may provide a window into one of many possible informational constraints on the dynamics of perception-action coupling.

3. Perceptual-Motor Compatibility in Perception-Action Coupling

3.1 S-R Compatibility: From Static to Dynamic

Research on S-R compatibility has long been the province of cognitive science (e.g., see Proctor & Reeve, 1990; however, see Michaels, 1988, for a recent ecological treatment of compatibility). However, recent dynamical explorations of perception-action coupling (e.g., Byblow et al., 1995; Wimmers et al., 1992) suggest that, within the language of dynamics, tools may be available to assess compatibility phenomena (specifically, spatial compatibility) at quantitatively and qualitatively different levels.

The concept of spatial S-R compatibility traditionally refers to the dependence of the speed and accuracy of response selection on the spatial relation between the stimulus and response. It has been repeatedly demonstrated, since the work of Fitts and Seeger (1953), that choice reaction time to stimuli in a spatial array are shorter when the arrangement of the stimulus and response alternatives is spatially compatible. In what has now become a classic study, Fitts and Seeger (1953) examined compatibility effects on a task in which subjects moved a stylus on a response panel to a position indicated by the spatial location of a stimulus light on a display panel. Three different displays and three different response panels were used in all possible combinations. The display and response panel configurations are shown in Figure 3.1. The results showed that performance (in terms of reaction time and errors) was best when the stimulus display configuration resembled the response panel.

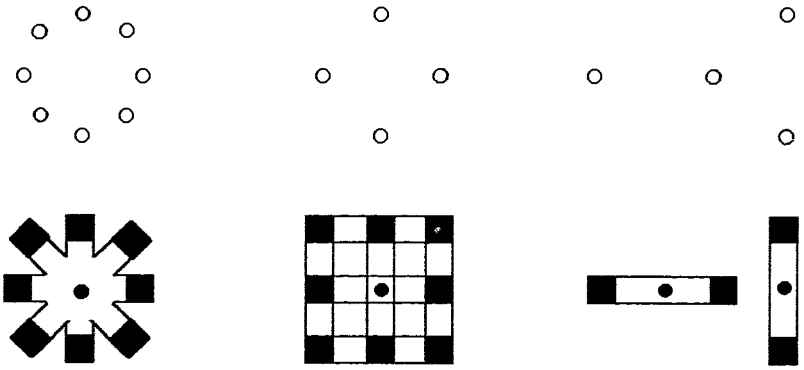

Figure 3.1 Schematic of stimulus displays (top) and response panels (bottom) employed by Fitts and Seeger (1953). Subjects moved a stylus from central position to a panel endpoint corresponding with spatial position of imperative stimulus.

The prototypical task for the study of spatial compatibility is a two-choice reaction time task in which visual stimuli are presented to the left or right of a central fixation point and a response (usually a keypress) at a left or right location is required. In a compatible situation, a left stimulus is mapped to a left response and a right stimulus is mapped to a right response. In an incompatible situation, the assignment of stimuli to responses is reversed.

In a typical two-choice reaction time task, compatibility effects have been shown to be generally independent of the actual effector used for responding, as well as the location of the effector. For example, rather than using the left and right hands to make left and right responses, respectively, the hands may be crossed such that the distinction between left and right response locations is unconfounded from that between left and right response effectors. In this crossed-limbs situation, a direct spatial correspondence between the stimulus location and response location, not effector identity, remains the compatible relation (e.g., Brebner, 1973; Wallace, 1971). A variation of the two-choice task in which sticks (that could either be crossed or uncrossed with respect to the body midline) are used to manipulate response keys has also been employed to demonstrate that compatibility effects depend upon the location of the response key, and not the location at which the effector action occurs (e.g., Riggio, Gawryzewski, & Umiltà, 1986). Moreover, it is the relative, and not the absolute, locations of the stimuli and responses that impact upon compatibility. Compatibility effects prevail when both stimuli and both responses occur in the same hemispace (e.g., Nicoletti, Anzola, Lupino, Rizzolatti, & Umiltà, 1982; Umiltà & Liotti, 1987). Compatibility phenomena also transcend the modality and category of the spatial parameter. Compatibility effects emerge when the spatial dimension of the stimuli are provided verbally (e.g., McCarthy & Donchin, 1981), when left and right responses are given verbally (e.g., Weeks & Proctor, 1990), or when the left and right dimension is specified symbolically with arrow stimuli (e.g., Proctor, Van Zandt, Lu, & Weeks, 1993; Weeks & Proctor, 1990).

Compatibility has been defined as "the degree to which relationships are consistent with human expectations ... where compatibility relationships are designed into the system, (1) learning is faster, (2) reaction time is faster, (3) fewer errors are made, and (4) user satisfaction is higher" (Sanders & McCormick, 1993, p. 302). This definition of compatibility, and others like it, has emerged from three prevalent aspects of the compatibility literature:

1) the concept of S-R compatibility is largely based upon information-processing effects that are indexed in reaction time and error measures;
2) choice reaction time tasks are the predominant tool of choice;
3) the tasks typically employ static stimulus and response arrays.

One outcome is that such definitions of compatibility may preclude a broader range of perceptual-motor interactions that might be captured by an extended theoretical framework.

As mentioned above, the large body of work on compatibility phenomena (e.g., Proctor & Reeve, 1990, for overview) is characterized by choice reaction tasks that employ static stimuli and responses. Not surprisingly, recent theoretical interest has emerged in the manner in which compatibility is expressed in tasks employing dynamic (as opposed to static) stimulus and response arrays (e.g., Michaels, 1988; Proctor et al., 1993). For example, Michaels (1988) employed a computer graphic of a moving, expanding square as a stimulus in conjunction with a joystick movement as a response to examine whether motion towards a position elicits faster responses at that position.

This recent interest in dynamic stimulus and response arrays is somewhat ironic given that Fitts and Seeger (1953) essentially employed a dynamic response set in their initial set of studies. Nevertheless, these studies (e.g., Michaels, 1988; Proctor et al., 1993) continue to employ reaction time as the primary measure of interest and examine efficiency in response selection.

3.2 Compatibility as Dynamic Stability

As a complement to more traditional definitions of compatibility, I propose a systematic alternative to assess compatibility in dynamic situations that assumes the logic laid out in earlier discussion concerning the application of a dynamical systems framework to the study of perceptual-motor behaviour. Specifically, to capture those perceptual-motor interactions in which some form of coordination is required between the stimulus (information) and response (action), I propose that:

1) the level of analysis and the concept of compatibility be extended to encompass the movement, particularly, the coordination between information and action,
2) the analytical tools from dynamical systems theory be employed to assess spatial compatibility in dynamic situations, and
3) an empirical strategy that integrates the concepts of compatibility and the dynamical notion of stability in the coordination of information and action be adopted.

A potential theoretical outcome would be the extension of compatibility to dynamic perceptual-motor interactions through the inclusion of dynamical stability of coordination as a defining feature. A key aspect of the above is the examination of compatibility relations at a level of analysis appropriate for the study of coordination. This entails moving from measures of response times to indices of dynamical stability. Just as dynamical stability (or instability) allows us to distinguish coordination patterns from one another (see Section 2.2), stability may allow us to distinguish preferred, or compatible, information-action relations from one another. In sum, compatibility effects are expected to be associated with the degree of stability of coordination.

3.3 Casting Compatibility in Dynamical Terms

As a a precursor to examining compatibility at the level of perception-action coupling, I propose the following characterization of the relations between information and action. In visual coordination tasks such as those employed by Byblow et al. (1995) and Wimmers et al. (1992), the spatial relations between information and action may be captured by a taxonomy that distinguishes between the:

a) Information-Action *Mapping*,

b) Information-Action *Configuration*, and

c) Information-Action *Global Relation*.

Information-action mapping refers to how visual information is mapped onto the movement, or action. This is associated with the characterization of the in-phase and anti-phase modes of coordination in compatibility terms. The in-phase mode, in which one's movement is in the same direction as the movement of the driving visual information, may be considered as a "compatible" mapping. In contrast, the anti-phase mode, in which one's movement is in the opposite direction of the visual information, may be considered as an "incompatible" mapping.

Information-action configuration refers to the orientation of the information with respect to the action; that is, for example, whether the stimulus and response arrays are arranged in parallel or orthogonal to one another. Information-action global relation refers to the overall spatial relation between the visual information and the movement. For example, whether information and action occur in the same or opposite side of the body midline would be subsumed under this category.

As it has been repeatedly demonstrated in previous coordination work (see Jeka & Kelso, 1989; Schöner & Kelso, 1988, for overview) the anti-phase mode is expected to be less stable than the in-phase mode. That is to say, an "incompatible" mapping of information to action is expected to be less stable than a "compatible" mapping. It remains to be elucidated whether compatibility in terms of the information-action (or S-R) configuration or global relation impinges upon the differential stability of "compatible" and "incompatible" mappings and acts as a constraint upon the dynamics of these information-action couplings.

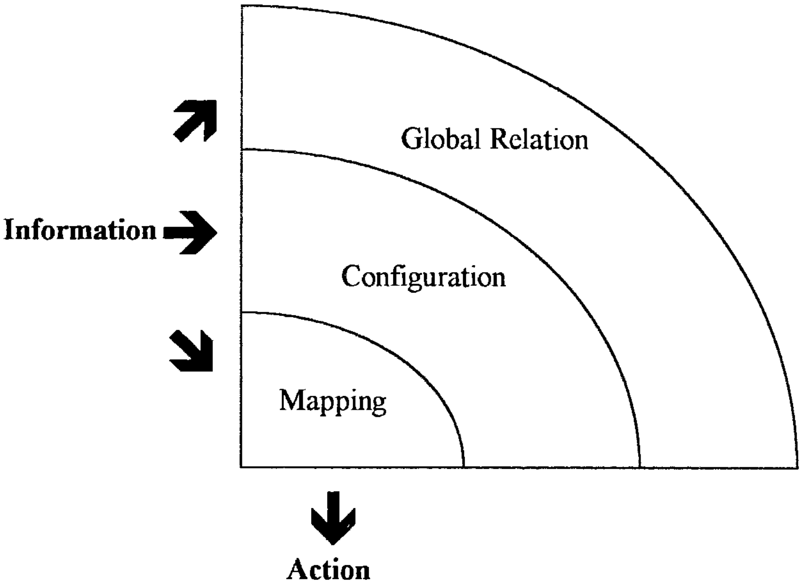

Figure 3.2 Levels of spatial relations.

The three levels of spatial relations may be considered to be arranged within a nested hierarchy and is summarized in Figure 3.2. The mapping of information to action bears directly on the movement or action. That is, the pattern of coordination is defined on the basis of the mapping. Mapping is nested within a configuration of information and action. The configuration may affect the dynamics of the action indirectly through its influence on the relation between the mapping and the action. Both mapping and configuration are, in turn, subsumed with the level of the global relation between information and action. The global relation may affect coordination dynamics indirectly through its constraint on the relation between the configuration, mapping, and action. The hierarchy is not necessarily meant to suggest that one level has precedence over the other. Rather, it provides a means to visualize or conceptualize the potential spatial, informational, constraints on the coordination dynamics.

3.4 Summary

My goals in the present work are two-fold. The first goal is to examine informational constraints on the coordination dynamics of perception-action coupling. Just as the study of compatibility has been used as a window into processes underlying translation and response selection, the study of dynamical compatibility may also provide a window into one of potentially several sources of informational constraints on coordination. The second goal, intimately linked to the first, is to extend and complement recent interests from the compatibility literature in dynamic S-R situations. However, rather than examine efficiency in selecting a response, compatibility in dynamic situations is studied through examination of the *dynamics* of coordination. The expectation is that by re-characterizing compatibility in dynamical language, compatibility phenomena can be assessed beyond response selection. Immediate questions may inquire into whether the range of spatial compatibility effects observed in movement preparation intrudes into the dynamics of the movement, and into the manner in which compatibility is expressed in coordination. More generally, does the spatial relation between visual information and the action serve as a constraint upon the coordination dynamics of the coupled system?

The framework for the present endeavour is encapsulated in Figure 3.3. I draw from two dominant perspectives within motor behaviour. From the information-processing framework comes the platform for the empirical issue of perceptual-motor, or S-R, compatibility. From the dynamical systems framework come the theoretical and analytical strategies and tools used to study coordination at an appropriate level of analysis.

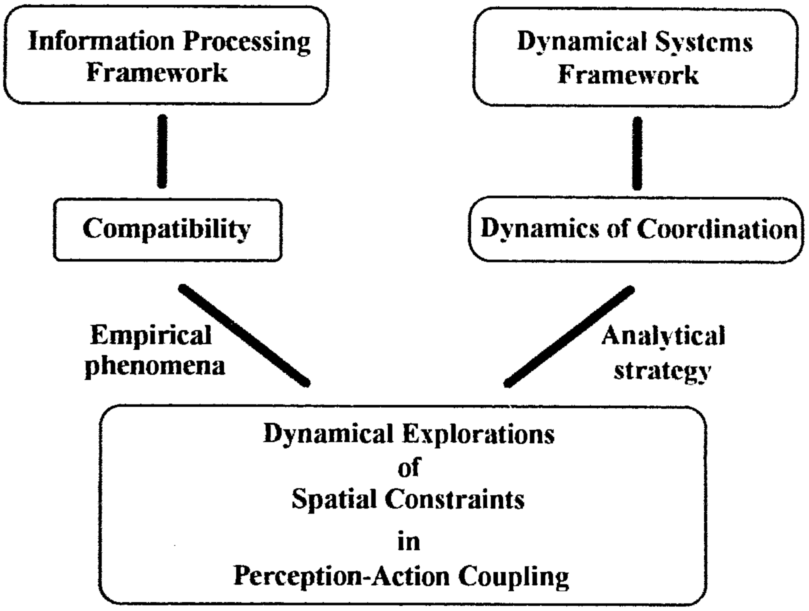

Figure 3.3 Framework for dynamical explorations of spatial constraints in perception-action coupling.

3.5 Preview

My entry point to the study of spatial constraints is the study of compatibility relations in information-action coordination. I employ a paradigm of person-environment coordination in which action is unilaterally coupled to visual information. In Experiment 1, I examine basic spatial constraints in perception-action coupling through the study of the relation between information-action mappings and configurations and their impact on coordination dynamics. In Experiment 2, I examine whether the global spatial relation between information and action mediates the interaction between configuration and mapping. In Experiment 3, I extend the investigation of the influence of spatial configurations on coordination dynamics. Finally, in Experiment 4, I study the asymmetric dynamics of perception-action coupling under the scaling of a spatial parameter. My goals are to investigate informational constraints in perception-action coupling through the study of spatial constraints and to extend the study of compatibility to coordination.

4. Experiment 1

4.1 Introduction

In human motor acts, it is often the case that, not only do we have to coordinate the movements of our body, but we must also coordinate our movements with some environmental event. This event may be in the form of some external, visual or auditory stimulus. In these cases, our actions must be coupled with the environmental information. Of interest is whether perceptual information specific to the external event can entrain our actions and whether similar dynamical principles as those observed in interlimb coordination apply.

A study by Schmidt et al. (1990) examining between-person coordination has demonstrated that the dynamics of an optically coupled system are characterized by many of the same properties as those observed in within-person coordination. In their study, Schmidt et al. asked a pair of subjects to each oscillate a leg, with the goal of coordinating the legs in either an in-phase or anti-phase pattern, as the frequency of oscillation was scaled upward. As with within-person interlimb coordination, a phase transition from an anti-phase pattern to an in-phase pattern was observed as oscillation frequency increased. Moreover, the phase transitions were dependent upon the presence of an visual coupling between the two persons. No phase transitions occurred if the subjects were asked to coordinate their legs without watching each other. Thus, it appears that, in the language of dynamics, anatomical and informational couplings between rhythmic actions are similar (Turvey, 1990). Phase information apparently can be communicated via kinesthetic or visual information within the individual or between individuals.

In a recent study, Wimmers et al. (1992) extended the study of perception-action coordination to the case of a unilaterally, visually coupled system. The question of interest was whether the dynamics observed in between-person coordination (Schmidt et al., 1990) generalized to the situation in which movement was coordinated with the motion of an external visual stimulus. Subjects were required to coordinate rhythmic forearm movements with a sinusoidal visual stimulus. The experimental set up was as follows. Subjects performed forearm flexion and extension movements in the horizontal plane. The visual stimulus was oriented horizontally, that is, in the same plane as the movement. Movements were performed in either anti-phase (in opposite direction to movement of the stimulus) or in-phase (in same direction as stimulus) coordination, as cycling frequency was increased. Results showed that when movements were initially prepared anti-phase, transitions to in-phase coordination occurred as cycling frequency increased, whereas there were no transitions when movements were initially prepared in-phase. In another experiment, the visual stimulus was oriented vertically, orthogonal to the plane of the movement. Subjects performed their movements such that they either coincided flexion with the down stimulus position or with the up stimulus position. In this orthogonal situation, no transitions from one mode of coordination to another occurred. These findings suggest that the intrinsic dynamics of the in-phase and anti-phase modes may have been influenced by the orientation of the driving visual signal.

Although not its original intent, the study by Wimmers et al. (1990, Experiment 1 & 3) led to the finding that the spatial relation between visual information and movement may impact upon the dynamics of visual coordination. Perhaps it should not be too surprising that spatial relations may impinge upon visual coordination dynamics. Indeed, coordination patterns in visual coordination are defined according to the spatial relation between the motion of the driving visual signal and the actor's movement. Specifically, anti-phase and in-phase patterns are defined respectively as movement in the opposite or same direction as the motion of the visual information. I refer to this type of relation as information-action mapping (see Section 3.3). What the Wimmers et al. study implicates is that the spatial orientation of the visual information relative to the action may be another spatial constraint. I refer to this relation as the information-action configuration.

The intrusion of mapping and configuration relations between information and action is well established in the literature on S-R compatibility. It has been repeatedly demonstrated that choice reaction times are shorter when the mapping between stimulus and response elements is spatially compatible (e.g., Fitts & Seeger, 1953). More recent interest has also been shown in the manner in which S-R configurations might affect compatibility phenomena. Specifically, investigators have considered whether mapping preferences are present for situations when the stimulus and response arrays are oriented orthogonally to one another (e.g., Bauer & Miller, 1982; Weeks & Proctor, 1990). Of even greater interest to the present investigation is the recent attention focussed on the manner in which compatibility effects might be expressed in dynamic (as opposed to static) stimulus-response arrays (e.g., Michaels, 1988; Proctor et al., 1993).

In light of the recent developments in both the coordination and compatibility literature, it is perhaps fortuitous that the two seem to be converging on a shared path. From the study of Wimmers et al. (1992) there are indications that visual coordination dynamics may be spatially dependent – reminiscent of compatibility effects. From the compatibility literature comes the interest in dynamic perceptual-motor interactions – interactions which may be amenable to examination using the tools of synergetics and dynamics.

The purpose of the present study was to examine spatial constraints in rhythmic, unilateral, visual coordination. My entry point was the study of compatibility relations in information-action coordination. In contrast to the dominant trend in the compatibility literature, observables relevant to the study of coordination, namely, the phase relation between the visual information and the action, were employed. The study of the stability and instability of the coordination variable provided a window into the degree of compatibility of spatial relations (e.g., see Section 3.2). In the present study, I examined spatial relations at two levels – the level of the information-action mapping, and the level of the information action configuration. How do the two levels of spatial relation interact in the visual coupling of information and action?

The present task was to coordinate rhythmic forearm rotations with a periodic visual stimulus. The visual stimulus (perceptual information) was oriented either along a horizontal or vertical dimension. The movements (action) were also performed either along a horizontal or vertical plane. For information-action orientations that were parallel to one another, in-phase mapping was characterized by the spatial correspondence of movement and stimulus cycle endpoints, whereas anti-phase mappings were characterized by the non-correspondence of the spatial endpoints. For information-action orientations that were orthogonal to one another, two further mappings were identified. The up-right/down-left mapping was characterized by the correspondence of the upper endpoint of the information (or action) with the right endpoint of the action (or information), and the lower endpoint of the information (or action) with the left endpoint of the action (or information). The reverse assignment characterized the up-left/down-right mapping.

On the basis of previous research (Byblow et al., 1995; Wimmers et al., 1992), I expected that the in-phase and anti-phase mappings or patterns would be differentiated on the basis of their stability when these patterns were clearly defined, namely, in parallel information-action configurations. That is to say, the spatially compatible mapping would be distinguishable from the spatially incompatible mapping. But what is expected for the mappings under orthogonal configurations? On the basis of Wimmers et al. (1992) alone, the two information-action mappings would be expected to be equivocal. However, Wimmers et al. based their conclusions primarily on the presence or absence of transitions between patterns, with no analysis of dynamical stability. Recent examinations of S-R compatibility in orthogonal configurations (Weeks & Proctor, 1990) suggest that the up-right/down-left stimulus-response relation may be the preferred mapping relative to the up-left/down-right relation (in terms of reaction time). The question arises, then, as to whether similar mapping preferences would emerge in visual coordination.

4.2 Method

4.2.1 Subjects

Six volunteers (4 female and 2 male) were recruited from the university population. All subjects were right-handed by self-report and had normal or corrected-to-normal vision.

4.2.2 Apparatus

Subjects were seated facing a 50 cm by 50 cm display composed of a translucent plastic panel mounted on a tabletop and an array of LEDs hidden behind the panel. Activation of a single LED resulted in a projection which was viewed by the subject as a single point source of light on the plastic panel. The visual display consisted of the periodic activation of two LEDs which defined the 0 and 180 degree endpoints of a cycle. Thus, the LED appeared to oscillate discretely between two endpoints, remaining illuminated for 100 ms at each endpoint. The LEDs were separated by a distance of 8 cm and were centred both horizontally (horizontal orientation) and vertically (vertical orientation) about the centre of the display panel.

Rhythmic rotational movements of the forearm (pronation and supination) were recorded with the use of a custom-built lever (diameter: 2 cm, length: 18 cm), mounted on a table directly in front of the seated subject. Angular displacement was continuously monitored with the use of a linear potentiometer (Bourns Instruments, Model #3540, 0.25% linearity) located coaxially with the centre of rotation of the lever (2 cm from end of lever).

The signal from the potentiometer was sampled at a frequency of 250 Hz with a 12 bit, 8 channel A/D converter. The intermittent, computer-generated signal controlling the display, providing information of the periodic visual stimulus, was sampled in a similar fashion.

4.2.3 Procedure

Subjects were asked to perform rhythmic forearm pronation and supination movements with their right hand, in coordination with the visual display. The display panel was located approximately 1.2 m from the seated subject and was raised such that the centre of the panel was approximately at eye level. Subjects were seated with their midline aligned with that of the display. The lever was also aligned with the midline of the subjects and display. Movements were thus performed about the midline.

The visual display was oriented either horizontally or vertically. Subjects' movements were performed along either the coronal plane (horizontal pronation/supination) or sagittal plane (vertical pronation/supination) (see Figure 4.1). For the vertical movement, the lever was mounted at an angle of 55 degrees from the horizontal. Seat height was adjusted for each subject such that for the horizontal movement, the elbows were flexed to approximately 90 degrees. The centre of oscillation for the vertical movement was located at approximately chest height of the seated subject. Thus, there were 4 information (stimulus)-action (response) configurations, comprised of the combination of the horizontal and vertical orientations of both the visual display and the movement.

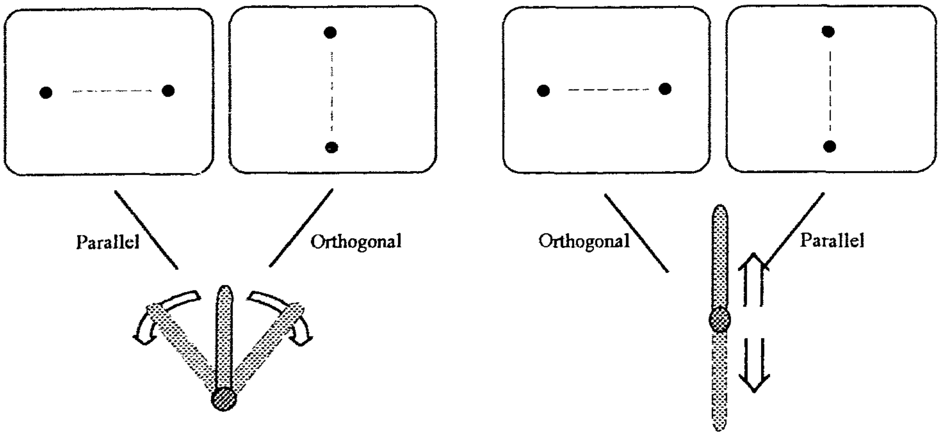

Figure 4.1 Information and action orientations.

For each of the four configurations, there were two prescribed modes of display-limb, or information-action, coordination. For parallel configurations (i.e., horizontal display-horizontal movement and vertical display-vertical movement), subjects were required to perform in either an *anti-phase* or *in-phase* mapping. Anti-phase mapping was defined as coordination of movement in the opposite direction specified by the visual display, such that the left movement endpoint was mapped onto the right display endpoint and vice versa. In-phase mapping was defined as coordination in the same direction as that specified by the display, such that the left and right movement endpoints were mapped onto the left and right display endpoints, respectively. For orthogonal configurations (i.e., horizontal display-vertical movement and vertical display-horizontal movement), subjects were required to perform in either an *up-right/down-left* or an *up-left/down-right* mapping. For the horizontal movement orientation, “left” and “right” were mapped onto the “pronation” and “supination” endpoints, respectively. Thus, the up-right/down-left mapping was defined as the synchronization of the supination (“right”) movement endpoint with the upper position of the display and the pronation (“left”) endpoint with the lower position of the display. The assignment was reversed for the up-left/down-right mapping. For the vertical movement orientation, “up” and “down” were mapped onto the vertical “supination” and “pronation” endpoints, respectively. Thus, the up-right/down-left mapping was defined as the synchronization of the supination (“up”) movement endpoint with the right position of the display and the pronation ("down") endpoint with the left position of the display. Again, the assignment was reversed for the up-left/down-right mapping.

At the start of each trial, display oscillation (i.e., the LED) was initiated at a frequency of 0.75 Hz, and subjects began moving with the display in the prescribed mode of coordination. Scaling of the display frequency began once subjects indicated to the experimenter that they were comfortably synchronized with the display. After an additional 3 cycles at 0.75 Hz, display frequency was scaled from 0.75 Hz to 1.75 Hz, with frequency plateaus at 1.0 Hz, 1.25 Hz, 1.5 Hz, and 1.75 Hz. Display frequency remained constant for 20 cycles at each plateau. The transition between each frequency plateau was designed in a ramp fashion such that it took 5 cycles (at 0.05 Hz steps) to reach the next frequency plateau.

Subjects were instructed to maintain the frequency specified by the display, and the coordination pattern or mapping in which they were prepared, as accurately as possible. However, subjects were also instructed that, in the event of any change in pattern, they were not to attempt to recover the original pattern but to establish the most comfortable pattern at the current frequency.

The study employed a 2 display orientation (horizontal, vertical) by 2 movement orientation (horizontal, vertical) by 2 information-action mapping (in-phase or up-right/down-left, anti-phase or up-left/down-right) by 4 frequency plateau (1.0, 1.25, 1.5, 1.75 Hz) repeated-measures design.[3] Subjects participated in two experimental sessions, each comprised of two blocks of trials. Each block corresponded to a particular combination of display and movement orientation. Movement orientation was performed in separate sessions and was counterbalanced across subjects. Display orientation was

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[3] The association of the "up-right/down-left" and "up-left/down-right" mappings to the "in-phase" and "anti-phase" modes are essentially arbitrary. Here the choice was made to associate the potentially "preferred" up-right/down-left mapping with the more stable in-phase mode.

randomized within a session. Each block of trials was comprised of 10 trials, 5 trials for each of the two possible information-action mappings. Subjects alternated mappings between trials. Subjects were allowed to familiarize themselves with the task at the start of each block. Rest periods were provided as required. Each session lasted approximately 60 minutes.

4.2.4 Data Reduction and Analyses

Angular displacement data from the potentiometer were low pass filtered with a dual pass, second order Butterworth filter (cutoff frequency of 10 Hz). Minimum and maximum angular displacements for each cycle, as well as discrete, cycle to cycle oscillation frequency, were delineated using in-house algorithms. Mean frequency of the limb oscillations and corresponding coefficients of variation were derived for each plateau. Amplitude variability about the movement endpoints were calculated to assess "anchoring" (compression of variability at movement endpoints - Byblow, Carson, & Goodman, 1994) over each plateau.

An estimate of relative phase was calculated for the phase relation between the visual display and limb, utilizing the output information from the display and potentiometer. Prior to the calculation of relative phase, the intermittent display signal was transformed into a continuous sine wave. The individual phase angles (θ_j) of the display and limb oscillations were calculated for each sample (j) of the angular displacement time series as:

$$\theta_j = \arctan(\dot{x}_j^* / \Delta x_j), \tag{4.1}$$

where $\dot{x}_j^*$ is the velocity of the time series of the limb (or display) at sample j divided by the mean angular frequency for the plateau, and Δx_j is the position of the time series at sample j minus the average position for the plateau. The relative phase (Φ_j) between the coupled display-limb system was then calculated for each sample as $\Phi_j = \theta_{j(display)} - \theta_{j(limb)}$ to yield a relative phase time series (see Beek & Beek, 1988).

To assess variability of relative phase for each plateau, measures of circular variance (uniformity) were calculated following Mardia (1972). The circular variance assumes values in the range of 0 to 1, unlike measures of variability on the line which lie in the range of 0 to ∞. The circular variance can be transformed to the range of 0 to ∞ by using a transformation of the form:

$$s_0 = [\ - 2 * \log_e(1 - S_0)\ ]^{0.5}, \tag{4.2}$$

where S_0 is the measure of uniformity in the range [0, 1], and s_0 is the transformed uniformity measure (see Mardia, 1972). The transformed uniformity measure corresponds inversely to the ordinary sample standard deviation on the line and allows the use of inferential tests based on standard normal theory (Burgess-Limerick, Abernethy, & Neal, 1991; Byblow et al., 1994).

In separate analyses, the relative phase time series was normalized to the interval [0.0, 0.5], where 0.0 and 0.5 represent in-phase and anti-phase relations, respectively. For each plateau, phase attraction was determined using the proportion of the plateau duration spent in regions centred about in-phase [0.0-0.17], anti-phase [0.33-0.5], and intermediate phase (0.17-0.33). An arcsin-square root transformation of the proportions was used for analysis.

An in-house switch detection algorithm and interactive graphics display (Byblow, Carson, Goodman, & Storlund, 1992) was used to delineate the onset of a transition or loss of stability of the initial coordination pattern. The interval from the beginning of the trial to the onset of a pattern change was defined as the time-to-transition.

4.3 Results

The study employed a 2 display orientation (horizontal, vertical) by 2 movement orientation (horizontal, vertical) by 2 information-action mapping (in-phase or up-right/down-left, anti-phase or up-left/down-right) by 4 frequency plateau (1.0, 1.25, 1.5, 1.75 Hz) repeated-measures design. In the following analyses, the parallel and orthogonal configurations were analyzed separately. Data for the parallel configurations were analyzed using a 2 orientation (horizontal, vertical) by 2 mapping (in-phase, anti-phase) by 4 frequency plateau repeated-measures design. Similarly, data for the orthogonal configurations were analyzed using a 2 orientation (horizontal display-vertical movement, vertical display-horizontal movement) by 2 mapping (up-right/down-left, up-left/down-right) by 4 frequency plateau repeated-measures design. All post-hoc analyses were performed using the Tukey HSD procedure with $\alpha = .05$. Data are reported for measures encompassing the dynamics of the limb alone (i.e., the "limit cycle") and for measures capturing the coordination between display and limb.

4.3.1 Limit Cycle Dynamics

Conformity to the prescribed oscillation frequency was assessed as the absolute error between the frequency of the limb and the display. For parallel configurations, deviation from the display frequency increased as frequency increased, $F(3, 15) = 9.40, p < 0.002$. A similar effect for plateau frequency was also found for orthogonal configurations, $F(3, 15) = 10.43, p < 0.001$ (see Figure 4.2).

In addition, there was an interaction between orientation, mapping, and plateau, $F(3, 15) = 4.41, p < .025$, as shown in Figure 4.3. There were no differences with respect to accuracy in following the prescribed display frequency for any of the combinations of orientation and mapping for the first 3 plateau frequencies. At the highest plateau frequency, a difference emerged for the up-left/down-right mapping between the two orthogonal configurations. In general, for both parallel and orthogonal configurations, accuracy in following the display frequency decreased as oscillation frequency increased. This increase in frequency deviation was essentially independent of the mapping conditions and the particular display-limb orientations within the two configurations.

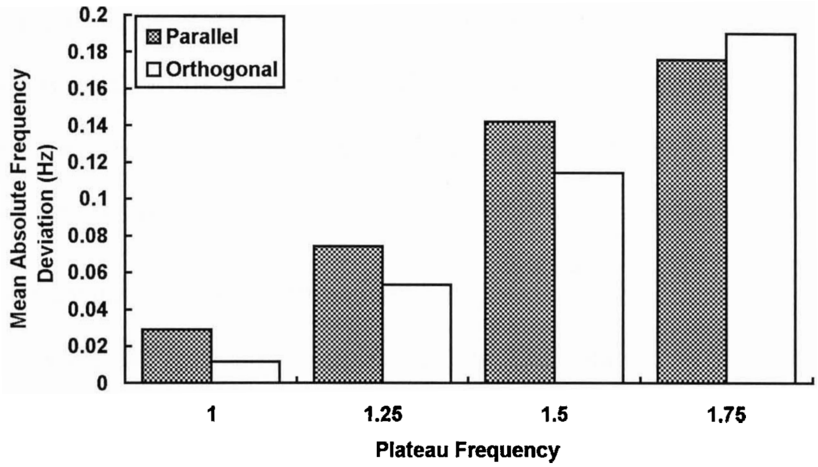


Figure 4.2 Absolute deviation from display frequency as a function of plateau frequency for Parallel and Orthogonal configurations.

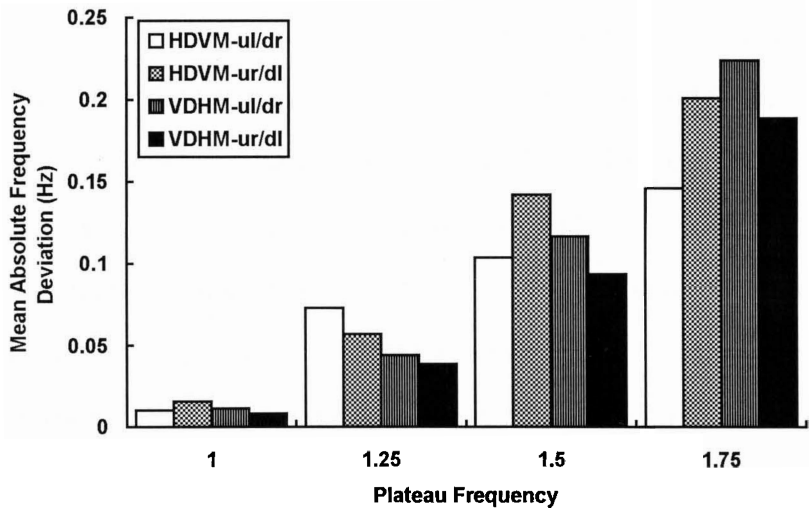


Figure 4.3 Absolute frequency deviation as a function of plateau frequency for both information-action mappings in the Orthogonal configurations. HDVM - horizontal display/vertical movement; VDHM - vertical display/horizontal movement; ul/dr - up-left/down-right; ur/dl - up-right/down-left.

Coefficients of variation of limb frequency were assessed in identical ANOVA designs. Analysis of parallel configurations yielded an interaction between orientation, mapping, and plateau frequency, $F(3, 15) = 3.47, p < .05$. There were no differences in frequency variability between any of the orientation and mapping conditions for the upper 3 frequency plateaus. At the first plateau, variability for the vertical orientation - anti-phase mapping was significantly greater than the other 3 orientation-mapping combinations. Analysis of orthogonal configurations yielded only an effect for plateau frequency, $F(3, 15) = 6.45, p < .006$, reflecting increased variability in cycle-to-cycle frequency at the upper frequency plateaus.

Amplitude variability about the movement endpoints was assessed in order to examine anchoring. A 2 endpoint (pronation, supination) by 2 orientation by 2 mapping by 4 plateau repeated-measures ANOVA was employed. Analysis of parallel configurations revealed an effect for orientation, $F(1, 5) = 25.6, p < .004$, and for plateau frequency, $F(3, 15) = 5.71, p < .009$. Movements in the vertical orientation were characterized by less overall endpoint variability ($\bar{x} = 27.0$) compared to movements in the horizontal orientation ($\bar{x} = 30.0$). Endpoint variability was also of lesser magnitude at lower frequency plateaus (1.0 Hz = 27.2, 1.25 Hz = 26.5, 1.5 Hz = 30.0, 1.75 Hz = 30.0). Analysis of orthogonal configurations revealed main effects for endpoint, $F(1, 5) = 13.0, p < .02$, orientation, $F(1, 5) = 9.61, p < .03$, and plateau, $F(3, 15) = 3.40, p < .05$, as well as an interaction of orientation and plateau, $F(3, 15) = 7.16, p < .004$. Movement variability about the supination (up) endpoint ($\bar{x} = 26.8$) was found to be less than about the pronation (down) endpoint ($\bar{x} = 30.6$). As in the parallel configurations, movements in the vertical orientation ($\bar{x} = 26.2$) were again found to have lesser endpoint variability than movements in the horizontal orientation ($\bar{x} = 31.2$), and overall endpoint variability also increased with plateau frequency (1.0 Hz = 28.2, 1.25 Hz = 27.3, 1.5 Hz = 29.5, 1.75 Hz = 29.9). Moreover, the increase in endpoint variability with increasing oscillation frequency was primarily reflected in the horizontal movements (see Figure 4.4). In sum, the anchoring effects revealed the intrusion of biomechanical constraints in the individual limb dynamics.

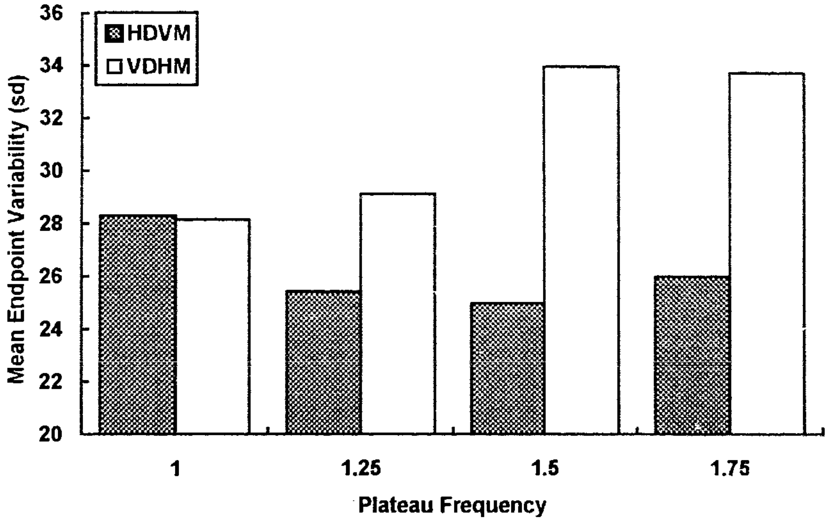


Figure 4.4 Endpoint variability as a function of plateau frequency for orthogonal configurations. HDVM - horizontal display/vertical movement; VDHM - vertical display/horizontal movement.

4.3.2 Relative Phase Dynamics

Uniformity of relative phase, an index of stability of relative phase, was analyzed in a 2 orientation by 2 mapping by 4 frequency plateau repeated-measures design. Analysis of parallel configurations revealed main effects for coordination mapping, $F(1, 5) = 10.05$, $p < .025$, and for frequency plateau, $F(3, 15) = 30.08$, $p < .001$. As might be expected, movements prepared under in-phase mappings were less variable than those prepared under anti-phase mappings. Moreover, uniformity decreased (reflecting an increase in variability) as a function of frequency plateau (see Figure 4.5). Analysis of orthogonal configurations revealed a similar effect for plateau, $F(3, 15) = 26.15$, $p < .001$, indicating that relative phase uniformity again decreased as oscillation frequency increased. There was also as an Orientation x Mapping x Plateau interaction, $F(3, 15) = 3.77$, $p < .04$, due primarily to a difference between the up-right/down-left mapping in the two orientations at the third frequency plateau (see Figure 4.6).

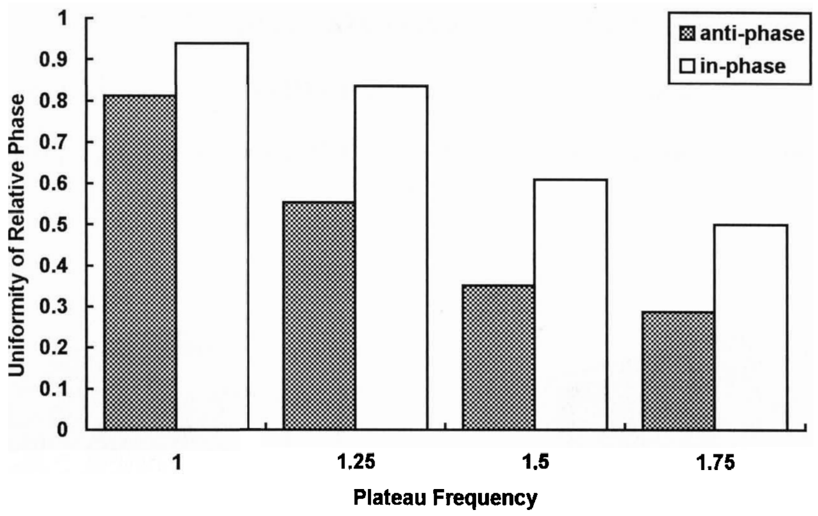


Figure 4.5 Relative phase uniformity as a function of plateau frequency for parallel configurations.

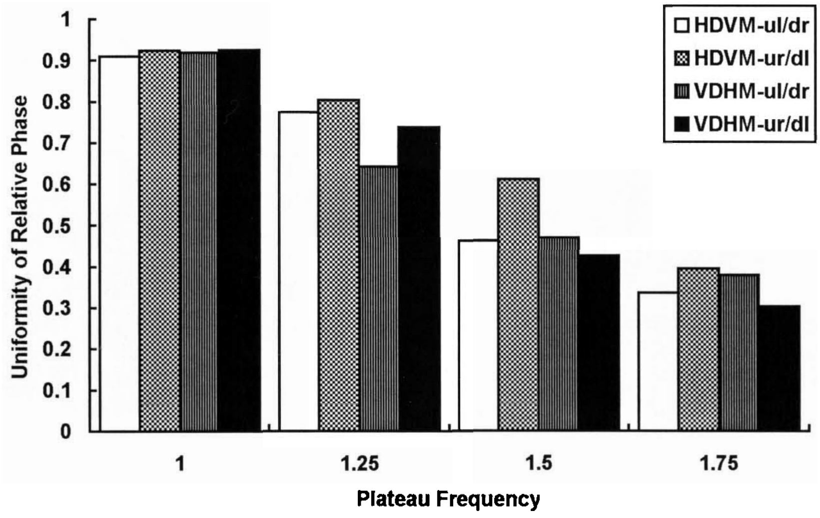


Figure 4.6 Relative phase uniformity as a function of plateau frequency for orthogonal configurations. HDVM - horizontal display/vertical movement; VDHM - vertical display/horizontal movement; ul/dr - up-left/down-right; ur/dl - up-right/down-left.

Attraction to specific phase regions was quantified as the proportion of the plateau duration spent within a phase region. Figures 4.7 and 4.8 show, for each subject, an average of the proportion of time spent within in-phase (or up-right/down-left) and anti-phase (or up-left/down-right) regions, when initially prepared in these coordination mappings. In general, for all information-action configurations, and for all initial coordination mappings, the proportion of time spent within a phase region decreased over plateau frequency.

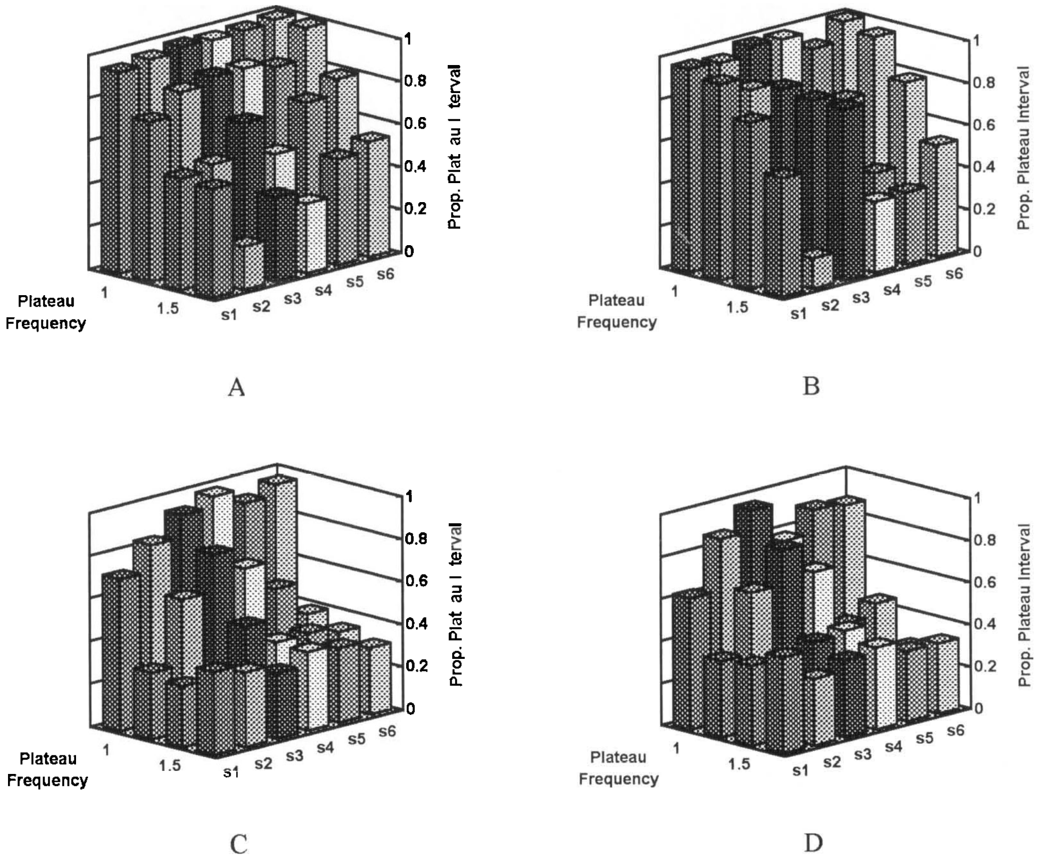


Figure 4.7 Proportion of plateau interval spent within regions of phase space for parallel configurations. (A) Horizontal orientation - in-phase; (B) Vertical orientation - in-phase; (C) Horizontal orientation - anti-phase; (D) Vertical orientation - anti-phase.

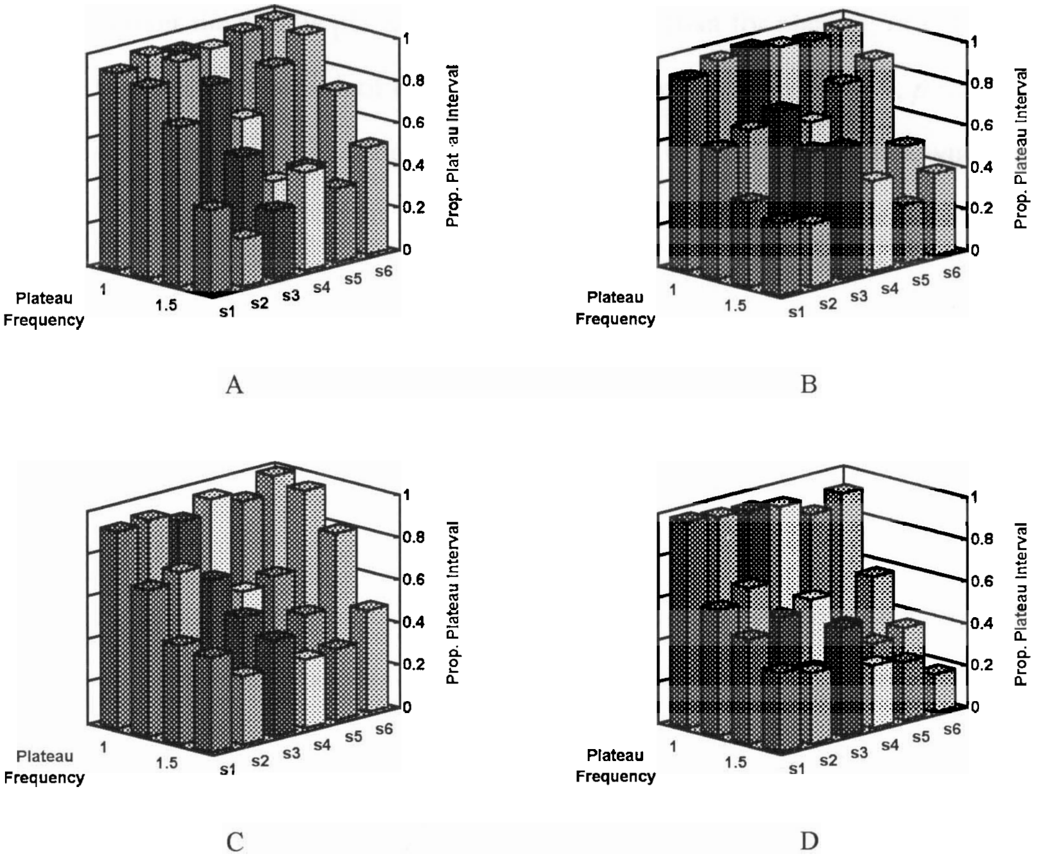
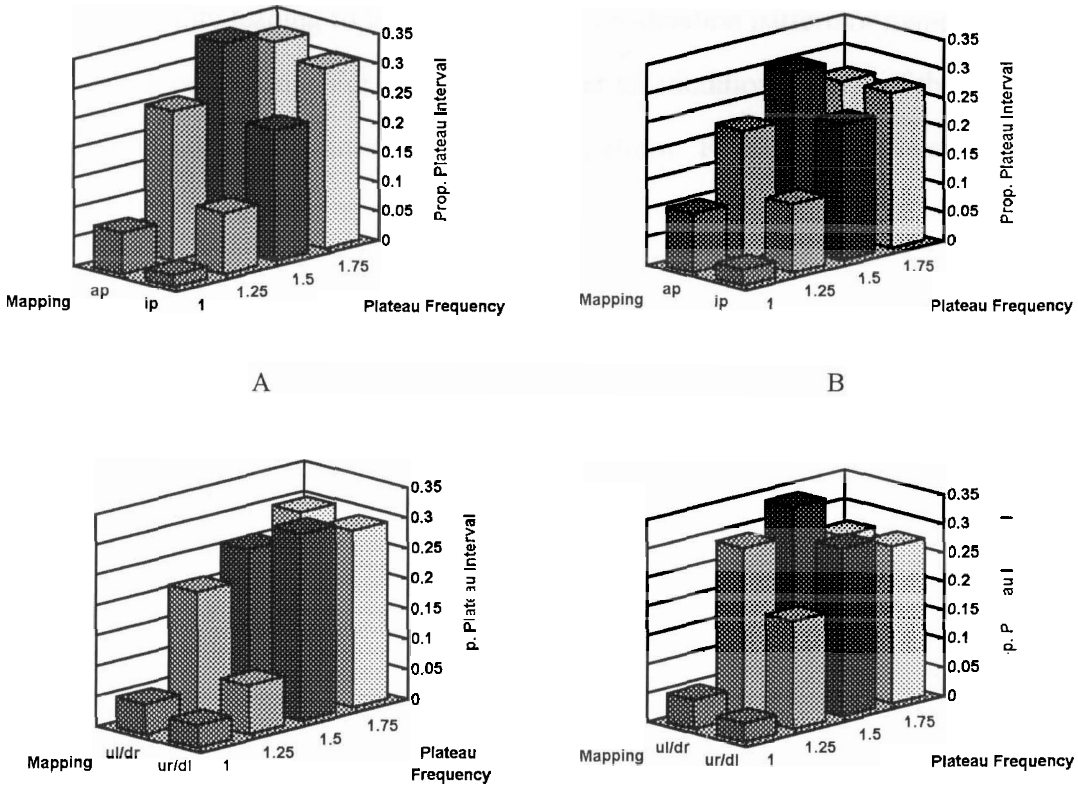


Figure 4.8 Proportion of plateau interval spent within regions of phase space for orthogonal configurations. (A) Horizontal display/vertical movement - up-right/down-left; (B) Vertical display/horizontal movement - up-right/down-left; (C) Horizontal display/vertical movement - up-left/down-right; (D) Vertical display/horizontal movement - up-left/down-right.

Separate analyses were performed for each mapping over the factors of orientation and plateau frequency for both parallel and orthogonal configurations. For parallel configurations, analysis of the proportion of time spent within in-phase regions when prepared in-phase revealed an effect for plateau, $F(3, 15) = 65.70, p < .001$. A similar plateau effect was found for the time spent within anti-phase regions when initially prepared anti-phase, $F(3, 15) = 40.15, p < .001$. For orthogonal configurations, analysis of the proportion of time spent within phase space designated as up-right/down-left when initially prepared in this mapping also confirmed the decrease over plateau, $F(3, 15) = 60.87, p < .001$. In addition, this plateau effect was mediated by orientation, $F(3, 15) = 3.74, p < .04$, reflecting a slight advantage for the horizontal display-vertical movement configuration over the middle plateaus. A similar main effect for plateau, $F(3, 15) = 77.17, p < .001$, and interaction of orientation and plateau, $F(3, 15) = 7.09, p < .004$, emerged for the analysis of the proportion of time spent within the up-left/down-right phase region. Again, there was an advantage for the horizontal display-vertical movement configuration, with subjects on average maintaining the up-left/down-right coordination mapping for a greater proportion of the plateau interval.

Examination of the attraction to intermediate phase relations allowed further insight into differences between mapping constraints. That is, it allowed further investigation of the respective stability of the mappings by comparing the amount of time spent in intermediate phase regions as a function of mapping. The proportion of time (of plateau interval) spent in intermediate phase regions was analyzed over orientation, mapping, and plateau. Figure 4.9 shows that, as might be expected, attraction to intermediate phase regions increased with oscillation frequency. This suggests the occurrence of phase slippages or phase wandering through this phase region. Analysis of parallel configurations (Figure 4.9 A & B) confirmed the effect of plateau frequency, $F(3, 15) = 63.53, p < .001$, as well as revealed a slight advantage for the in-phase mapping, $F(1, 5) = 20.10, p < .007$. That is, there was less attraction to intermediate phase regions when prepared under the in-phase mapping compared to the anti-phase mapping. Moreover, this finding was confined to the lower frequencies, as indicated by a Mapping x Plateau interaction, $F(3, 15) = 4.74, p < .02$.



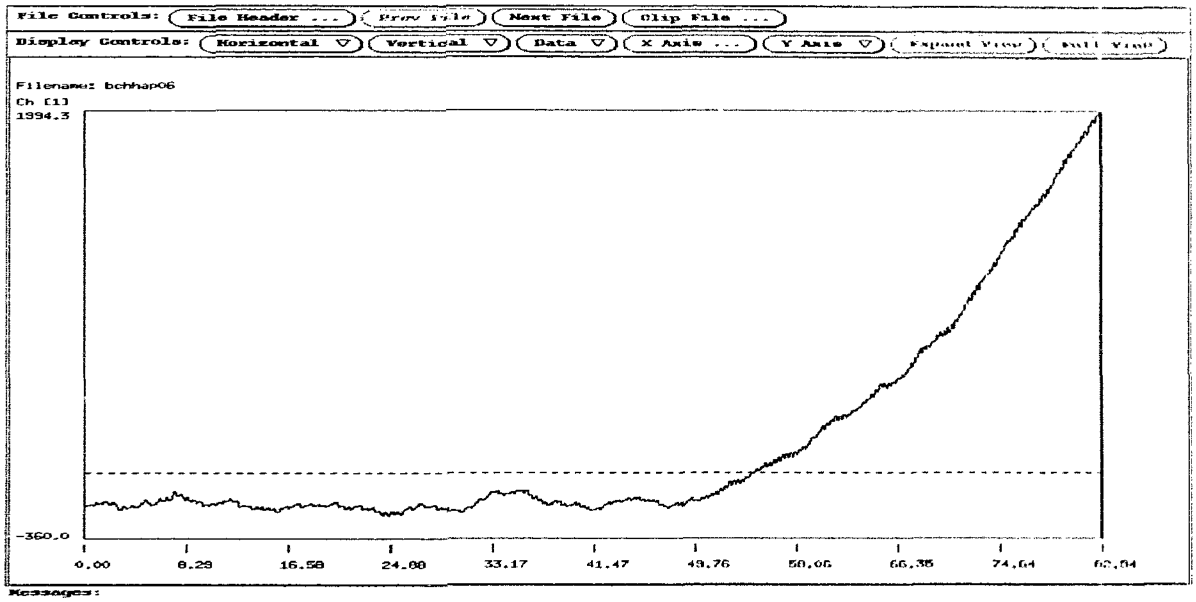
A B

C D

Figure 4.9 Proportion of plateau interval spent within intermediate phase regions for parallel and orthogonal configurations. (A) Parallel - Horizontal orientation; (B) Parallel - Vertical orientation; (C) Orthogonal - Horizontal display - Vertical movement; (D) Orthogonal - Vertical display - Horizontal movement.

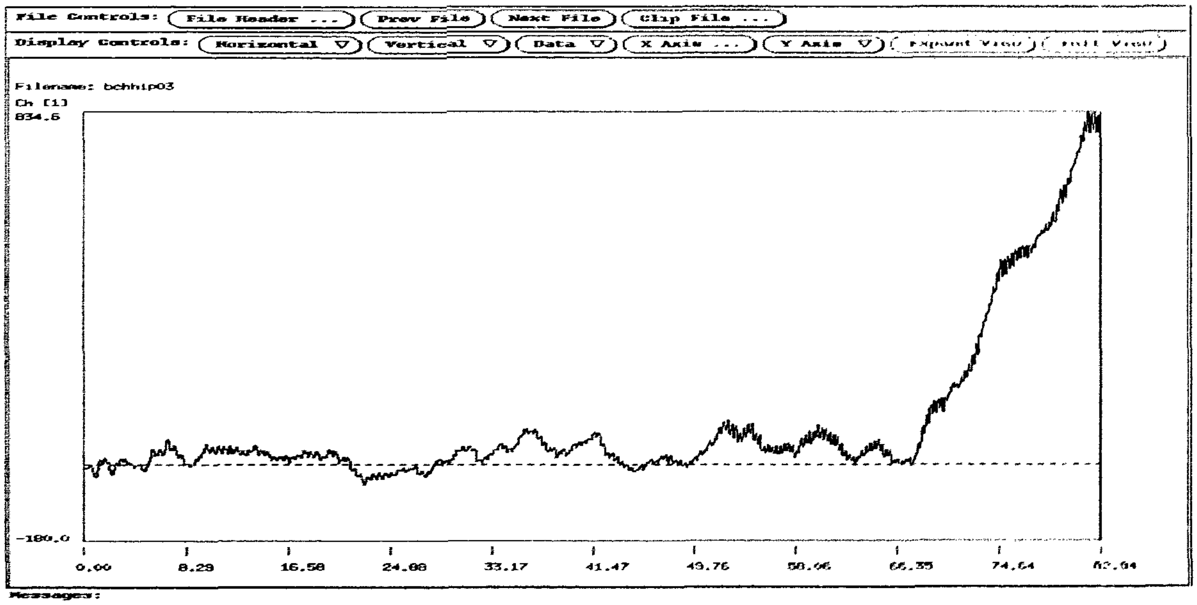
Analysis of the orthogonal configurations (Figure 4.9 C & D) also confirmed an effect of plateau, $F(3, 15) = 78.53, p < .001$, and revealed less intermediate phase attraction for the up-right/down-left mapping, $F(1, 5) = 29.38, p < .003$. Plateau further interacted separately with orientation, $F(3, 15) = 4.54, p < .02$, reflecting less attraction to intermediate regions for the horizontal display-vertical movement configuration at the second plateau frequency, and with mapping, $F(3, 15) = 7.43, p < .003$, revealing that the decreased intermediate phase attraction for the up-right/down-left mapping was confined also to the second plateau frequency.

Loss of stability leading to loss of the initial coordination pattern or mapping were noted under all conditions. For all subjects, under all conditions, a loss of the initial pattern did not result in a transition to the other pattern. Rather, the prevalent occurrence was that of a loss of entrainment, resulting in phase wandering (see Figure 4.10).



Filename: bchhap06

A: parallel (horizontal) configuration - anti-phase mapping



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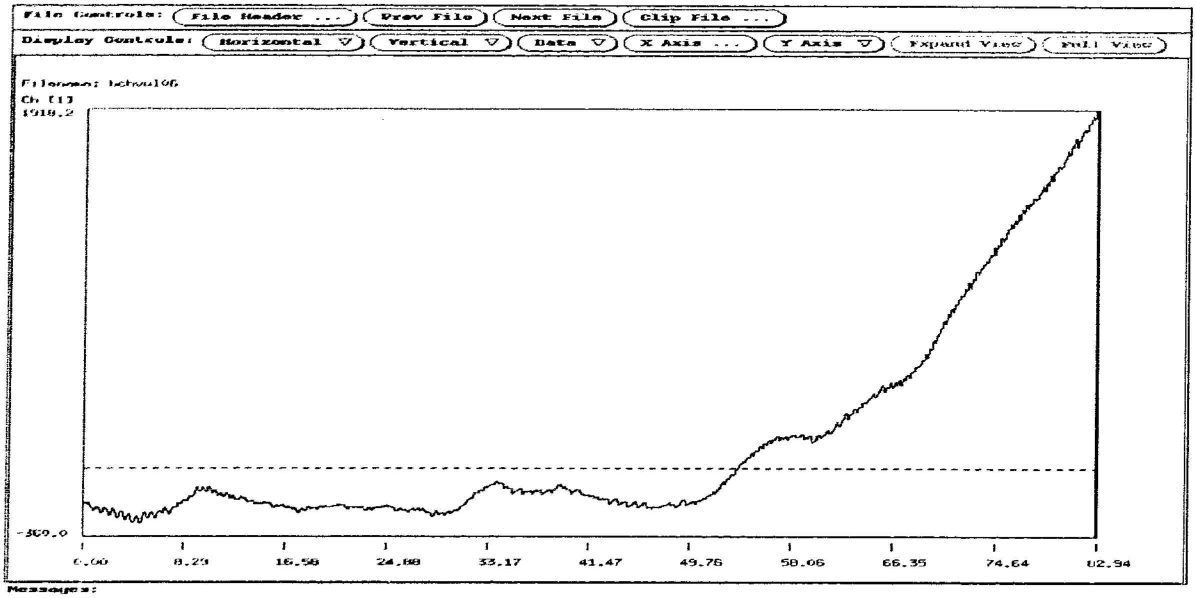
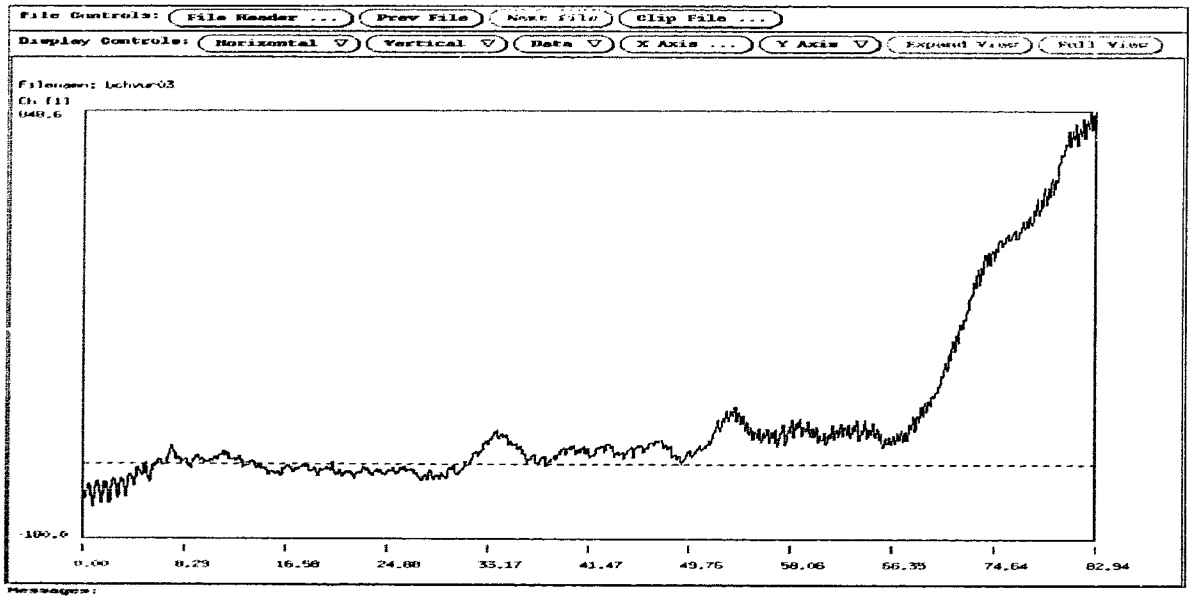
B: parallel (horizontal) configuration - in-phase mapping



C: orthogonal (horizontal display) configuration - up-left/down-right mapping



D: orthogonal (horizontal display) configuration - up-right/down-left mapping

Figure 4 10 A-D: Actual data from a single subject: relative phase time series illustrating loss of entrainment and onset of phase wandering.

Due to the infrequent occurrence of transitions to another stable pattern, the duration for which an initial coordination mapping was maintained, rather than the number of phase transitions (e.g., Wimmers et al., 1992), was examined. As shown in Figure 4.11, subjects tended to maintain in-phase mappings for a longer duration of the trial than anti-phase mappings under the parallel configurations. Under orthogonal configurations, any difference between the two mappings seems less evident.

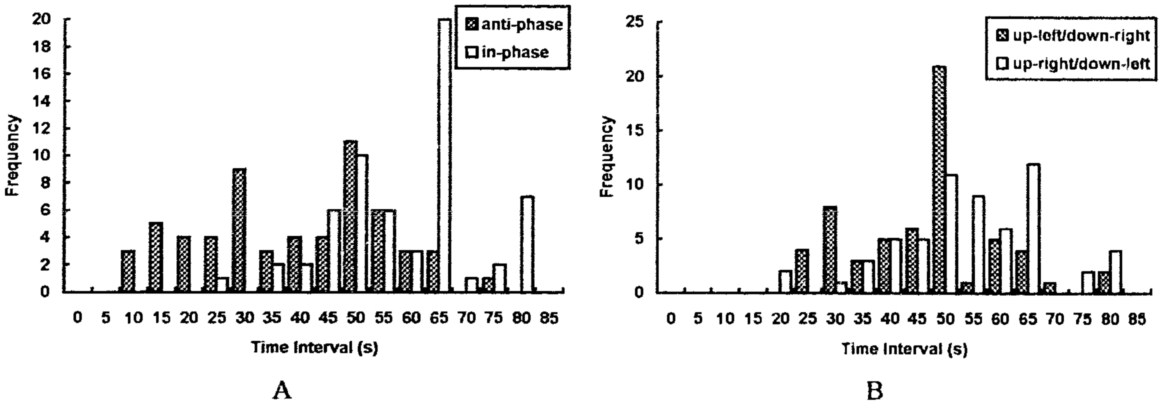


Figure 4.11 Histograms of time intervals at which initial coordination patterns were lost. (A) Parallel configurations; (B) Orthogonal configurations.

Analysis of the data for parallel configurations over the factors of orientation and mapping confirmed that the initial coordination pattern was maintained for a longer duration on trials in which subjects were prepared in-phase, ($\bar{x}$ = 61.3 s), $F(1, 5) = 11.86$, $p < .02$, compared to anti-phase trials ($\bar{x}$ = 41.1 s). For orthogonal configurations, the mapping effect approached conventional levels of significance, $F(1, 5) = 6.54$, $p < .051$, reflecting that stability was maintained slightly longer for up-right/down-left trials ($\bar{x}$ = 56.7 s) over up-left/down-right trials ($\bar{x}$ = 49.1 s).

4.4 Summary and Discussion

The purpose of the present study was to examine spatial constraints in rhythmic, unilateral, visual coordination. The entry point was the study of compatibility relations in information-action coordination. In contrast to the dominant trend in the compatibility literature, observables relevant to the study of coordination were employed, namely, the phase relation between the visual information and the action. The study of the stability and instability of the coordination variable provided a means of assessing the degree of compatibility of, and the constraints imposed by, spatial relations. In the present study, spatial constraints were examined at two levels – the level of the information-action mapping, and the level of the information action configuration.

Variables sensitive to the dynamics of the limb in isolation reflected the effects of oscillation frequency and the intrusion of biomechanical constraints into the movement. Measures of frequency deviation and cycle to cycle variability were essentially independent of the mapping constraints and were primarily influenced by the oscillation frequency. Endpoint variability was unaffected by the mapping of information to action but varied as a function of movement orientation.

Of primary interest was the manner in which the information-action mappings and configurations may have influenced the coupling between information and action. This was expected to be manifested in the dynamics of the collective variable relative phase. Under configurations in which the spatial correspondence of information to action was clearly defined, the differential stability (assessed through the uniformity of relative phase) of the in-phase (compatible) and anti-phase (incompatible) mappings emerged. This confirmed previous findings in interlimb coordination (e.g., Kelso, 1984) and perception-action coordination (e.g., Byblow et al., 1995; Schmidt et al., 1990) and lent credence to a dynamical treatment of perception-action coordination (e.g., Kelso et al., 1990). Under configurations in which the spatial correspondence between information and action was less direct, the two information-action mappings, up-right/down-left and up-left/down-right, were not differentiated on the basis of relative phase uniformity.

The stability of phase relations decreased, and fluctuations increased, with increasing oscillation frequency. The decreasing stability of the phase relations was accompanied by a weakening attraction to previously stable phase regions. Phase wandering, characteristic of the dynamics of asymmetric systems (e.g., Byblow et al., 1995; Kelso et al., 1990; Wimmers et al., 1992), was prevalent as oscillation frequency increased. While actual transitions to another stable pattern happened infrequently, onset of phase wandering (continuous changes in relative phase) occurred later for the compatible, in-phase, mapping relative to the incompatible, anti-phase, mapping. This indicates that in-phase patterns remain stable for a longer duration. A tendency toward a similar effect for the up-right/down-left mapping was also observed in relation to the up-left/down-right mapping.

The impact of the visual stimulus and movement orientations within each configuration was minimal. Thus, the coordination dynamics were influenced to a greater extent by the information-action mapping and the overall information-action configuration, rather than the particular orientations within a given configuration. The coordination dynamics characteristic of a given mapping depended upon the configuration. That is, the compatibility (or incompatibility) of a particular mapping of information to action was mediated by the information-action configuration.

Did spatial compatibility effects intrude into coordination dynamics? Taken together, the manipulation of mapping and configuration suggested that, not surprisingly, that there were indeed "compatibility" effects in visual coordination. By their definition (spatially based), anti-phase and in-phase patterns were classified as incompatible and compatible mappings, respectively. The often observed greater relative stability of the in-phase mapping corresponded to what would be expected for a spatially compatible relation. The lesser degree of stability of the anti-phase mapping corresponded to expectations for a spatially incompatible relation. These expectations were not only based on previous work on dynamics (e.g., Kelso, 1981) but also on previous work examining S-R compatibility (e.g., Fitts & Seeger). The literature on orthogonal compatibility (e.g., Michaels & Schilder, 1991; Weeks & Proctor, 1990; Weeks, Proctor, & Beyak, 1995) further indicated that an up-right/down-left mapping may be preferred over an up-left/down-right mapping, at least, in terms of reaction time measures. For orthogonal configurations, I found only a slight advantage (in terms of phase attraction) for the up-right/down-left relation. However, the apparent similarity of the two orthogonal mappings may not be too surprising, given that, even in the compatibility literature, there are indications that orthogonal compatibility effects may be small, particularly when S-R arrays are located at the midline (Weeks et al., 1995) (for more on this, see Experiment 2).

Thus, the results suggest that visual coordination dynamics may be influenced by informational, spatial constraints. The nature of the coordinative system's intrinsic dynamics can be influenced by the spatial relation between the driving visual information and the movement to which it is coupled. In the present perception-action system of interest, coordination patterns are spatially defined (in contrast, for example, to a neuromuscular definition). The stability of a given coordination pattern depends upon the spatial correspondence of the mapping between the movement of the stimulus (information) and the movement (action). Change the mapping and you change the constraints, leading to differences in stability. Moreover, whether differential stability between coordination patterns or mappings emerges is also dependent upon the spatial configuration of the information and action. At this level, change the configuration and you once again seemingly change the informational, spatial, constraints, leading this time to changes in the constraints imposed by the mappings.

Informational Symmetry Breaking in Perception-Action Coupling

5. Experiment 2

5.1 Introduction

In a recent study, Wimmers et al. (1992) extended the study of perception-action coordination to the case of a unilaterally, visually coupled system. The question of interest was whether the dynamics observed in between-person coordination (Schmidt et al., 1990) generalized to the situation in which movement was coordinated with the motion of an external visual stimulus. Subjects were required to coordinate rhythmic forearm flexion and extension movements with a sinusoidal visual stimulus. The visual stimulus was oriented horizontally, in the same plane as the movement. Movements were performed in either anti-phase (in opposite direction to movement of the stimulus) or in-phase (in same direction as stimulus) coordination, as cycling frequency was increased. Wimmers et al. (1992) showed that when movements were initially prepared anti-phase, transitions to in-phase coordination occurred as cycling frequency increased, whereas there were no transitions when movements were initially prepared in-phase. In another experiment, the visual stimulus was oriented vertically, orthogonal to the plane of the movement. Subjects performed their movements such that they either coincided flexion with the down stimulus position or with the up stimulus position. In this orthogonal situation, no transitions from one mode of coordination to another occurred. These findings suggest that the intrinsic dynamics of the coordination modes as defined within the present task may have been influenced by the orientation of the driving visual signal.

These findings by Wimmers et al. (1992) have, particularly for the orthogonal configuration, essentially been replicated (Experiment 1, this volume). Rather than simply enumerating phase transitions, however, relative phase uniformity was examined to assess the stability of the coordination dynamics. The two coordination mappings under the orthogonal information-action configuration were not differentiated in terms of variability in relative phase. In contrast, under parallel configurations, the coordination mappings of in-phase and anti-phase differed in terms of stability.

The absence of transitions in the orthogonal information-action configuration has been attributed to an equivalence of the informational constraints imposed by the two possible information-action mappings (Wimmers et al., 1992). The two mappings are said to be equally (in)compatible. This equivalence of informational constraints might be interpreted as, in essence, a symmetry, or specifically, an informational symmetry. This informational symmetry, in terms of the Wimmers et al. study, creates a condition in which the informational constraints imposed by the information-action mappings are equivalent, and therefore neither mapping has precedence over the other (in terms of stability). That is, both information-action mappings are equally compatible, or stable.

Thus, on the basis of Wimmers et al. (1992) and present findings (Experiment 1, this volume), the intrinsic dynamics (patterns that arise due to nonspecific changes in a control parameter) under orthogonal configurations seem to be characterized by phase attractors that may be relatively equivalent in their topology. That is, in terms of the potential landscape of the collective variable dynamics, as modelled by the HKB equation (see Section 2.4, Figure 2.1), the topology of the "wells" of the attractors are similar.

Given the apparent symmetry imposed by the informational, spatial, constraints under orthogonal information-action configurations, the question arises as to whether the symmetry can be broken, and how. Recent examinations of compatibility relations under orthogonal S-R configurations (e.g., Michaels, 1989; Weeks & Proctor, 1990) have revealed that there exists a slight preference for an up-right/down-left mapping over an up-left/down-right mapping. That is, an up-right/down-left mapping yields faster reaction times. However, this is not the entire picture. Weeks et al. (1995) have recently shown, for an orthogonal S-R condition, a trend toward a preferred mapping of the up/down positions of a vertical stimulus to the right/left positions of a response. Moreover, Weeks et al. demonstrated that for a stimulus oriented along the midline, there existed an advantage for the up-right/down-left mapping when the response occurred in the right hemispace. This preference diminished when the response moved toward the midline, and reversed in direction in contralateral space (see also Michaels & Schilder, 1991). The data from Weeks et al. (1995) is replotted in Figure 5.1 and illustrates the mapping preferences as a function of response location.

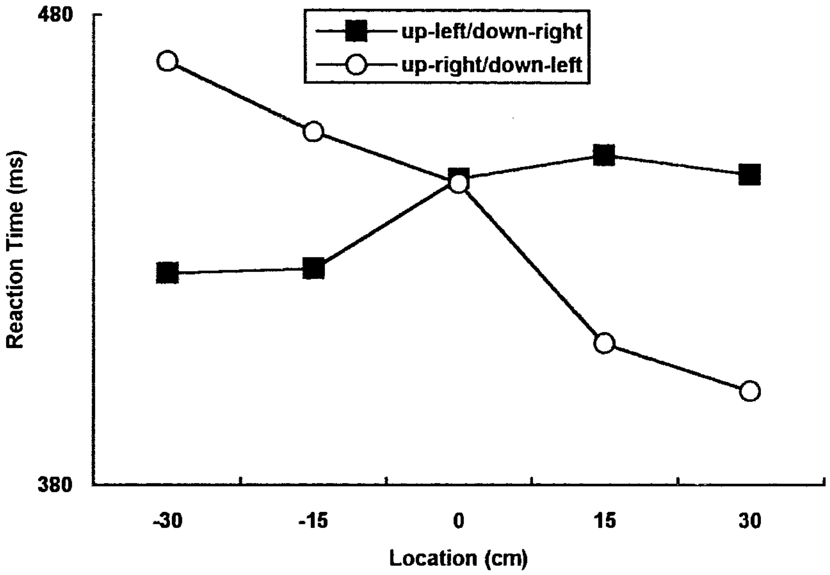


Figure 5.1 Data replotted from Weeks, Proctor, & Beyak (1995). Reaction time is plotted as a function of limb position (0: midline; +: right hemispace; -: left hemispace) and mapping.

In light of these findings from the compatibility literature, I was interested in whether a change in what I refer to as the *information-action global relation* (see Section 3.3) could influence coordination dynamics in perception-action coupling. Could the manipulation of the global relation between information and action be a method for breaking the informational symmetry of the *information-action mappings* observed under orthogonal information-action configurations?[4]

Experiment 1 indicated that the informational constraints imposed by the information-action mappings may be influenced by the configuration. In Experiment 2, I examined whether the global spatial relation between information and action further mediated the interaction between configuration and mapping. In the present study, a paradigm of rhythmic visual coordination was employed as in Experiment 1. The global relation between information and action was varied by manipulating movement location.

5.2 Method

5.2.1 Subjects

Six subjects (2 female, 4 male) were recruited from the university population. All participants had normal or corrected-to-normal vision and were right-handed by self-report. Subjects were paid $15.00 for their participation.

5.2.2 Apparatus

The visual display was presented on an LED display panel, as described in Experiment 1. The nature of the display was identical to that in Experiment 1. Rhythmic rotational movements of the forearms were recorded also as described in Experiment 1.

5.2.3 Procedure

Subjects were asked to perform rhythmic forearm rotation movements with their right hand, in coordination with the visual display. The display was presented aligned with the midline of the subjects and was again oriented either horizontally or vertically. Movements were performed at three positions: in ipsilateral and contralateral space, eccentric to the

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[4] Note that the treatment here of symmetry breaking is in contrast to the notion of symmetry breaking entailing differences in eigenfrequency (e.g., Kelso & Jeka , 1992; Kelso et al., 1990; Kugler & Turvey, 1987).

display, and at the midline. For movements at the midline, the lever was placed in line with the midline of the subject. For movements in ipsilateral space, the lever was placed approximately 30 cm to the right of the midline. For movements in contralateral space, the lever was placed approximately 15 cm to the left of the midline. Due to biomechanical constraints, the lever could not be placed 30 cm to the left of midline. The contralateral lever placement resulted in some changes in the nature of the forearm movement. The movement involved extension and pronation of the arm as the lever was moved to its left endpoint, and flexion and supination of the arm as the lever was moved to its right endpoint. Despite the change in the movement, it was the salience of the left and right endpoints of the movement that were deemed to be of greater importance.

For each of the 2 display orientations, there were two prescribed modes of coordination. For the horizontal orientation, subjects were required to perform in either an anti-phase or in-phase mapping. For the orthogonal orientation, subjects were required to perform in either an up-right/down-left or a up-left/down-right mapping. The frequency of oscillation of the visual signal was scaled as in Experiment 1, with the exception that each plateau was now comprised of 15 cycles at a given frequency.

Subjects were instructed to maintain the frequency specified by the display, and the coordination pattern or mapping in which they were prepared, as accurately as possible. However, subjects were also instructed that, in the event of any change in pattern, they were not to attempt to recover the original pattern but to establish the most comfortable pattern at the current frequency.

Each subject participated in two experimental sessions. Each session was comprised of six blocks of trials, one block for each combination of limb position and display orientation. All blocks under a particular display orientation were performed as a set. Order of presentation of display orientation was counterbalanced across subjects. Within each orientation, subjects first performed with the limb positioned at midline. Subsequent limb positions were randomized. Subjects performed 10 trials, 5 for each mapping condition, within each combination of orientation and limb position. Mapping was alternated between trials. Subjects performed the first 5 trials for each of the six blocks in the first session, and the remaining half in the second session. Subjects were allowed to familiarize themselves with the task and were given brief rest periods as required. Each session lasted approximately 70 minutes.

5.2.4 Data Reduction and Analyses

Data reduction procedures were identical to those in Experiment 1.

5.3 Results

The study employed a 2 display orientation (horizontal, vertical) by 3 limb position (contralateral, midline, ipsilateral) by 2 mode-mapping (in-phase or up-right/down-left, anti-phase or up-left/down-right) by 4 frequency plateau (1.0, 1.25, 1.5, 1.75 Hz) repeated-measures design.

Separate sets of analyses were performed for the parallel (horizontal display) and orthogonal (vertical display) information-action configurations. Data for each configuration were subjected to a 3 limb position by 2 mapping by 4 frequency plateau repeated-measures ANOVA. All post-hoc analyses were performed using the Tukey HSD procedure with $\alpha = .05$

5.3.1 Limit-Cycle Dynamics

Conformity to the prescribed oscillation frequency was assessed as the absolute error between the frequency of the limb and the display frequency. Analysis for the horizontal display orientation revealed only an effect of plateau, $F(3, 15) = 5.16, p < .02$, with the largest frequency deviation occurring at the highest oscillation frequency. Analysis for the vertical display revealed a similar effect for plateau, $F(3, 15) = 7.76, p < .003$ (see Figure

5.2). In addition, there was an interaction of limb position and mapping, $F(2, 10) = 9.72$, $p < .005$. As shown in Figure 5.3, there was significantly less deviation from the display frequency for the up-right/down-left mapping compared to the up-left/down-right mapping in the ipsilateral limb position. There was also a decrease in deviation from the contralateral to ipsilateral position for the up-right/down-left mapping.

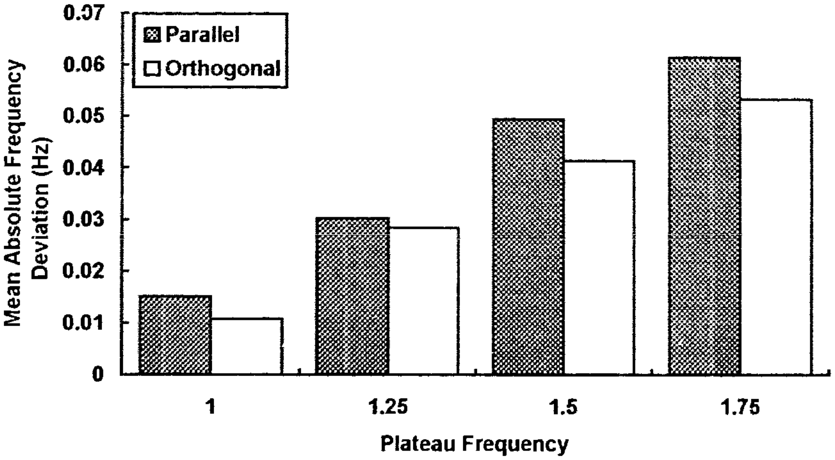


Figure 5.2 Absolute deviation from display frequency as a function of plateau frequency for parallel (horizontal display) and orthogonal (vertical) configurations.

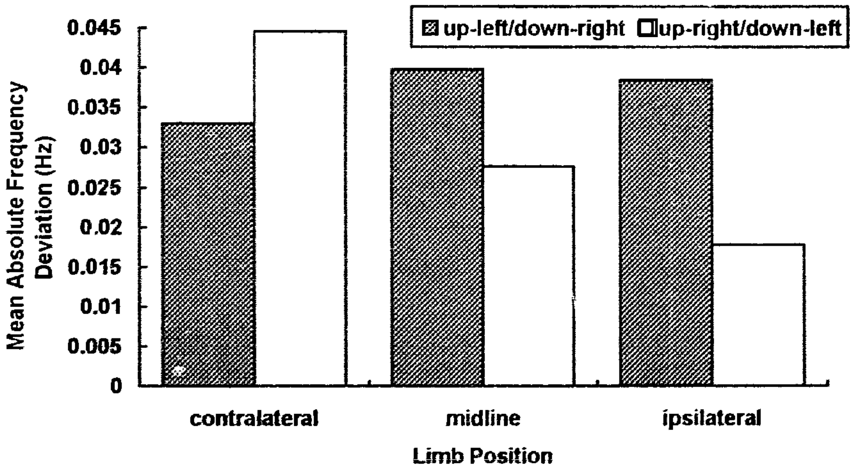


Figure 5.3 Absolute deviation from display frequency as a function of limb position and plateau for orthogonal configuration.

Variability in oscillation frequency (coefficients of variation) was assessed in identical ANOVA designs. Whereas there were no significant effects found in the analysis of the parallel configuration, an effect for plateau, $F(3, 15) = 8.39, p < .002$, was found in the analysis of the orthogonal configuration. Variability in oscillation frequency was greatest for the 1.25 and 1.5 Hz plateaus ($\bar{x}$ = 5.19 and 5.16, respectively) compared to the 1.0 and 1.75 Hz plateaus ($\bar{x}$ = 4.51 and 4.68, respectively).

Variability about the movement endpoints was assessed in order to examine expressions of anchoring. Data were subjected to a 2 endpoint (left, right) by 2 limb position by 2 mapping by 4 plateau repeated-measures ANOVA. Analysis of data for the parallel configuration revealed an interaction of endpoint and limb position, $F(2, 10) = 15.11, p < .002$. As might be expected from the biomechanical constraints of the movement, there was significantly less endpoint variability about the right movement endpoint than the left movement endpoint when the limb was placed contralaterally (see Figure 5.4A).

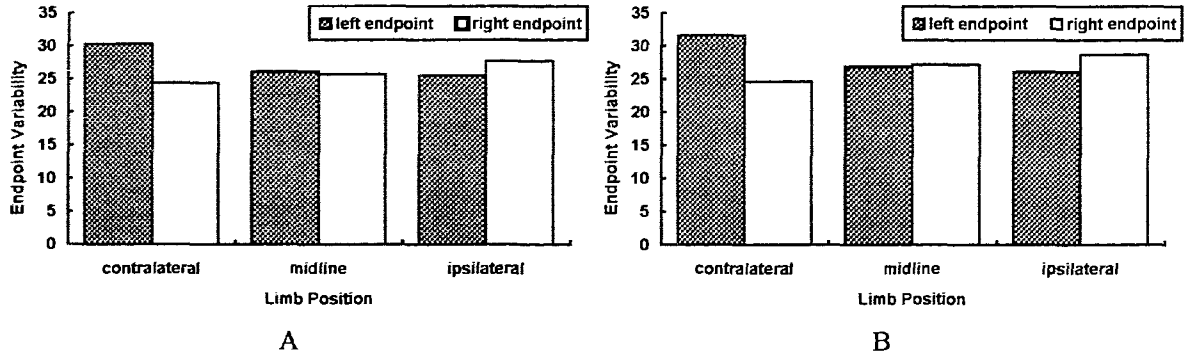


Figure 5.4 Endpoint variability as a function of limb position and endpoint for (A) parallel configuration and (B) orthogonal configuration.

Analysis of the orthogonal configuration revealed a similar interaction of endpoint and limb position, $F(2, 10) = 26.78, p < .001$, again reflecting a difference in variability between left and right endpoints at the contralateral limb position (see Figure 5.4B). There was also an effect of plateau, $F(3, 15) = 3.52, p < .05$, due primarily to a significant difference in endpoint variability between the 1.0 ($\bar{x}$ = 25.7) and 1.5 Hz ($\bar{x}$ = 27.8) plateaus.

5.3.2 Relative Phase Dynamics

Variability of relative phase, assessed through measures of uniformity, was analyzed in a 3 limb position by 2 mapping by 4 frequency plateau repeated-measures design. Analysis of parallel data revealed main effects for mapping, $F(1, 5) = 20.83, p < .007$, and for plateau, $F(3, 15) = 37.31, p < .001$. Relative phase between information and action on trials in which subjects began anti-phase was found to be more variable ($\bar{x}_{\text{unif}} = 0.73$), or less uniform, than trials in which subjects began in-phase ($\bar{x}_{\text{unif}} = 0.85$). Overall, uniformity decreased as a function of plateau frequency (see Figure 5.5). Analysis of the orthogonal configuration also revealed a main effect for plateau, $F(3, 15) = 32.16, p < .001$, reflecting a decrease in uniformity with increasing cycling frequency.

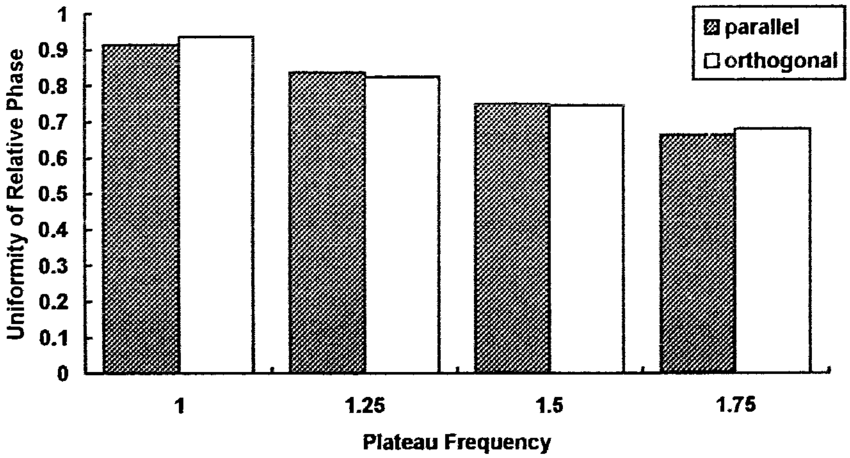


Figure 5.5 Uniformity of relative phase as a function of mapping and plateau for parallel and orthogonal configurations.

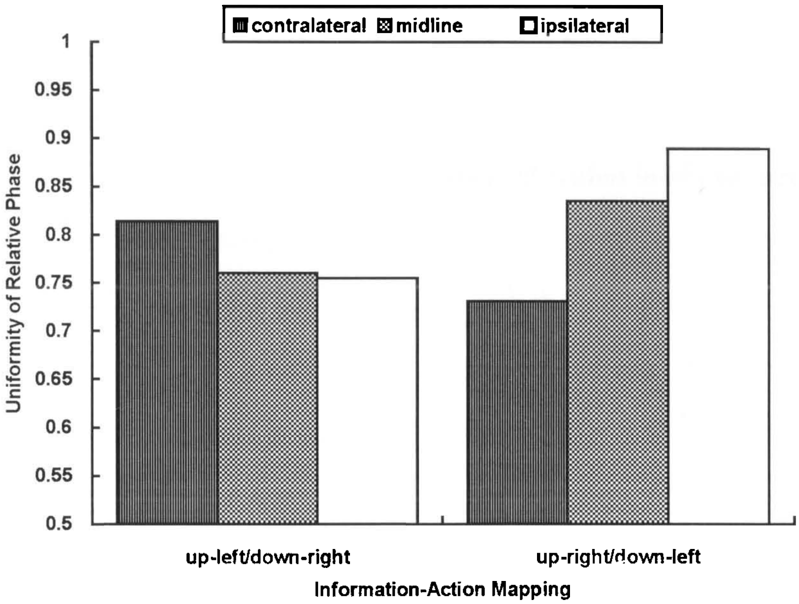
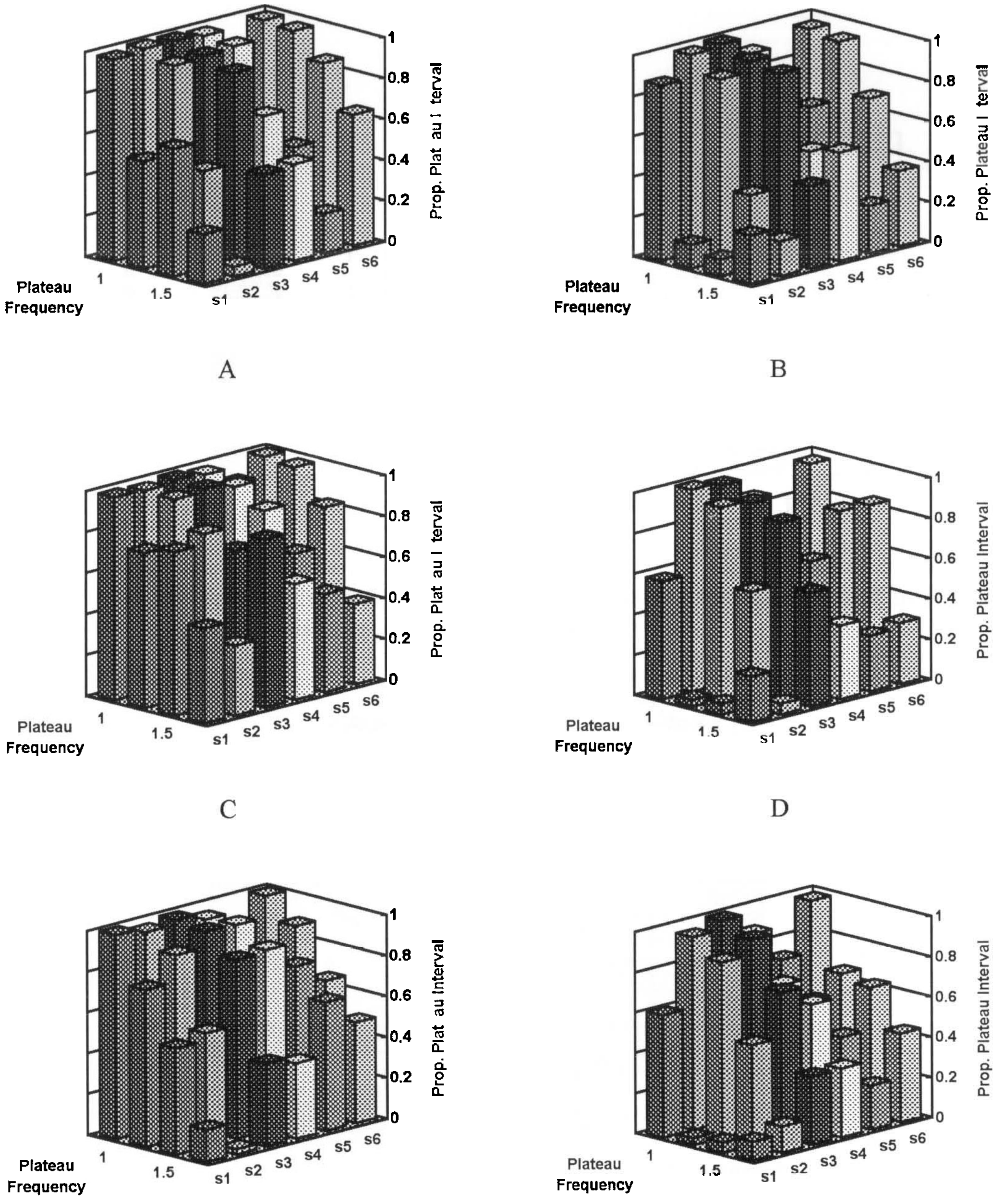


Figure 5.6 Uniformity of relative phase as a function limb position and mapping.

In addition, as Figure 5.6 illustrates, the preferred mapping, for which coordination was less variable, changed as a function of the global relation between information and action (i.e., whether the action was performed in ipsilateral versus contralateral space). Post-hoc analyses of the interaction between limb position and mapping, $F(2, 10) = 18.10$, $p < .001$, revealed that for actions performed in ipsilateral space, the up-right/down-left mapping produced more uniform coordination than the up-left/down-right mapping. Although there were no significant differences between the mappings for the midline and contralateral positions, there was a trend toward a reversal of mapping preferences for the contralateral position, as evident in Figure 5.6.

Phase attraction, quantified as the proportion of the plateau interval spent within particular regions of relative phase space, was analyzed separately for each mapping over the factors of limb position and plateau frequency. For the parallel configuration, analysis of the proportion of time spent in-phase when prepared in-phase revealed main effects for limb position, $F(2, 10) = 4.64, p < .05$, and plateau, $F(3, 15) = 38.46, p < .001$. On average, attraction to in-phase regions was slightly greater for movements with the limb placed at the midline ($\bar{x}$ = 0.80) compared to contralateral space ($\bar{x}$ = 0.70), with movements in ipsilateral space being intermediate ($\bar{x}$ = 0.72). In-phase attraction decreased with increasing oscillation frequency, as indicated by the decreasing proportion of the plateau interval for which relative phase remained within in-phase regions (see Figure 5.7). A similar breakdown in anti-phase coordination with increasing frequency was also evident for trials in which subjects began with the anti-phase mapping, $F(3, 15) = 16.98$, $p < .001$ (Figure 5.7). A greater proportion of the plateau interval was spent within anti-phase regions for movements in contralateral space ($\bar{x}$ = 0.61) compared to ipsilateral space ($\bar{x}$ = 0.56), as reflected in a main effect for limb position, $F(2, 10) = 4.16$, $p < .05$.

Examination of phase attraction for the orthogonal configuration revealed a somewhat clearer picture in terms of how the mapping and global relation between information and action might interact. For movements prepared up-right/down-left, there was greater attraction to this region of phase space when the movement was performed in ipsilateral, as opposed to contralateral, space, $F(2, 10) = 8.13$, $p < .009$. In contrast, for movements prepared up-left/down-right, there was greater attraction to this region of phase space when the movement was performed in contralateral, as opposed to ipsilateral, space, $F(2, 10) = 4.43$, $p < .05$ (see Figure 5.10). There was also an effect of plateau frequency for both the up-right/down-left trials, $F(3, 15) = 31.16$, $p < .001$, and the up-left/down-right trials, $F(3, 15) = 30.01$, $p < .001$ (see Figure 5.9 and 5.11).



A

B

C

D

E

F

Figure 5.7 Proportion of plateau interval spent within regions of phase space for parallel configuration. (A) Contralateral - in-phase; (B) Contralateral - anti-phase; (C) Midline - in-phase; (D) Midline - anti-phase; (E) Ipsilateral - in-phase ; (F) Ipsilateral - anti-phase.

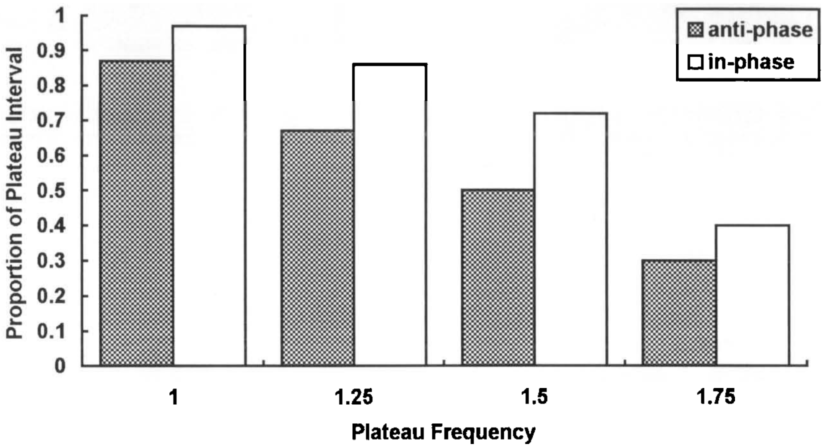


Figure 5.8 Proportion of plateau interval spent within in-phase regions for trials prepared in-phase and within anti-phase regions for trials prepared anti-phase.

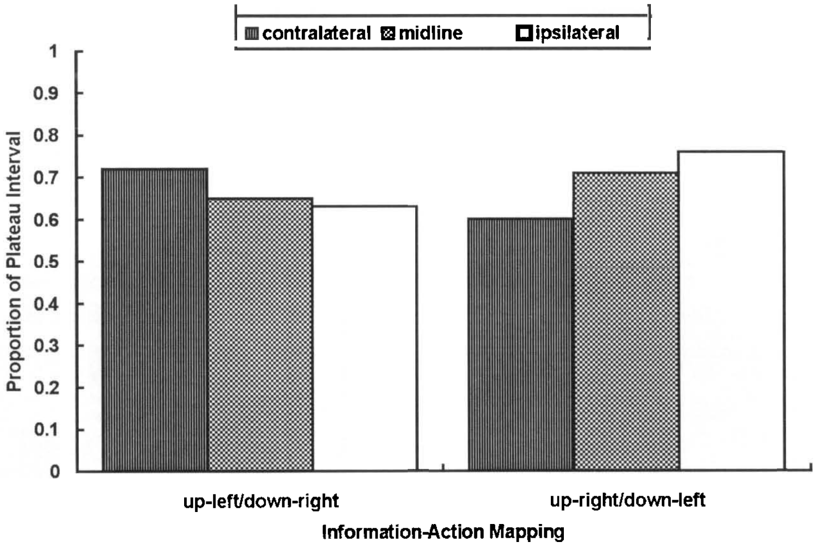
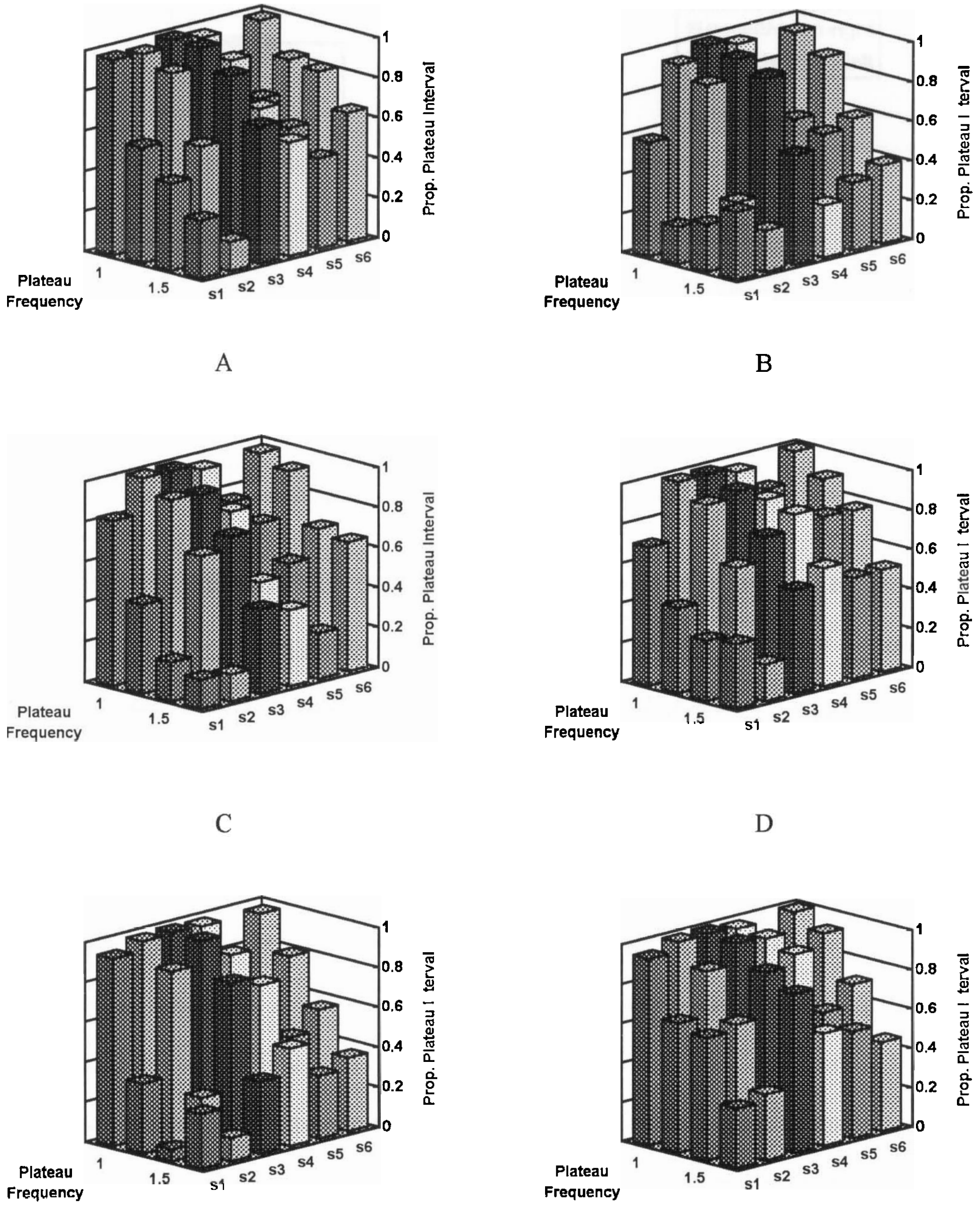


Figure 5.10 Proportion of plateau interval spent within up-left/down-right regions for trials prepared up-left/down-right and within up-right/down-left regions for trials prepared up-right/down-left.



A

B

C

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E

F

Figure 5.9 Proportion of plateau interval spent within regions of phase space for orthogonal configuration. (A) Contralateral - up-left/down-right; (B) Contralateral - up-right-down-left; (C) Midline - up-left/down-right; (D) Midline - up-right-down-left; (E) Ipsilateral - up-left/down-right; (F) Ipsilateral - up-right-down-left.

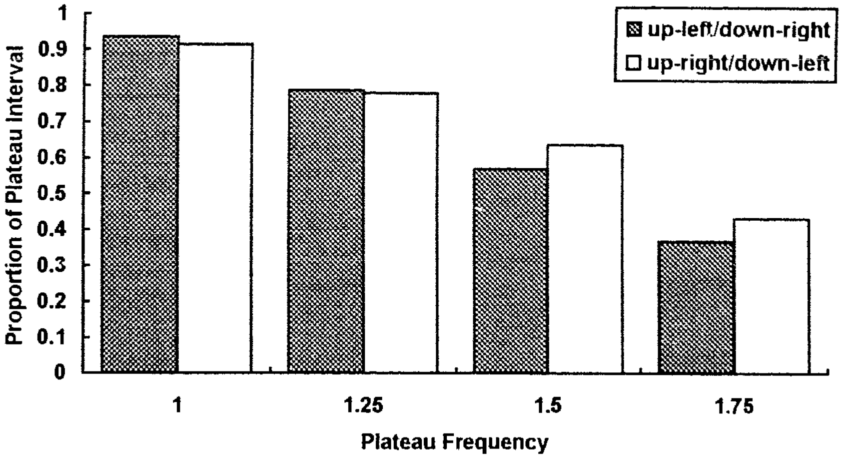


Figure 5.11 Proportion of plateau interval spent within up-left/down-right regions for trials prepared up-left/down-right and within up-right/down-left regions for trials prepared up-right/down-left.

Examination of the attraction to intermediate phase relations allowed further insight into differences between mapping constraints. The proportion of time (of plateau interval) spent in intermediate phase regions was analyzed over limb position, mapping, and plateau. For the parallel configuration, there was a trend toward a greater degree of intermediate phase attraction for movements under the anti-phase mapping, $F(1, 5) = 6.31, p < .06$, ($\bar{x} = 0.21$) compared to movements under the in-phase mapping ($\bar{x} = 0.19$). There was also an increase in intermediate phase attraction as the frequency of oscillation increased with plateau, $F(3, 15) = 25.50, p < .001$. For the orthogonal configuration, limb position interacted with mapping, $F(2, 10) = 8.06, p < .009$. As illustrated in Figure 5.12, whereas there were no differences between the two mappings under midline and ipsilateral limb placements, the up-left/down-right mapping under the contralateral placement was characterized by less attraction to intermediate phase regions compared to the up-right/down-left mapping. The effect for plateau frequency, $F(3, 15) = 20.34, p < .001$, was also mediated by limb position, $F(6, 30) = 2.64, p < .04$. While attraction to intermediate phase regions increased with oscillation frequency, the increase between the final two plateaus was somewhat less for the contralateral limb position.

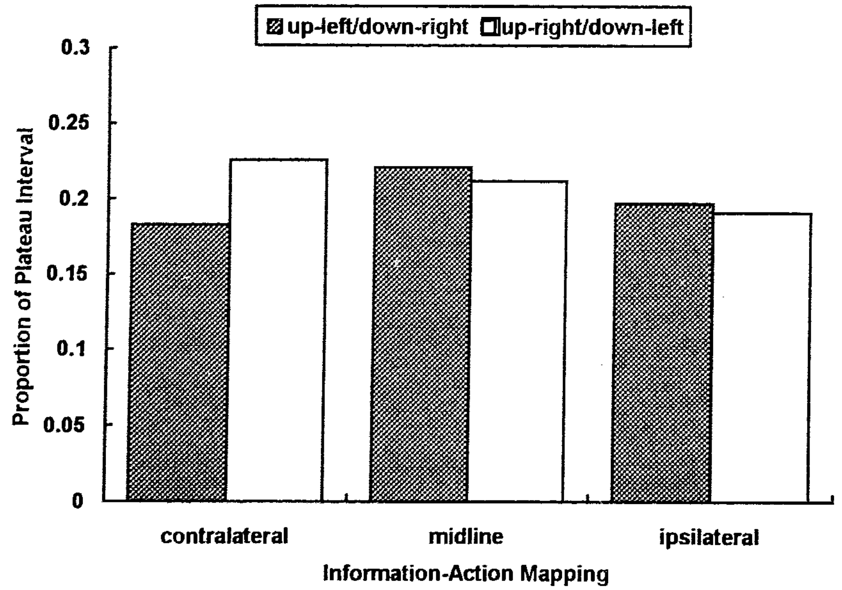
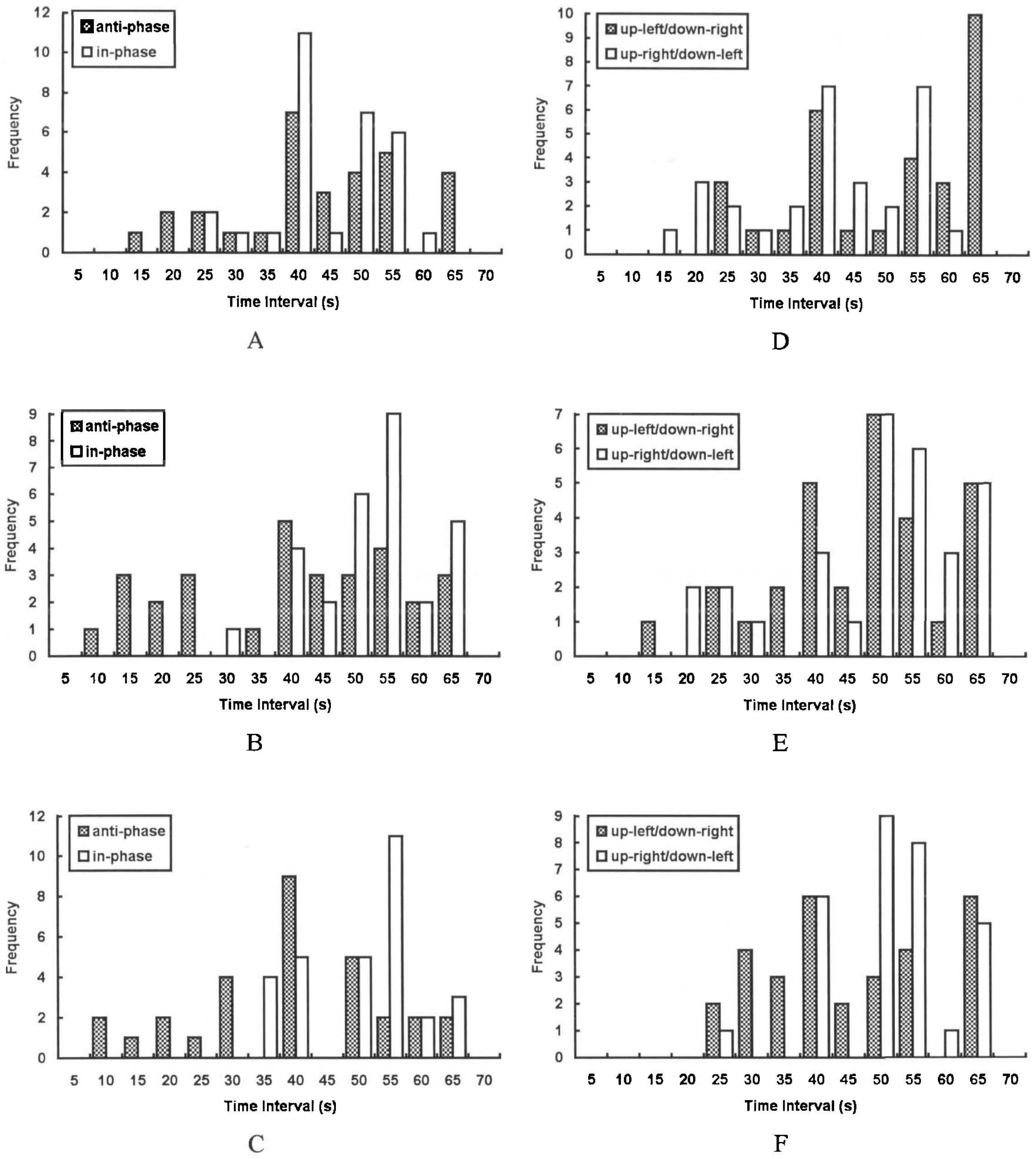


Figure 5.12 Proportion of plateau interval spent within intermediate phase regions for trials prepared up-left/down-right and up-right/down-left as a function of limb position.

The relative phase time series were characterized almost exclusively by a complete loss of entrainment of the initial coordination pattern, leading to phase wandering, as oscillation frequency increased (see also Experiment 1; Byblow et al., 1995). Figure 5.13 shows a series of histograms of the time intervals at which onset of phase wandering or loss of the initial pattern occurred.

Analysis of these times (measured from the beginning of the trial) over limb position and mapping revealed an interaction between the two factors for both parallel, $F(2, 10) = 5.47, p < .025$, and orthogonal, $F(2, 10) = 14.31, p < .002$, configurations. For the parallel configuration, the anti-phase pattern was lost at an earlier time interval relative to the in-phase pattern when the limb was placed at the midline and ipsilateral positions. There were no differences for the contralateral position. The pattern was somewhat reversed for the orthogonal configuration. Whereas there were no differences between the two mappings for the midline and ipsilateral position, the up-left/down-right pattern was maintained for a longer duration relative to the up-right/down-left pattern at the contralateral limb placement.



A D B E C F

Figure 5.13 Histograms of time intervals at which initial coordination patterns were lost. (A)-(C): Parallel configuration - A: contralateral, B: midline, C: ipsilateral; (D)-(F): Orthogonal configuration - D: contralateral, E: midline, F: ipsilateral.

5.4 Summary and Discussion

Of interest in the present study was whether a change in the information-action global relation can influence coordination dynamics in perception-action coupling. Experiment 1 showed that the informational constraints imposed by the information-action mappings was influenced by the configuration. The present study examined whether the global spatial relation between information and action further mediated the interaction between configuration and mapping.

The manipulation of the global spatial relation between the driving visual information and the movement was intended to break the apparent symmetry between information-action mappings under an orthogonal configuration (e.g., Experiment 1, this volume; Wimmers et al., 1992). The results for the collective variable dynamics indicate that the manipulation was, at least partially, successful. The preferred orthogonal mapping (based on relative phase variability and phase attraction) changed as a function of limb position, or global relation. Indications were of an up-right/down-left preference for movements performed in ipsilateral space and an opposite preference (a trend toward) for contralateral space. A reason for the less robust effect for the up-left/down-right mapping may be that, due to biomechanical constraints, the movement could not be performed to the same eccentricity in contralateral space compared to ipsilateral space. Nevertheless, such mapping preferences have previously been observed for discrete tasks employing reaction time measures (e.g., Michaels, 1989; Weeks & Proctor, 1990). Moreover, Michaels and Schilder (1991) and Weeks et al., (1995) have both demonstrated the impact of manipulating the eccentricity of response locations with respect to stimulus locations. Specifically, the up-right/down-left mapping has been shown to yield faster reaction times when the response is to the right of the midline and the stimulus array, whereas the up-left/down-right mapping yields faster reaction times when the response is to the left of midline (e.g., Weeks et al., 1995; see Figure 5.1). The present findings are thus consistent with previous work in the compatibility literature (e.g., Michaels & Schilder, 1991; Weeks et al., 1995). An important difference, however, is the demonstration of the intrusion of these orthogonal compatibility effects at the level of coordination.

The influence of the global relation manipulation on the coordination dynamics under the parallel configuration was, in terms of relative phase variability and transition times, indicative of what might be termed relative spatial compatibility (or constraints). That is, as might be expected from previous work (e.g., Schmidt et al., 1990), the anti-phase pattern or mapping was less stable, or more variable, than the in-phase mapping. This was essentially regardless of the global relation between the visual information and the movement. Thus, in terms of spatial constraints, it seems that under a parallel configuration, when the mapping of information to action in terms of spatial direction is clearly defined, relative direction (or location) may be more important than absolute direction. Having said this, it should be noted that the results for phase attraction were less clear. Attraction to in-phase and anti-phase regions was influenced by limb position, but no consistent pattern was evident. The indications that relative direction (or location) may be more important than absolute direction is interesting, given that this characteristic is a feature of spatial S-R compatibility (e.g., Umiltà & Nicoletti, 1990). That is, the spatial dependence of reaction times that characterize compatibility effects has been shown to be based upon the relative locations of stimuli and responses, and not their absolute locations (e.g., Umiltà & Liotti, 1987).

Initially, the apparent equistability of the mappings under the orthogonal configuration was characterized as a form of symmetry, in this case, an informational symmetry. The term symmetry as it was used here was meant specifically to capture the observation that the stability of the coordination patterns under the orthogonal mappings seemed equivocal, in contrast to the differential stability normally exhibited between parallel mappings (i.e., in-phase vs. anti-phase). Given this conception of a symmetry in the informational constraints imposed by the mappings, the term symmetry breaking was then meant to denote specifically breaking the equistability of the mappings — thus, the manipulation of the global relation between information and action. The usage of term symmetry and symmetry breaking in the present context is different from its more common usage (e.g., Jeka & Kelso, 1995). For example, symmetry breaking usually refers to situations which entail differences in the eigenfrequencies of the coordinating components (e.g., Kugler & Turvey, 1987) or involve non-identical components (e.g., Kelso & Jeka, 1992; Kelso et al., 1990). In terms of its more common context, the present perception-action system under study may be considered an asymmetric system, in that the components in coordination, a rhythmic visual signal and a human limb, are quite different from one another.

Experiment 1 demonstrated that the configuration of information to action in a visually coupled perception-action system may influence the intrinsic coordination dynamics of the system. For an orthogonal configuration, the dynamic stability of the mappings were essentially equivalent. The present study adds another element to this story, namely, that the global relation between information and action can also have an impact on the relation between the configuration and mapping, and the stability of the coordination dynamics.

6. Experiment 3

6.1 Introduction

In Experiment 1, basic spatial and mapping constraints in the coordination dynamics of a unilaterally coupled coordinative system were examined. It was demonstrated that respective stabilities of the coordination patterns were influenced by the configuration between information and action. Experiment 2 showed that the global relation between information and action may also play a role in determining stability. In the present study, I returned to the question of how information-action configurations in an optically coupled coordinative system influence the intrinsic dynamics of the system.

In both Experiments 1 and 2, only two orientations of the visual display were employed — 0° and 90°. In the present study, I employed configurations of 0, 30, 60, 90, 120, 150 and 180 degrees. In Experiment 1, for example, differences in the stability of the two coordination patterns were most clearly expressed when the visual display and the movement were configured in parallel. In contrast, the two patterns were equistable under an orthogonal configuration. In the present study, similar results were expected, respectively, for orientations of 0 (180) and 90 degrees. Of additional interest was the nature of the coordination dynamics under intermediate configurations.

In the present study, I manipulated configuration by varying the orientation of the visual display, while maintaining the movement orientation constant. Presuming that the coordination patterns would be differentially stable at parallel orientations and equistable at the orthogonal orientation, I sought to examine whether the relative differences between mappings would diminish as one progressed from the parallel to the orthogonal configuration. The implication would be a gradual change in the landscape of the intrinsic dynamics as the configuration between information and action is varied.

6.2 Method

6.2.1 Subjects

Six subjects (4 female, 2 male) were recruited from the university population. All participants had normal or corrected-to-normal vision and were right-handed by self-report. Two of the subjects had previously participated in Experiment 1. Subjects were paid $10.00 for their participation.

6.2.2 Apparatus

A computer-generated visual stimulus was presented on a computer monitor (Viewsonic 4E SVGA monitor, model 7033) positioned in front of a seated subject. The visual display consisted of the periodic activation of two solid circles (4 mm diameter) which defined the 0 and 180 degree endpoints of a cycle. Thus, the circle appeared to oscillate discretely between two endpoints, remaining illuminated for approximately 100 ms at each endpoint. The display endpoints were separated by a distance of 5.5 cm and were presented about the centre of the monitor. The circles denoting the endpoints were of two colours: one yellow and one magenta. The endpoints were also joined by a grey coloured line.

Rhythmic rotational movements of the forearm were recorded with the use of a custom-built lever, as described in Experiment 1. The remainder of the apparatus was identical to Experiment 1.

6.2.3 Procedure

Subjects were asked to perform rhythmic forearm pronation and supination movements with their right hand, in coordination with the visual display. The display monitor was located approximately 1.2 m from the seated subject and was raised such that the centre of the panel was approximately at eye level. Subjects were seated with their midline aligned with that of the display. The lever was also aligned with the midline of the subjects and display. Thus, subjects' movements were performed along the coronal plane about the midline. Seat height was adjusted for each subject such that the elbows were flexed to approximately 90 degrees.

The visual display could be oriented at 7 angles: 0, 30, 60, 90, 120, 150, and 180 degrees from the horizontal plane. For the 0° orientation, the circle denoting the left endpoint was coloured yellow, and the circle denoting the right endpoint was coloured magenta. This arrangement was reversed when the display was oriented at 180°. At 90°, the upper circle was magenta and the lower circle was yellow.

The different display orientations resulted in 7 information-action configurations, one for each angle of display orientation. For each configuration, there were two prescribed modes of display-limb, or information-action, coordination. For each configuration, subjects were required to perform in either a *yellow-left/magenta-right* (yl/mr) or *magenta-left/yellow-right* (ml/yr) mapping. Yellow-left/magenta-right mapping was defined as movement coordination such that the left movement endpoint was mapped onto the yellow display endpoint and the right movement endpoint with the magenta display endpoint. Magenta-left/yellow-right mapping was simply the opposite arrangement.

The frequency of oscillation of the visual signal was scaled as in Experiment 1, with the exception that each plateau was now comprised of 12 cycles at a given frequency. Subjects were instructed to maintain the frequency specified by the display, and the coordination mapping in which they were prepared, as accurately as possible. However, subjects were also instructed that, in the event of any change in pattern, they were not to attempt to recover the original pattern but to establish the most comfortable pattern at the current frequency.

Subjects performed in 7 blocks of trials, with each block corresponding to a particular display orientation. Order of presentation of display orientation was randomized for each subject. Each block was comprised of 10 trials, 5 trials for each information-action mapping. Subjects alternated mappings between trials. Subjects performed the first 5 trials for each block in one session, and the remaining 5 for each block in a second session. Subjects were allowed to familiarize themselves with the task at the beginning of a session. Rest periods were provided as required. Each session lasted approximately 70 minutes.

6.2.4 Data Reduction and Analyses

Data reduction procedures were identical to those in Experiment 1.

6.3 Results

Data were subjected to a 7 display orientation (0, 30, 60, 90, 120, 150, 180 degrees) by 2 information-action mapping (yellow-left/magenta-right, magenta-left/yellow-right) by 4 frequency plateau (1.0, 1.25, 1.5, 1.75 Hz) repeated-measures ANOVA. All post-hoc analyses were performed using the Tukey HSD procedure with $\alpha = .05$.

6.3.1 Limit Cycle Dynamics

Conformity to the prescribed oscillation frequency was assessed as the absolute error between the frequency of the limb and the display frequency. As shown in Figure 6.1, frequency deviation increased as a function of plateau frequency, $F(3, 15) = 23.15, p < .001$. In addition, this relation was mediated by both orientation and mapping, as revealed in an Orientation x Mapping x Plateau interaction, $F(18, 90) = 2.09, p < .02$. Also evident in Figure 6.1 is the tendency for the frequency deviation to be greater for the ml/yr mapping compared to the yl/mr mapping for display orientations up to 90 degrees, particularly with higher frequencies. In contrast, this trend was reversed for orientations greater than 90 degrees.

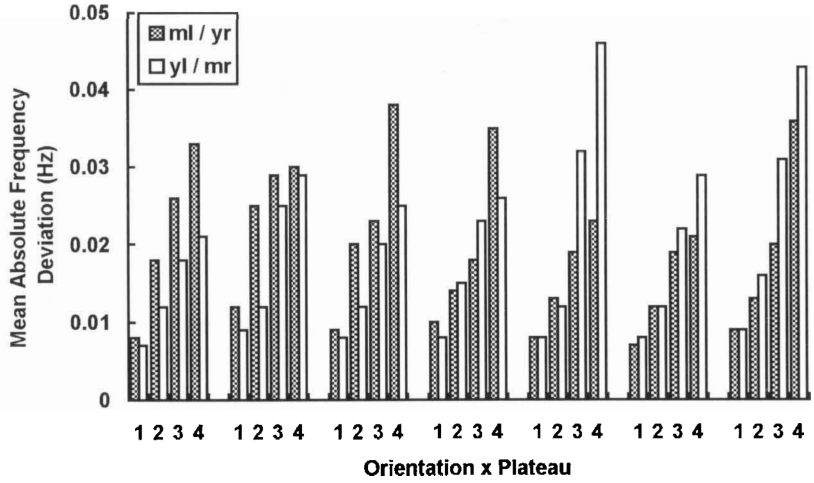


Figure 6.1 Absolute deviation from display frequency as a function of plateau frequency and display orientation. Axis labels 1-4 correspond to plateau level. Orientation proceeds from left to right: 0, 30, 60, 90, 120, 150, and 180 degrees.

No effects were found for cycle-to-cycle variability, assessed through coefficients of variation of cycle frequency.

Analysis of anchoring, or endpoint variability, included the additional factor of movement endpoint in a 4-way repeated-measures ANOVA. The analysis revealed a main effect for endpoint, $F(1, 5) = 24.78, p < .005$, which was further mediated by plateau, $F(3, 15) = 6.05, p < .007$. As shown in Figure 6.2, the right, or supination, movement endpoint was characterized by less overall variability than the left, or pronation, endpoint. Moreover, the difference in variability between the two endpoints decreased as a function of plateau. There was also an interaction of orientation and plateau, $F(18, 90) = 1.95, p < .025$, reflecting differences in endpoint variation between orientations as cycling frequency increased. However, the interaction did not decompose meaningfully.

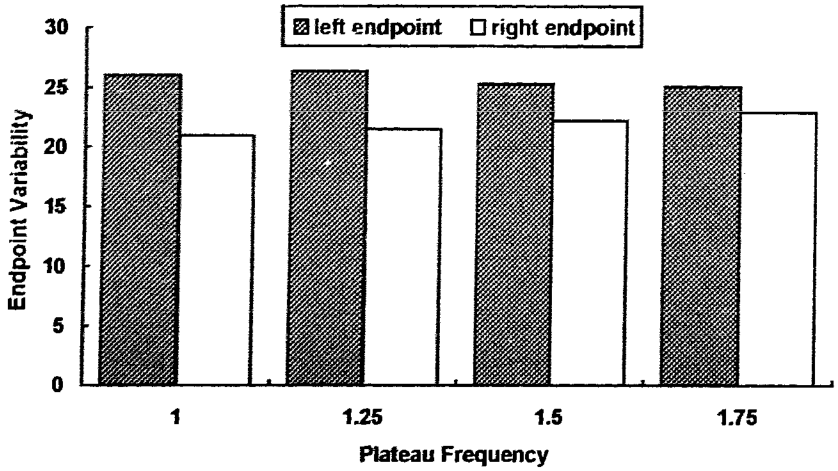
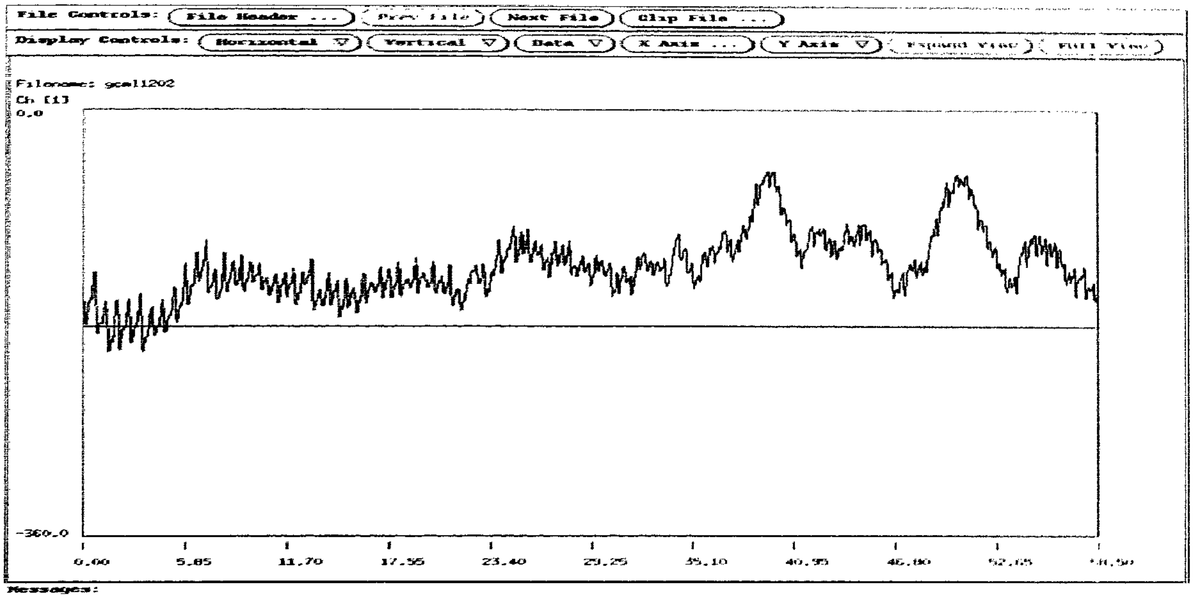


Figure 6.2 Endpoint variability as a function of endpoint and plateau.

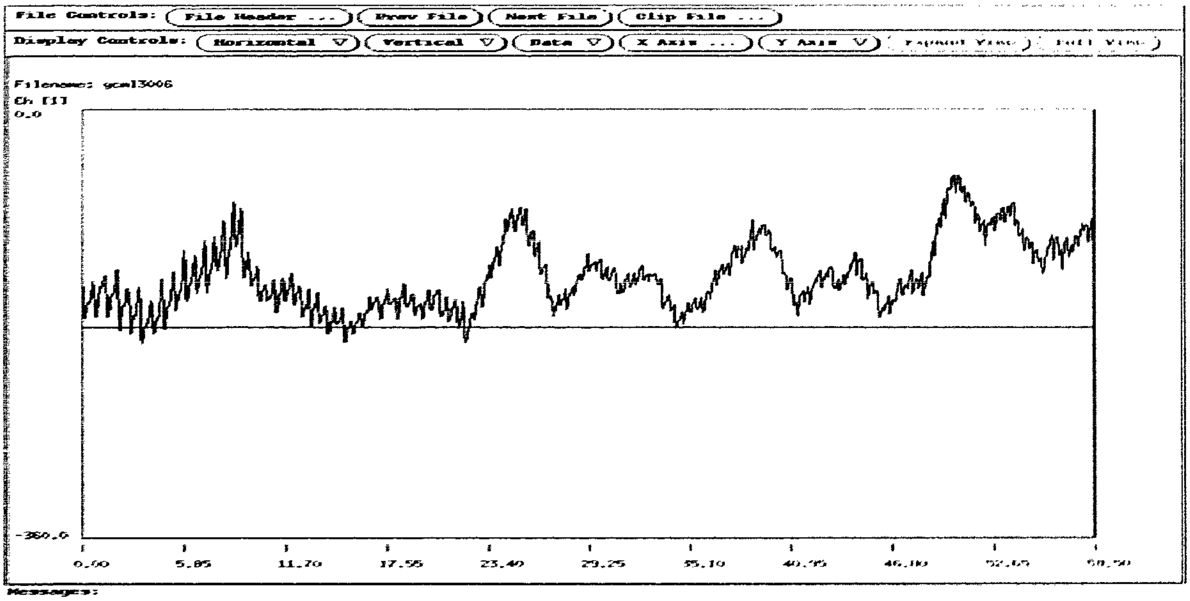
6.3.2 Relative Phase Dynamics

Initial inspection of the relative phase time series revealed many instances in which there were no clear transitions (either to another stable phase relation or to phase wandering) (see, for example, Figure 6.3). Thus, time to transition (or loss of entrainment) data were not derived from the relative phase time series. The present results focussed instead on the variability of relative phase and on phase attraction.



Filename: gcml1202
Ch [1]

A: ml/yr mapping - 0° orientation



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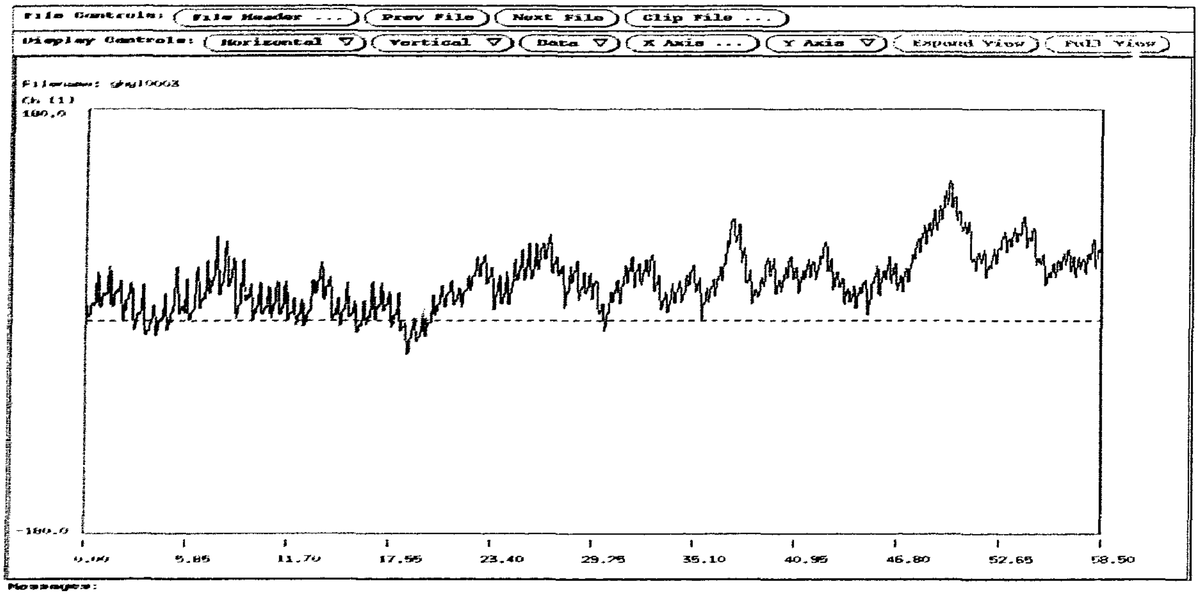
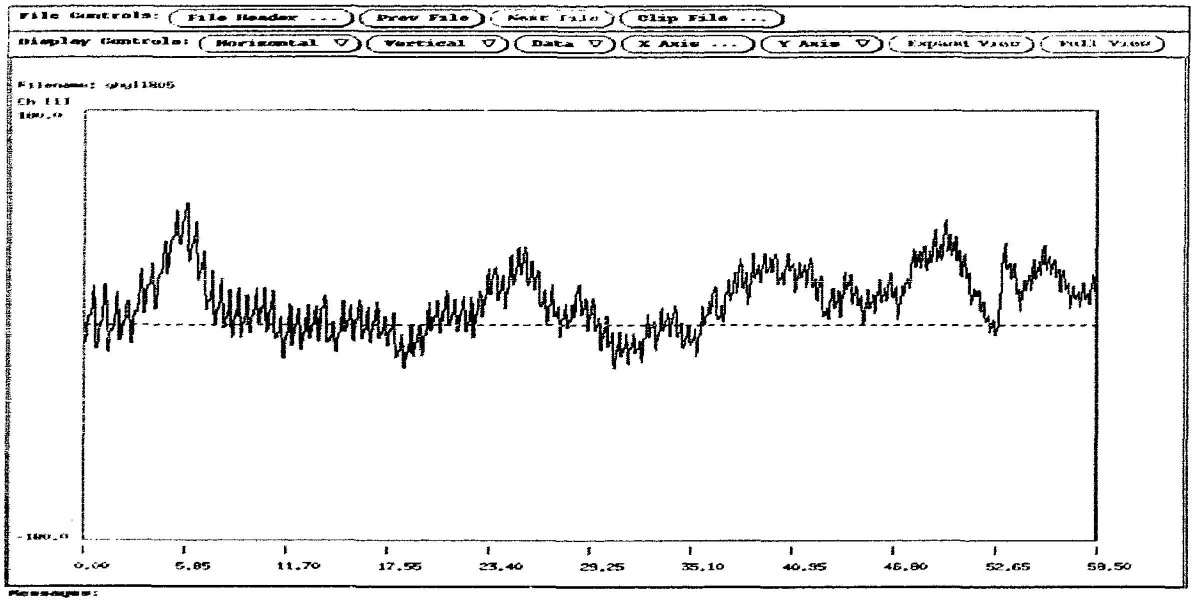
Ch [1]

B: ml/yr mapping - 30° orientation



C: yl/mr mapping - 0° orientation



D: yl/mr mapping - 180° orientation

Figure 6.3 A-D: Examples of relative phase time series showing entrainment to prescribed mapping.

Uniformity of relative phase, an index of variability (and stability) of relative phase, was analyzed in a 7 orientation by 2 mapping by 4 frequency plateau repeated-measures ANOVA. Analysis revealed a main effect for plateau, *F*(3, 15) = 30.66, *p* < .001, reflecting a decrease in relative phase uniformity as oscillation frequency increased (see Figure 6.4).

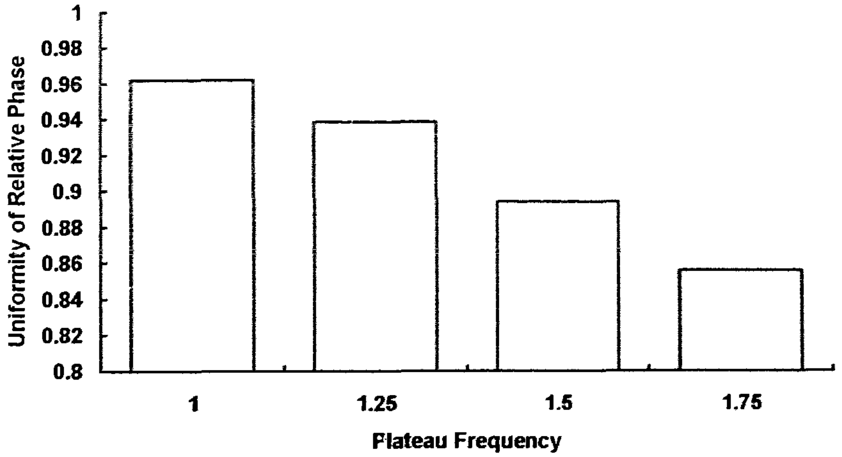
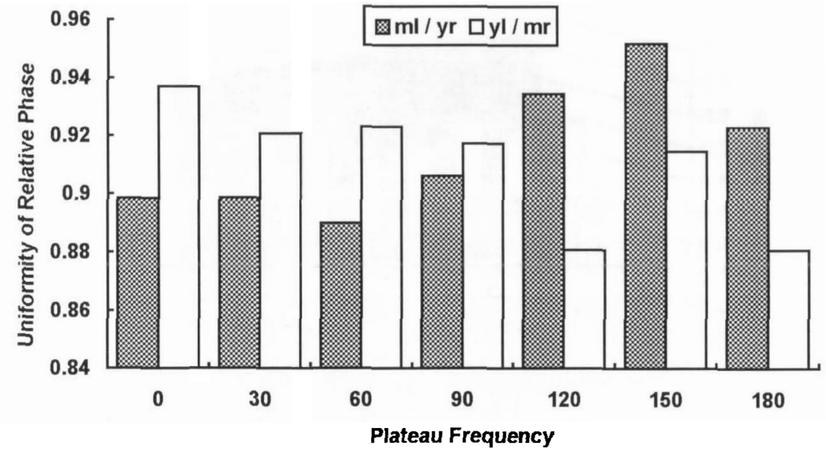
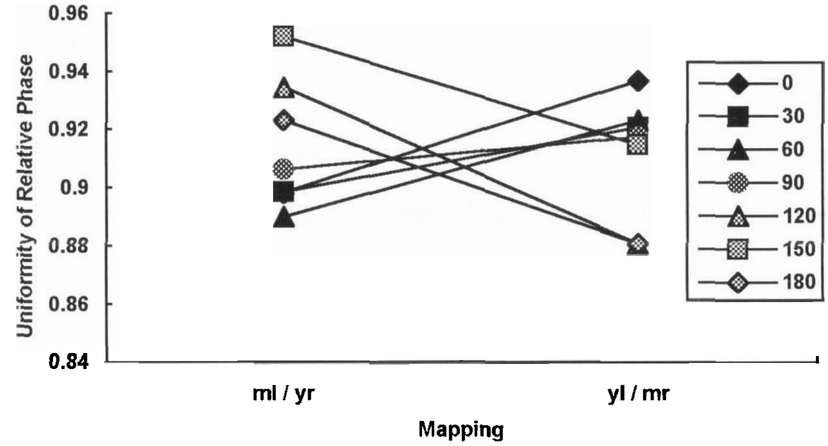


Figure 6.4 Uniformity of relative phase as a function of plateau frequency.

There were also interactions between orientation and mapping, *F*(6, 30) = 6.07, *p* < .001, and between orientation, mapping, and plateau, *F*(18, 90) = 2.77, *p* < .001. As Figure 6.5A illustrates, there was a general trend for uniformity to be lower for the ml/yr mapping for orientations up to 90 degrees, increasing thereafter for orientations 120-180 degrees. The reverse trend was apparent for the yl/mr mapping. Figure 6.5B provides another view of the same interaction. Here the difference in pattern of results between the mappings is somewhat more apparent. Although post-hoc comparisons revealed that there were no significant differences between the two mappings at each orientation considered separately, Figure 6.5B illustrates that the trends are consistent with expected directions. The 3-way interaction reflected that differences between the mappings across orientation varied with plateau frequency.



A



B

Figure 6.5 (A) and (B): Uniformity of relative phase as a function of plateau frequency.

Attraction to specific phase regions was quantified as the proportion of the plateau duration spent within a phase region. Given the data reduction procedures employed in the present study, perfect coordination under the yl/mr mapping was always characterized numerically by a 0 degree phase relation. Perfect coordination under the ml/yr mapping was characterized by a 180 degree phase relation. Figure 6.6 displays the mean proportions, as a function of plateau and orientation, for phase attraction under the yl/mr mapping.

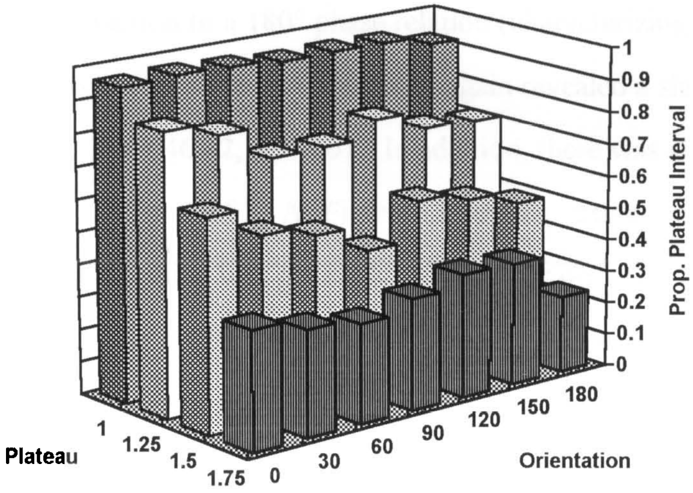


Figure 6.6 Mean proportion of plateau interval spent within yl/mr phase region as a function of plateau and orientation.

Analysis of phase attraction to a 0° phase relation (characterizing yl/mr coordination pattern) for trials prepared under the yl/mr mapping, over orientation and plateau, confirmed the effect of plateau frequency, $F(3, 15) = 37.54, p < .001$. As evident in Figure 6.6, attraction to phase space associated with the yl/mr pattern decreased as oscillation frequency increased. Figure 6.7 displays a similar graph for the ml/yr mapping.

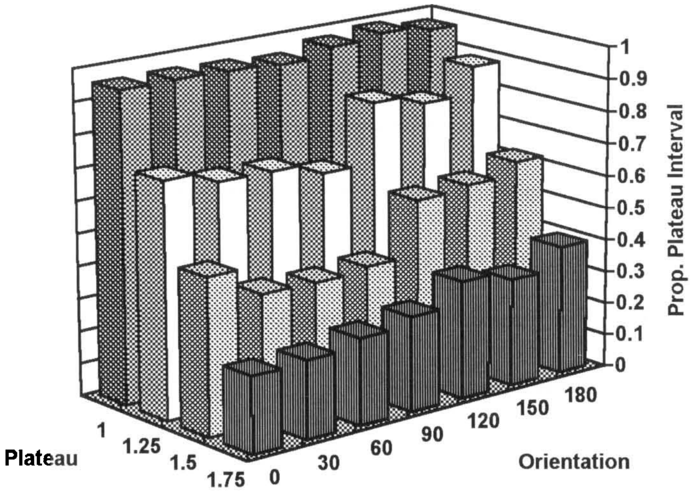


Figure 6.7 Mean proportion of plateau interval spent within ml/yr phase region as a function of plateau and orientation.

Analysis of phase attraction to a 180° phase relation (characterizing ml/yr coordination pattern) for trials prepared under the ml/yr mapping again revealed a similar effect of plateau frequency, $F(3, 15) = 46.42, p < .001$. In addition, there was an effect of orientation, $F(6, 30) = 5.22, p < .001$. As Figure 6.8 reveals, attraction to phase space consistent with the ml/yr mapping was generally stronger for orientations above 90 degrees. Significant pairwise differences were found for the comparisons between 180 degrees and 30, 60, and 90 degrees.

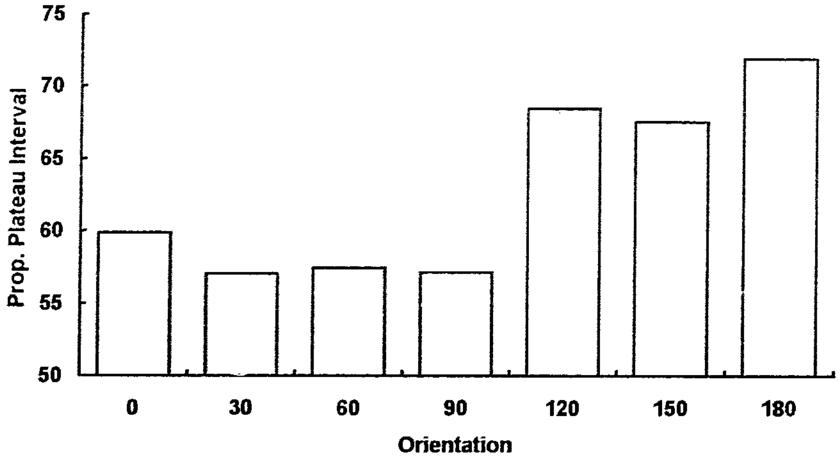
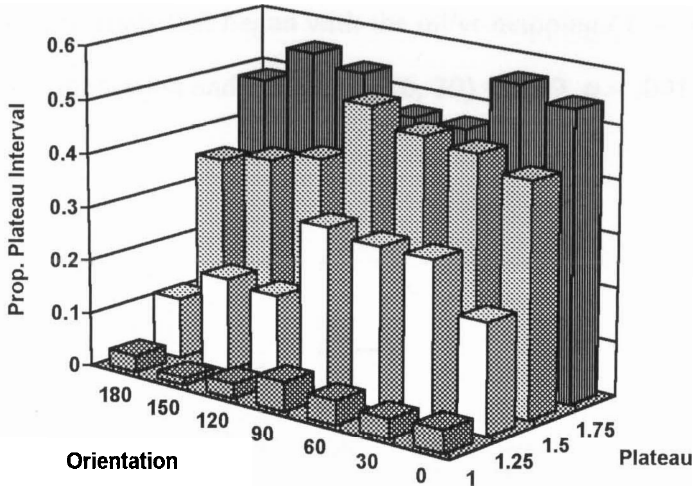
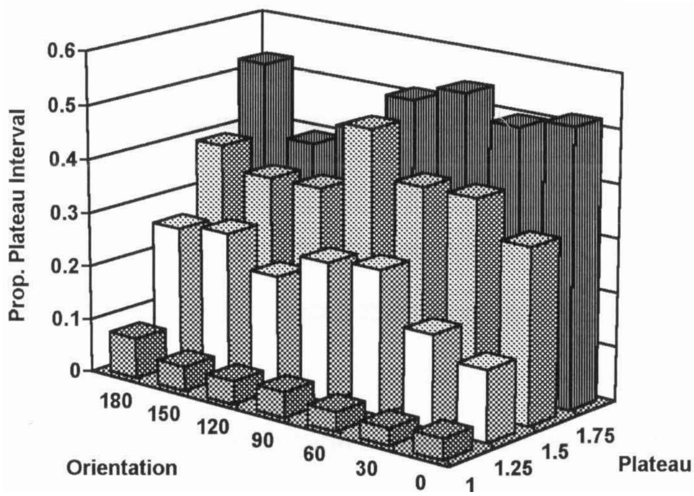


Figure 6.8 Mean proportion of plateau interval spent within ml/yr phase region as a function of orientation.

Another way in which to obtain a picture of the stability of the coordination under the two possible mappings is to examine the degree to which intermediate phase relations were evident during coordination. An increased attraction to intermediate phase regions would suggest that attraction to, and the stability of, either the ml/yr or yl/mr pattern is decreasing. Figures 6.9 A and B show clearly that for coordination under both mappings, an increased prevalence of intermediate phase regions is seen with increasing oscillation frequency. These data were subjected to an analysis over the factors of orientation, mapping, and plateau frequency. The analysis confirmed the effect of plateau frequency, $F(3, 15) = 22.09, p < .001$.



A



B

Figure 6.9 Mean proportion of plateau interval spent within intermediate phase regions under (A) ml/yr and (B) yl/mr mapping conditions as a function of plateau and orientation.

There was also a main effect for orientation, $F(6, 30) = 2.66, p < .05$, reflecting a marginally significant difference between the two extreme values for 90 and 150 degrees. An effect of mapping, $F(1, 5) = 23.11, p < .005$, reflected a trend toward an overall advantage for the yl/mr mapping, in that a somewhat lesser degree of phase attraction toward intermediate regions was observed for trials that began with this mapping

($\bar{x}$ = .285), compared to trials that began with the ml/yr mapping ($\bar{x}$ = .302). There was a further interaction of orientation and mapping, $F(6, 30) = 5.39$, $p < .001$, as illustrated in Figure 6.10.

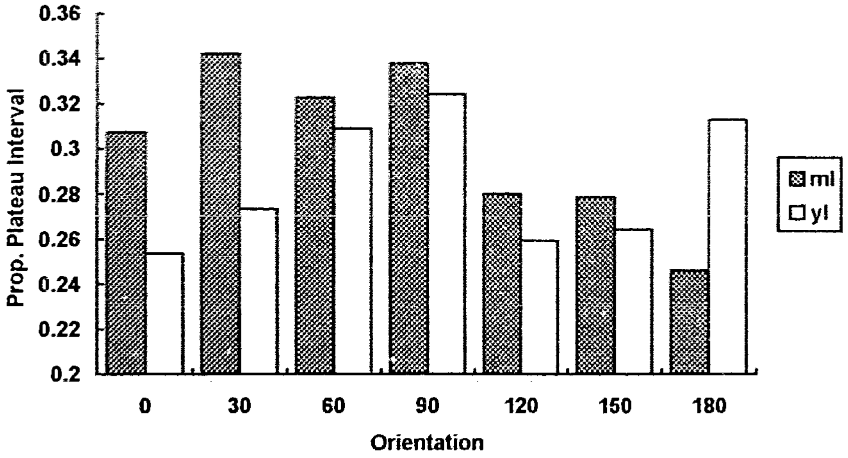
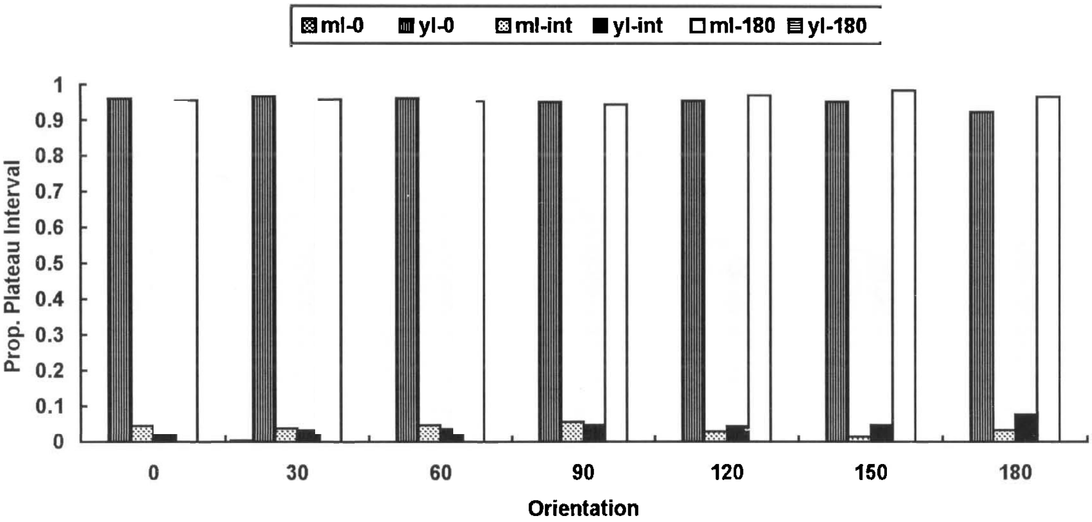


Figure 6.10 Mean proportion of plateau interval spent within intermediate phase region as a function of orientation and mapping.

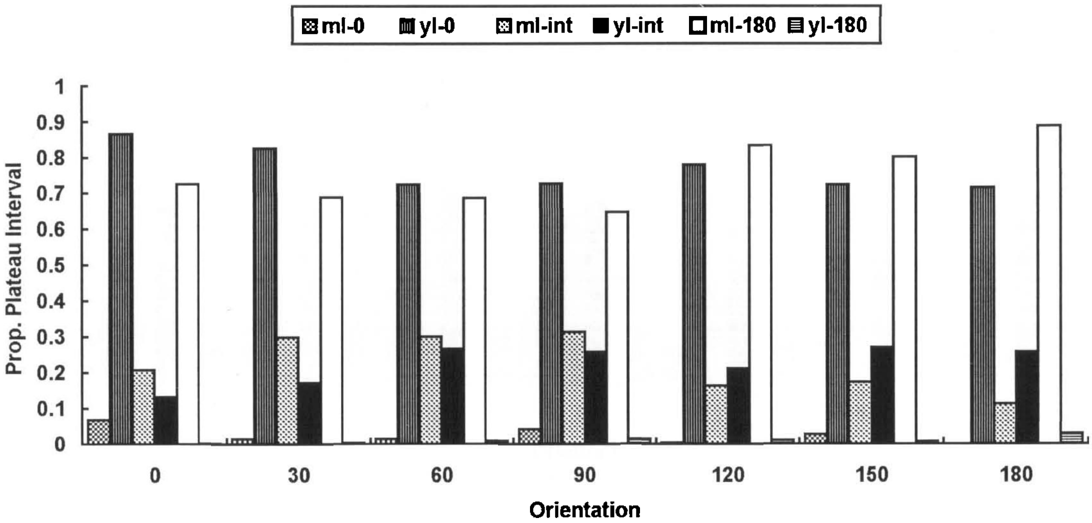
The pattern of results for the phase attraction data may be viewed as a whole in the series of graphs shown in Figure 6.11. Recall that for each trial, the coordination pattern begins with either the yl/mr or ml/yr mapping. At the lower frequency of the first plateau, the attraction to the respective pattern (characterized by the proportion of time spent in the given phase region) is relatively strong. In the graph for plateau 1, there is, almost exclusively, attraction to 0° phase space for yl/mr trials and 180° phase space for ml/yr trials, regardless of orientation. Consistent with previous data (this volume), therefore, even when the particular mapping and orientation result in a spatially incompatible or anti-phase pattern (i.e., ml/yr at 0° and yl/mr at 180°) the coordination pattern is maintained, and is presumably stable. There is little or no intrusion of other phase relations. That is, at low oscillation frequencies, both coordination patterns are relatively stable.

As oscillation frequency increases, attraction to phase space associated with the prescribed pattern of coordination is expected to weaken or decrease. Concurrently, due, perhaps, to either drifts in coordination, momentary phase slippages, or even transitions or phase wandering, other phase relations are expected appear. In the graph for plateau 2, there is indeed evidence of somewhat decreased proportion values for the yl/mr (yl-0) and ml/yr (ml-180) phase regions. Moreover, there is a concomitant increase in intermediate phase relations (ml-int and yl-int), perhaps indicative of some momentary phase slippages or phase drifts toward this region of phase space. There also seems to be a trend, albeit small, toward relatively stronger attraction being maintained for the 0° and 180° orientations, for the yl/mr and ml/yr mappings, respectively. These combinations of mapping and orientation (i.e., yl/mr at 0° and ml/yr at 180°) yield clearly the spatially compatible, or in-phase, arrangement.

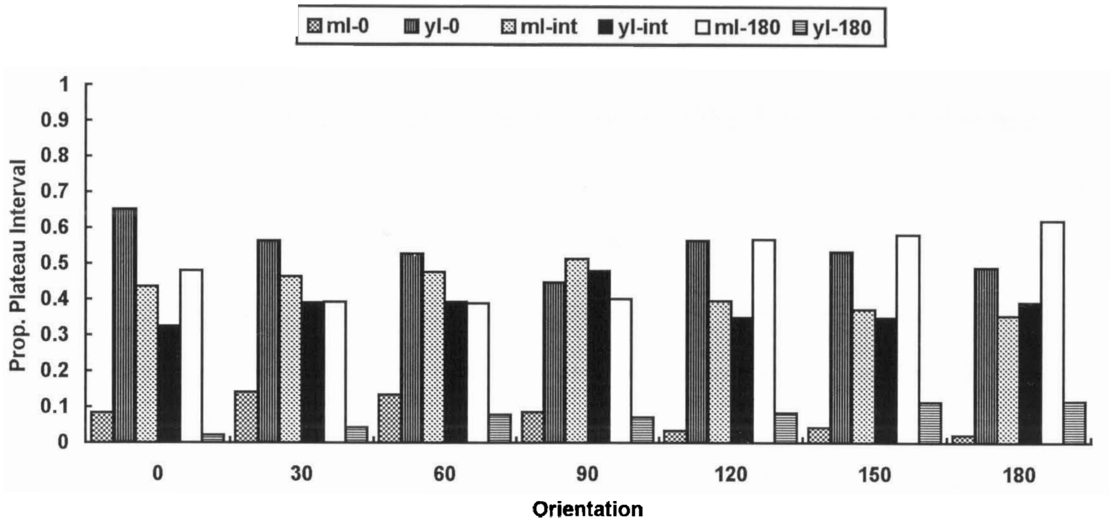
In the graphs for plateaus 3 and 4, the drift toward intermediate phase relations becomes more prevalent. However, there is one trend worth noting. Beginning in plateau 3 and increasing somewhat in plateau 4, there is evidence of attraction toward a 0 (yl/mr) degree phase relation for trials began ml/yr (see ml-0). Moreover the attraction seems to be greater for orientations below 90 degrees. These are the orientations at which the ml/yr mapping becomes spatially incompatible and the yl/mr mapping becomes spatially compatible. The same type of pattern, reversed in direction, is also evident for trials prepared yl/mr. There seems to be greater attraction toward a 180 (ml/yr) degree phase relation (see yl-180). Again, at orientations above 90 degrees, the yl/mr mapping would be spatially incompatible and the ml/yr mapping would become more spatially compatible.



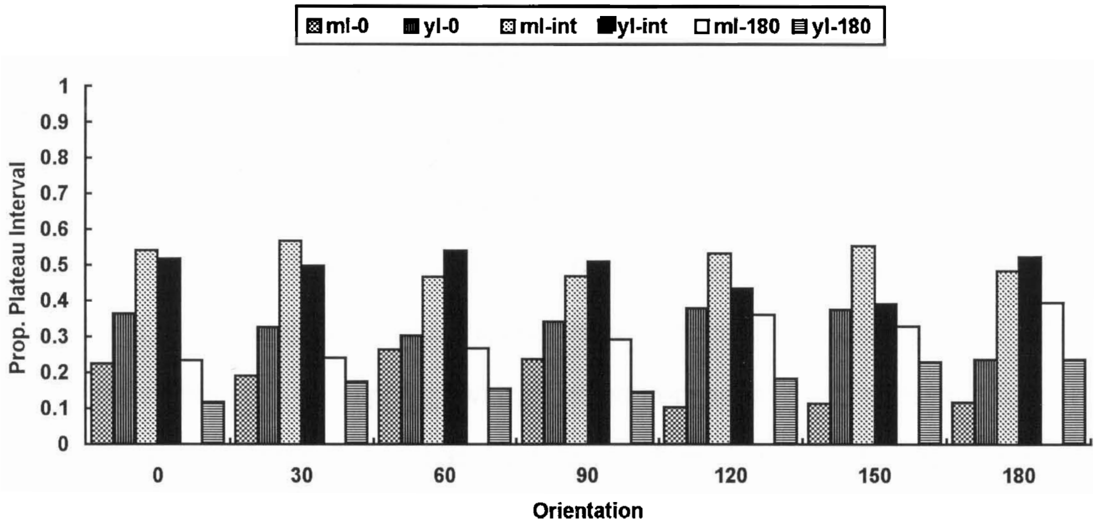
Plateau 1
A



Plateau 2
B



Plateau 3
C



Plateau 4
D

Figure 6.11 (A)-(D) Mean proportion of plateau interval spent within 0 (yl/mr), intermediate, and 180 (ml/yr) phase regions as a function of orientation, mapping, and frequency plateau. ml - ml/yr mapping; yl - yl/mr mapping; 0 - yl/mr phase region; int - intermediate phase region; 180 - ml/yr phase region.

6.4 Summary and Discussion

Subjects generally conformed to the prescribed oscillation frequencies, as indicated by the relatively low frequency deviations. It appeared that the display orientation had an effect on this aspect of performance. The combination of mapping and orientation which resulted in in-phase motion exhibited less deviation than the combination which resulted in anti-phase motion. At lower oscillation frequencies, there was also a tendency for the right movement endpoint to exhibit less variability (see also Experiment 1). This anchoring effect has been noted in previous work utilizing similar movements, except that the results have been in the opposite direction (e.g., Byblow et al., 1994). That is, greater anchoring has typically been found for the left, pronation, endpoint. However, in previous work (Byblow et al., 1994, 1995) the limb was placed laterally, as opposed to at the midline, as in the present study. This difference may have been sufficient to change the biomechanical constraints, leading to a change in the expression of anchoring effects.

The results for the collective variable dynamics from the present study were less robust than in Experiment 1 or 2. However, the pattern of findings that emerged from the results indicated that for orientations in which spatial correspondence was direct (0° and 180°), the differential stabilities of mappings which yielded in-phase and anti-phase motion generally became evident (albeit not as strongly as in Experiment 1). For intermediate orientations, there was a tendency for mapping differences to persist then diminish at an orthogonal orientation.

The impact of the different orientations seemed to be somewhat greater for the ml/yr mapping. For example, whereas no differences in phase attraction (attraction to yl/mr) emerged for the yl/mr mapping as a function of orientation, attraction to ml/yr coordination was generally higher for orientations above 90 degrees. The effects were small, but there may be a reason why orientation might have had less of an impact on yl/mr mapping, given the context of the present study and in light of previous results

(Experiment 1 and 2). First, consider that for the intermediate orientations of 30, 60, 120, and 150 degrees, the apparent movement of the visual stimulus has both a left-right and an up-down dimension. Second, when the orientation is changed from 0°, through 90°, to 180°, the nature of the display is such that the yellow stimulus endpoint is the left stimulus endpoint at 0°, becomes the lower endpoint as the display is rotated through the orientations, finally becoming the right stimulus endpoint at 180°. At 0°, the yellow-left mapping would yield the spatially compatible in-phase pattern. At 30° and 60°, the yellow-left mapping would yield in-phase motion if one were to consider the left-right component of the stimulus orientation, or an up-right/down-left mapping if one were to consider the up-down component. At 90°, the mapping would be up-right/down-left. At 120° and 150°, the yellow-left mapping would yield the incompatible anti-phase pattern with respect to the left-right stimulus dimension. However, the mapping would remain up-right/down-left with respect to the up-down component. Finally, at 180°, yellow-left would correspond solely to the anti-phase pattern. In contrast, the magenta-left mapping would yield an in-phase pattern for orientations above 90° and an anti-phase pattern for orientations below 90°, with respect to the left-right dimension of the stimulus. With respect to the up-down component, the magenta-left mapping would always correspond to an up-left/down-right mapping. Thus, assuming (given previous results presented here) the possibility of a small advantage for the up-right/down-left mapping, the fact that this mapping exists for the yellow-left conditions under all orientations between 0° and 90° may help to diminish stability differences across orientations. In comparison, at orientations below 120°, the patterns that result from a magenta-left mapping (anti-phase and up-left/down-right) are presumably less stable, giving rise therefore to the somewhat greater impact of orientation on this mapping.

Experiment 1 examined basic spatial and mapping constraints in the dynamics of a unilaterally coupled coordinative system and demonstrated that respective stabilities of the coordination patterns may be influenced by the configuration between information and action. Experiment 2 provided evidence to suggest that the global relation may also mediate the relation between the mapping and configuration and its impact upon the intrinsic dynamics. The present study provides evidence to confirm the intrusion of spatial constraints in the coordination dynamics of perception-action coupling. Moreover, there is a subtle, but interesting, difference between the present study and Experiments 1 and 2, in terms of the relation between the spatial mappings and configurations. Whereas in both Experiments 1 and 2, coordination patterns were based explicitly on a spatially defined mapping, the mapping in the present study was only implicitly based on a spatial parameter. The coordination patterns here were based on a mapping of an informational feature (display colour) to action (movement endpoint) and not based on both the spatial dimensions of the information and action (cf. Experiment 1 & 2). Nonetheless, the intrusion of the spatial parameter still emerged.

This aspect of the results is reminiscent of a variant of S-R compatibility known as the Simon effect (Simon & Rudell, 1967). The Simon effect refers to the dependency of reaction time on task-irrelevant spatial correspondence between stimulus and response. For example, suppose a subject is required to press a left-hand key in response to a square and a right-hand key in response to a circle, presented randomly to the left or right side of fixation. Although stimulus location is irrelevant to the task, left-hand responses will be more rapid to a square on the left side than to a square on the right side, and right-hand responses will be more rapid to a circle on the right side than to a circle on the left side. Thus, the spatial dimension of the information (stimulus), although irrelevant to the prescribed information-action mapping, may nevertheless intrude in the selection of the response. In the present study, the spatial dimension of the information, although only implicit in the mapping, influenced coordination dynamics.

In Experiments 1, 2, and 3, a paradigm of person-environment coupling, specifically, visual coupling, has been employed in the examination of spatial constraints in perception-action coupling. The coupled system under study, whose components differ in structure, is characterized by broken symmetry. Indications of asymmetric dynamics have emerged in the visual coordination dynamics. The presence of momentary phase slippages, phase drift (present study), and phase wandering (Experiment 1 & 2) is consonant with features of broken symmetry. In the next study, I turned my attention toward the asymmetric dynamics of perception-action coupling. In the current context, the present work thus far indicates that the spatial configuration between information and action may be a candidate control parameter of the visual coordination dynamics.

7. Experiment 4

7.1 Introduction

Consider the following (somewhat modified) popular example (see von Holst, 1973). Imagine two parents taking a walk with their child. Assume that the two adults are roughly equal in stature, having similar stride lengths and frequencies. Further assume that the adults are walking in unison (in coordination) with one another. That is, the two adults achieve 1:1 coordination with each other. Now, how about the child? Due to differences in stature compared to the adults, it is likely that the child, although attempting to keep in step with the adults, will gradually lose the tempo and drift out of step. In order to fall in step once more, the child may take one or two additional, accelerated, steps, or alternatively, the adults may retard their steps and allow the child to fall in pace. This example illustrates two types of coordination classified by von Holst (1973). The adults, walking in unison with one another, maintain a relatively rigid harmony, exemplified by mode locking (phase and frequency synchrony). von Holst referred to this class of coordination as *absolute coordination*. The coordination between the child and the adults is of a different, more fluid, nature. Here, there is no strict mode locking, but rather, periods of phase and frequency entrainment (tendencies toward certain spatiotemporal relations), interspersed with momentary phase slippages and desynchronization. von Holst referred to this as *relative coordination*.

The study of absolute coordination in human bimanual movement has been exemplified in studies by Kelso (1981, 1984). As originally described in Section 2.3 (this volume), Kelso observed certain relative phase patterns to emerge in bimanual movements under the scaling of movement frequency. Moreover, transitions in relative phase were observed in which one stable phase pattern gave way to another, more stable, pattern. Haken et al. (1985) introduced the order parameter equation,

$$\dot{\phi} = - a \sin \phi - 2b \sin 2\phi \tag{7.1}$$

to provide a mathematical description and model of the main qualitative features of the phase transitions. Equation (7.1) describes the vector field of the relative phase dynamics and can be visualized by plotting the time derivative of phase ($\dot{\phi}$) versus the phase (ϕ), as illustrated in Figure 7.1 (compare this to the potential landscape in Figure 2.1, Section 2.4). The system defined by the HKB equation contains fixed points wherever the function crosses the ϕ-axis. If the slope of $\dot{\phi}$ is negative at the point of the crossing, then the fixed point is stable and an attractor. If the slope of $\dot{\phi}$ is positive, then the fixed point is unstable and a repellor. There are two parameters in the equation, a and b, the ratio of which corresponds empirically to the scaling of movement frequency. Figure 7.1 A-D illustrates the effects of scaling the parameter ratio b/a on the dynamics. At a b/a ratio of unity (A) two stable fixed points, at $\phi = 0$ and $\phi = \pi$, exist. The unstable fixed points demarcate the boundaries of the basis of attraction of the stable fixed points. As b/a is scaled, the stable point at $\phi = \pi$ gradually diminishes until, beyond a critical point, only one stable point at $\phi = 0$ remains (a pitchfork bifurcation — see Kelso, 1994). The potential landscape of the HKB equation is shown in Figure 7.2 for comparison.

Equation (7.1) captures the essence of the phase transitions observed by Kelso (1981, 1984), as well as characteristics of absolute coordination, as exhibited by the walking couple described previously. Inherent in Equation (7.1) is a symmetry of the coordination dynamics. That is, the relative phase dynamics remain invariant under the transformation $\phi \rightarrow -\phi$. Researchers typically expect the coordination dynamics to exhibit symmetry when the components in coordination are essentially identical (e.g., two index fingers or two identical pendula).

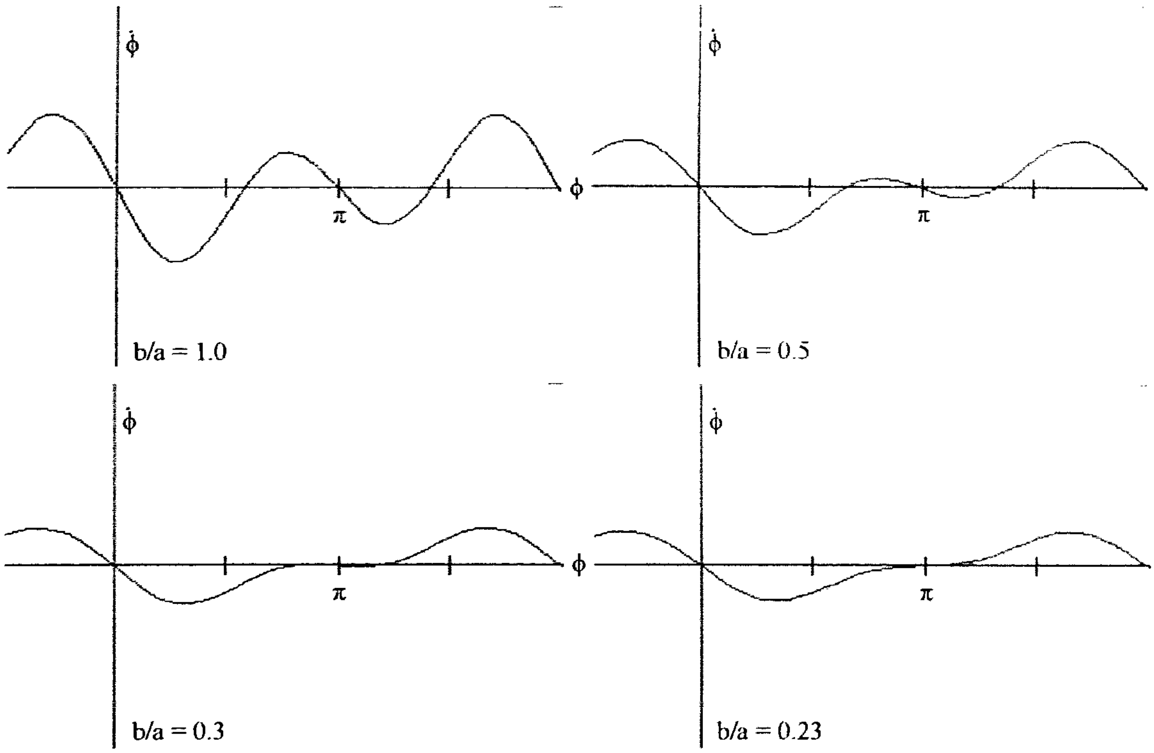


Figure 7.1 HKB vector field ($\dot{\phi} = -a \sin \phi - 2b \sin 2\phi$). As ratio of parameters b/a is decreased, the stable fixed point at $\phi = \pi$ disappears, leaving only the stable point at $\phi = 0$.

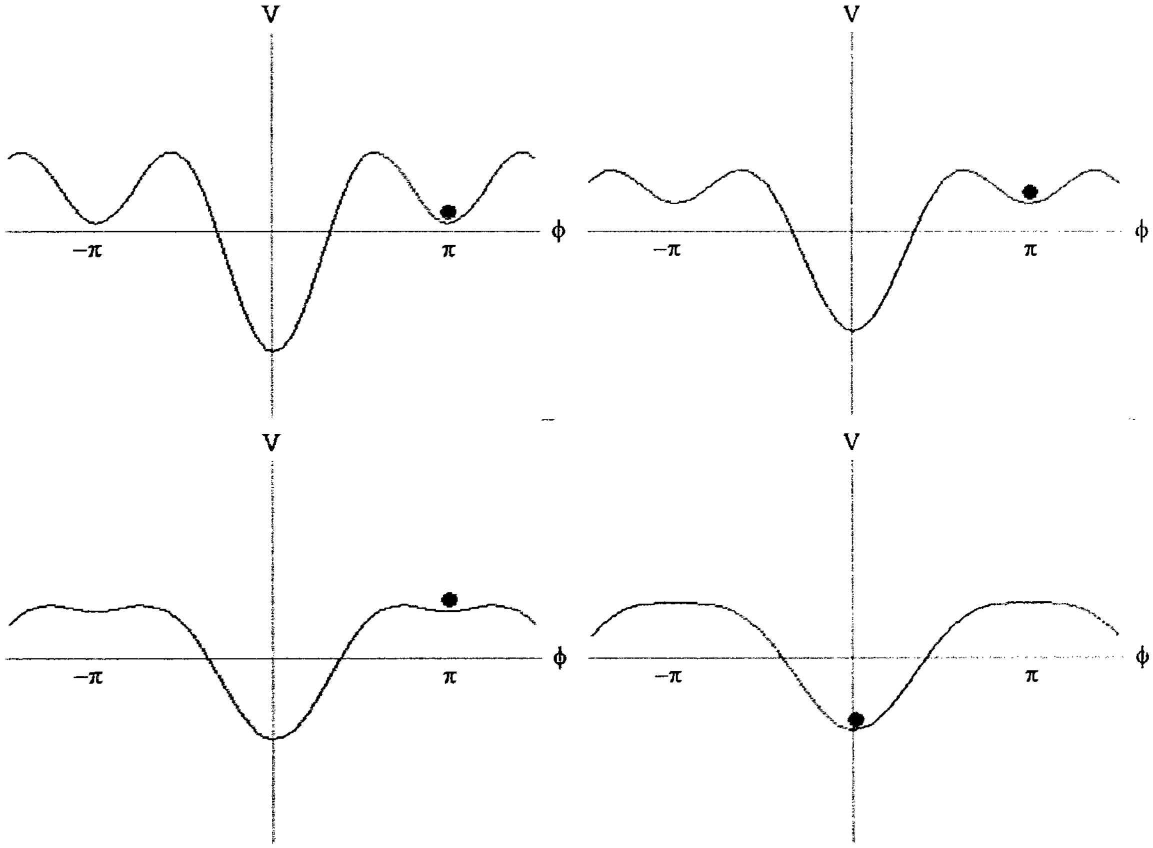


Figure 7.2 HKB potential ($V = -a \cos \phi - b \cos 2\phi$). System state is represented by overdamped motion of a ball on the landscape.

What happens when differences between coupled components are no longer negligible? As intimated earlier in the example of the coordination between the child and adults, absolute coordination is expected to give way to relative coordination, typified by drifts in spatiotemporal relations and momentary desynchronizations. Relative coordination is expected to occur in situations in which differences between component oscillators lead to, for example, differences in individual inherent frequencies. The coordination dynamics would be influenced by both cooperative (oscillators attracted to some mutual relation) and competitive (each oscillator tending toward its own inherent frequency) forces in the coupling between the components (e.g., von Holst, 1973). An end result of factors which magnify differences between components in coordination, whether it be handedness (Treffner & Turvey, 1995), differing physical magnitudes (e.g., child versus adult legs; pendula differing in length and mass — Kugler & Turvey, 1987), or differing structure (e.g., biological versus physical oscillator — Kelso et al., 1990), is symmetry breaking. That is, the coordination dynamics no longer exhibit symmetry.

Kelso et al. (1990) originally introduced a symmetry breaking term to Equation (7.1) to model the coordination dynamics of a perception-action system, in which movement was coupled with an auditory signal whose periodicity was varied. The modified equation is of the form,

$$\dot{\phi} = \delta\omega - a \sin \phi - 2b \sin 2\phi \qquad (7.2)$$

in which $\delta\omega$ represents the symmetry breaking term (see also Schmidt & Turvey, 1995; Turvey & Schmidt, 1994, for a different derivation of the symmetry breaking term and study of symmetry breaking dynamics). Figure 7.3 shows representative plots of $\dot{\phi}$ versus ϕ as $\delta\omega$ is increased with $b/a = 1$, and Figure 7.4 shows similar plots as b/a is scaled with $\delta\omega = 1$. When $\delta\omega \neq 0$, the function is no longer symmetric; that is, the relative phase dynamics are no longer invariant under the transformation $\phi \rightarrow -\phi$. There are several consequences due to symmetry breaking. For example, as illustrated in Figure 7.3, for a given *b/a* (in this case, *b/a* = 1), increasing the magnitude of the symmetry breaking term results in a drift of both stable and unstable fixed points. Although the system still exhibits stable states, these states have deviated from the previous values of $\phi = 0$ and $\phi = \pi$. The evolution of the asymmetric dynamics (with $\delta\omega = 1$) as a function of the parameters *b/a* can be seen in Figure 7.4. At *b/a* close to unity, the asymmetric system exhibits stable points at $\phi \approx 0$ and $\phi \approx \pi$. As the parameters are scaled, there is once again a drift of the fixed points. Further scaling results in the drift of the stable and unstable solutions between $\phi = \pi$ and $\phi = 3\pi/2$ to coalesce, resulting in the loss of both states (otherwise known as a saddle-node bifurcation — see Kelso, 1994; Kelso, Ding, & Schöner, 1992). A similar bifurcation phenomenon occurs as the stable and unstable states between $\phi = 0$ and $\phi = \pi$ eventually collide as the parameters are scaled even further. Beyond this point, the asymmetric system no longer exhibits any stable solutions, and a phase wandering regime, characterized by a continuous change in relative phase, is entered (comparison with Figure 7.1 reveals that the symmetric system ($\delta\omega = 0$) never enters this regime). Notice, however, that in the region about a saddle-node bifurcation, there remains a "ghost" of the previously stable state, in that the flow of relative phase is retarded within this region (there remains a weak attraction to the phase region - - see DeGuzman & Kelso, 1991, 1992).

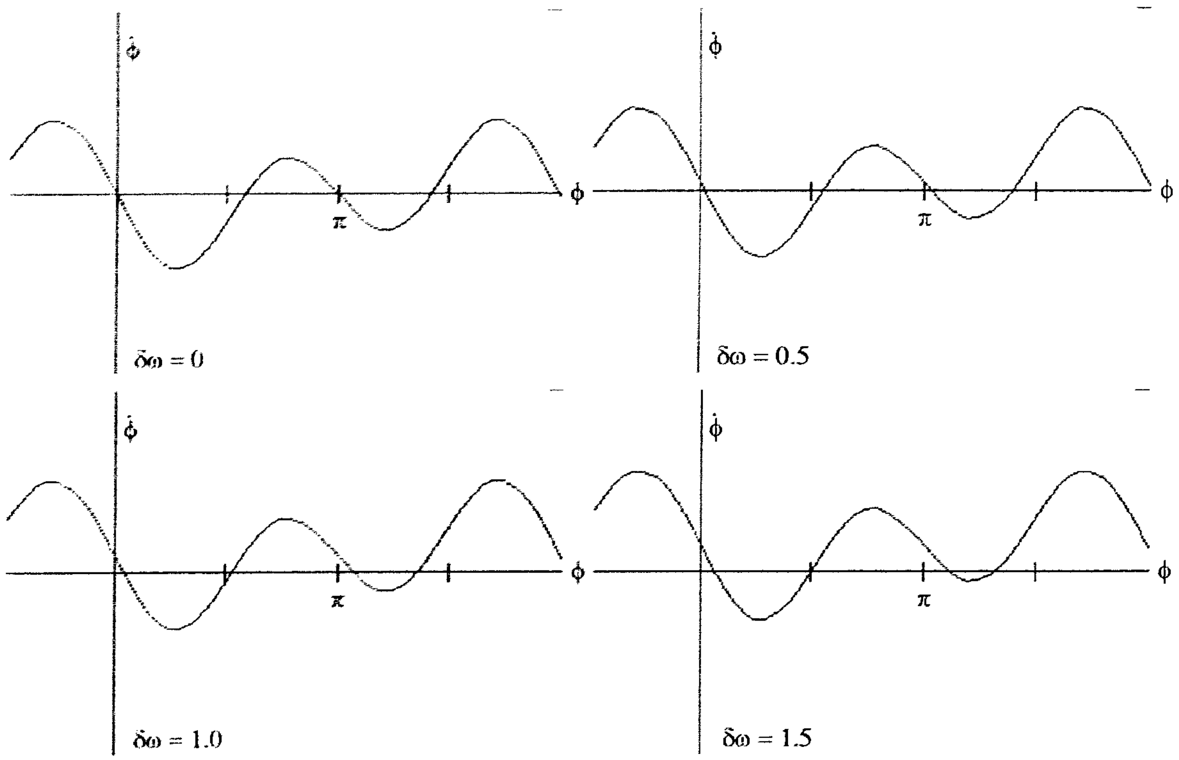


Figure 7.3 Vector field of $\dot{\phi} = \delta\omega - a \sin \phi - 2b \sin 2\phi$. As $\delta\omega$ is increased ($b/a = 1$), stable fixed points at $\phi = 0$ and $\phi = \pi$ are displaced. Note the slightly greater drift for $\phi = \pi$.

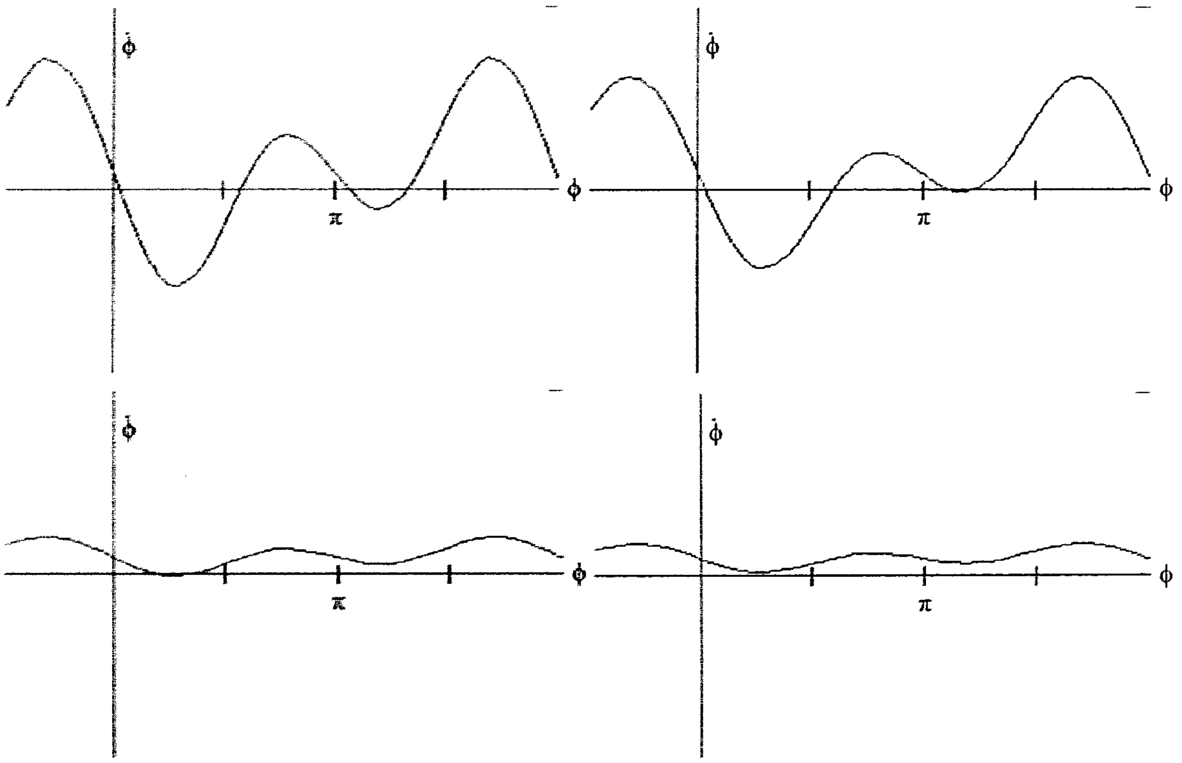


Figure 7.4 Vector field of $\dot{\phi} = \delta\omega - a \sin \phi - 2b \sin 2\phi$, with $\delta\omega = 1$, under scaling of the parameters b/a.

As mentioned earlier, Kelso et al. (1990) introduced the asymmetric form of the HKB equation to model the coordination between movement and a periodic auditory stimulus. Kelso and colleagues asked subjects to either coordinate finger flexion with the beat of the auditory stimulus (in-phase pattern) or off the beat (anti-phase). As might be expected, transitions from an off-the-beat pattern to an on-the-beat pattern occurred. More importantly, Kelso et al. observed coordination dynamics characteristic of relative coordination and symmetry breaking. That is, subjects' coordination patterns exhibited periods of relatively rigid phase entrainment, along with periods of phase drift and phase wandering. Turvey and colleagues, using the pendulum paradigm (Kugler & Turvey, 1987), have also studied extensively both absolute and relative coordination under situations in which the magnitude of the symmetry breaking term can be systematically manipulated (for reviews, see Schmidt & Turvey, 1995; Schmidt et al., 1993; Turvey, Beek, & Schmidt, 1994; Turvey & Schmidt, 1994). The pendulum paradigm allows for systematic manipulation of the $\delta\omega$ term by varying the physical characteristics (i.e., length, mass) of the pendula (subjects coordinate the pendula typically through wrist flexion/extension movements). The findings from these studies (examinations of phase drift) are generally consistent with predictions from the asymmetric HKB equation (see Schmidt & Turvey, 1995 for discussion of a model based on Rand, Cohen, and Holmes (1988) that also has been employed to model symmetry breaking coordination dynamics). More recently, Amazeen, Schmidt, and Turvey (1995) have examined whether the predictions of Equation (7.2) extend to between-person coordination. Employing the pendulum paradigm, Amazeen et al. manipulated $\delta\omega$ (eigenfrequency difference between pendula), cycling frequency, and intended phase mode. The results were consistent with previous work (e.g., Schmidt et al., 1993) and with predictions from Equation (7.2). Specifically, examination of phase drift revealed that, when $\delta\omega = 0$, ϕ was equal to 0 or π, and was independent of oscillation frequency. When $\delta\omega \neq 0$, stable fixed points were displaced from 0 or π. Further, larger values of $\delta\omega$ induced greater fixed point drift, as did a higher oscillation frequency when $\delta\omega \neq 0$. The dynamics expressed by the HKB equation, therefore, appear to be independent of a system's physical instantiation but expresses a more general principle of coordination dynamics.

In the present study, I examined the coordination dynamics of a unilateral, visually coupled, perception-action system. In the present examination of equilibrium points, I varied oscillation frequency as well as the intended coordination pattern. Further, previous work (Experiments 1, 2, & 3, this volume) suggested that spatial relations between information and action may act as a control parameter on the coordination dynamics. Therefore, I also varied the configuration between information and action as an additional control parameter.

I employed a coordination task identical to that used in Experiment 3. The frequency of oscillation and the spatial orientation of the driving visual signal were scaled independently as control parameters. As in Experiment 3, subjects were required to coordinate their movements with the visual display according to a prescribed mapping of display endpoint (defined by colour) and movement endpoint. Scaling of the spatial parameter occurred during a trial and proceeded from either a 0° or 180° orientation. Note that it was not a specific phase relation per se that subjects intended to perform, but rather a coordination pattern corresponding to the prescribed mapping. This pattern, depending upon the display orientation, corresponded to a particular phase relation. Thus, for example, for a magenta-left/yellow-right mapping (as described in Experiment 3), an orientation of 180° would produce a phase relation corresponding to in-phase (display and movement synchronized in same direction). An in-phase relation was expected to stabilize and reduce drift from the intended coordination mapping/pattern. In contrast, the same mapping at 0° would result in an anti-phase pattern (display and movement synchronized in opposite direction). An anti-phase relation was expected to lead to less stability and greater phase drift from the intended mapping/pattern. The oscillation frequency was kept constant during a trial. Oscillation frequency was also expected to influence the degree of phase drift and stability of coordination.

7.2 Method

7.2.1 Subjects

Six self-professed right-handers (4 female, 2 male) were recruited from the university population. All participants had normal or corrected-to-normal vision and were paid $10.00 for their participation. All subjects had previously participated in Experiment 3.

7.2.2 Apparatus

The visual display was presented on a computer monitor, as described in Experiment 3. The nature of the display was identical to that in Experiment 3. Rhythmic rotational movements of the forearms were recorded as described in Experiment 1.

7.2.3 Procedure

Subjects were asked to perform rhythmic forearm pronation and supination movements with their right hand, in coordination with the visual display. The display monitor was located approximately 1.2 m from the seated subject and was raised such that the centre of the panel was approximately at eye level. Subjects were seated with their midline aligned with that of the display and the lever. Movements were performed along the coronal plane about the midline. Seat height was adjusted for each subject such that the elbows were flexed to approximately 90 degrees.

The visual display (an oscillating circle and adjoining line) could be oriented and rotated through 7 angles: 0°, 30°, 60°, 90°, 120°, 150°, and 180° from the horizontal plane. For the 0 degree orientation, the circle denoting the left endpoint was coloured yellow, and the circle denoting the right endpoint was coloured magenta. This arrangement was reversed when the display was oriented at 180°. At 90°, the upper circle was magenta and the lower circle was yellow.

The angular orientation of the display resulted in 7 levels of the information-action configuration, one for each angle of orientation. For each configuration, there were two prescribed modes of information (display)-action (limb) coordination. For each configuration, subjects were required to perform in either a *yellow-left/magenta-right* (yl/mr) or *magenta-left/yellow-right* (ml/yr) mapping. Yellow-left/magenta-right mapping was defined as movement coordination such that the left movement endpoint was mapped onto the yellow display endpoint and the right movement endpoint with the magenta display endpoint. Magenta-left/yellow-right mapping was simply the opposite arrangement.

A trial began with the display either at 0° or 180°, with the subject performing in one of the two coordination mappings. Subjects were allowed to begin their movements with the display, and once they indicated to the experimenter that they had achieved synchrony, data collection commenced. Once a trial started, the orientation of the display changed during a trial after every 10 cycles. For trials in which the display began at 0°, the display was rotated through to 180°. The opposite was true for trials in which the initial orientation was 180°. The display frequency was kept constant during a trial. Four frequencies were used: 1.0 Hz, 1.25 Hz, 1.5 Hz, and 1.75 Hz. Subjects were instructed to maintain the frequency specified by the display, and the coordination mapping in which they were prepared, as accurately as possible. Subjects were also instructed that, in the event of any change in pattern, they were not to attempt to recover the original pattern but to establish the most comfortable pattern.

The display frequency and the initial display orientation were varied between blocks of trials. Subjects performed in 8 blocks of trials, each block corresponding to a particular combination of display frequency and initial orientation. Order of presentation of these factors was randomized. Each block consisted of 10 trials, 5 trials for each information-action mapping. Subjects alternated mappings between trials. Subjects performed the first 5 trials for each block in one session, and the remaining 5 for each block in a second session. Subjects were allowed to familiarize themselves with the task at the beginning of a session. Rest periods were provided as required. Each session lasted approximately 80 minutes.

7.2.4 Data Reduction and Analyses

Data reduction procedures were similar to those described in Experiment 1. The apparatus and data collection were configured such that the yl/mr mapping corresponded quantitatively to a relative phase of 0° and the ml/yr mapping corresponded to 180°, regardless of the orientation of the display. A continuous estimate of relative phase, ϕ, was calculated as described in Experiment 1, with the exception that averages were taken over the whole trial period and not over plateau. Mean relative phase was calculated following Mardia (1972). Briefly, the calculation involved obtaining the phase angle of the mean vector derived from a sample of relative phase values. Mean relative phase was calculated over each plateau, corresponding to a given display orientation. The deviation of mean relative phase from the intended coordination pattern was obtained by subtracting the phase value associated with the intended pattern (yl/mr = 0°; ml/yr = 180°) from mean relative phase. Relative phase uniformity and phase attraction were calculated as described in Experiment 1.

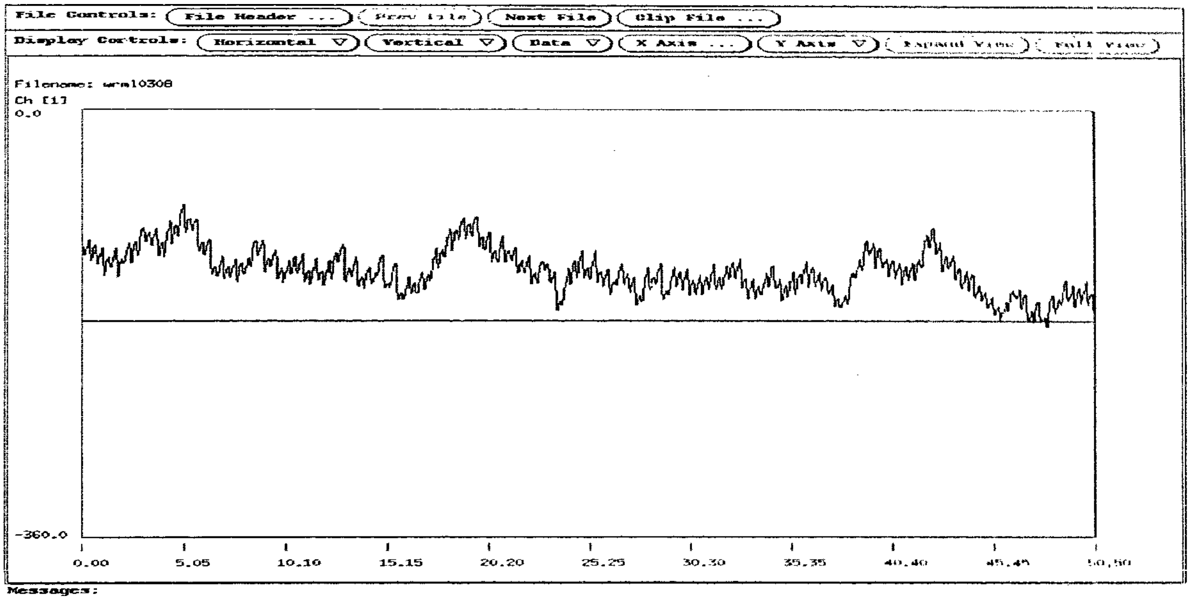
The study employed a 2 information-action mapping (ml/yr, yl/mr) by 2 direction of orientation change ($0 \rightarrow 180$, $180 \rightarrow 0$) by 4 frequency (1.0, 1.25, 1.5, 1.75 Hz) by 7 orientation (0°, 30°, 60°, 90°, 120°, 150°, 180°) repeated-measures design.

7.3 Results

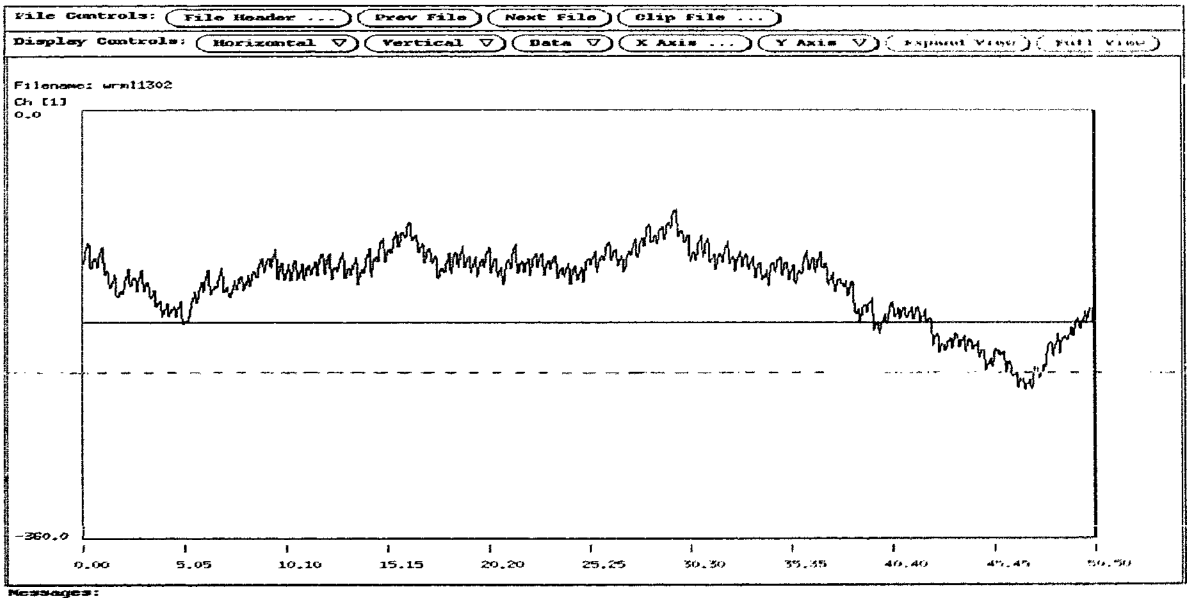
One of the primary interests in the present study was the study of drifts in mean relative phase. I therefore decided to exclude trials in which a complete loss of entrainment was apparent and included only those in which relative phase remained relatively stable, despite slow drifts in the mean phase. Although phase wandering is a dynamical feature of asymmetric systems, present interest in fixed point drift warranted the exclusion of trials with phase wandering. In the present data set, only 9 trials were excluded. All analyses were performed on the remainder of the data set.

7.3.1 Relative Phase Dynamics

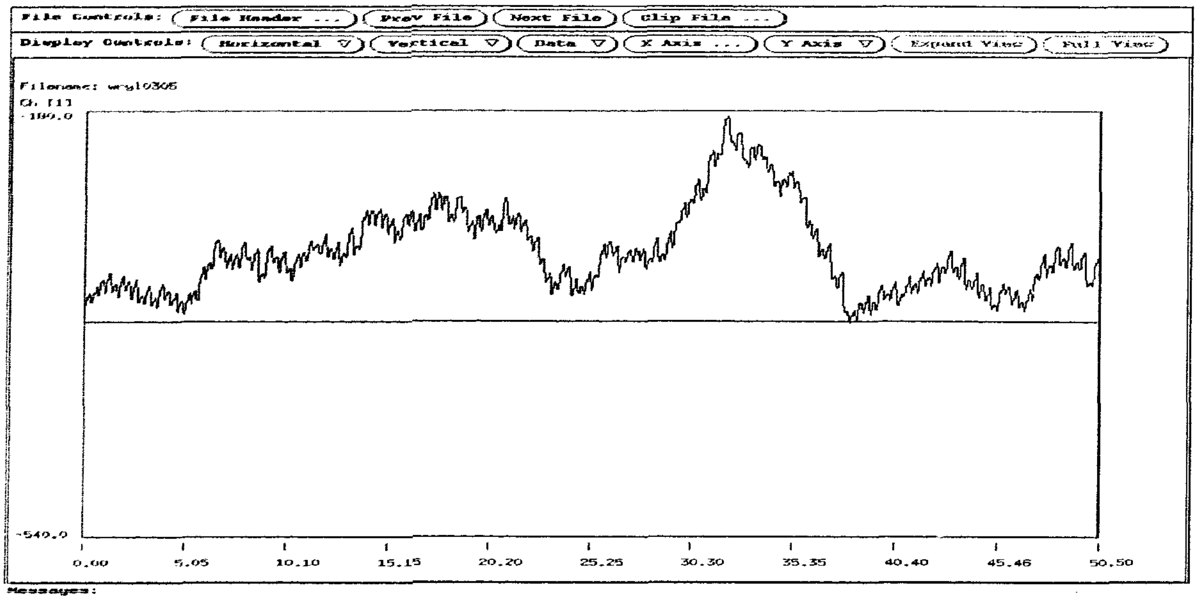
Figure 7.5 provides examples of relative phase time series from the study. Evident in these plots is the drift of mean relative phase away from the intended phase pattern.



A: ml/yr mapping - 0°→180° - 1.5 Hz



B: ml/yr mapping - 180°→0° - 1.5 Hz



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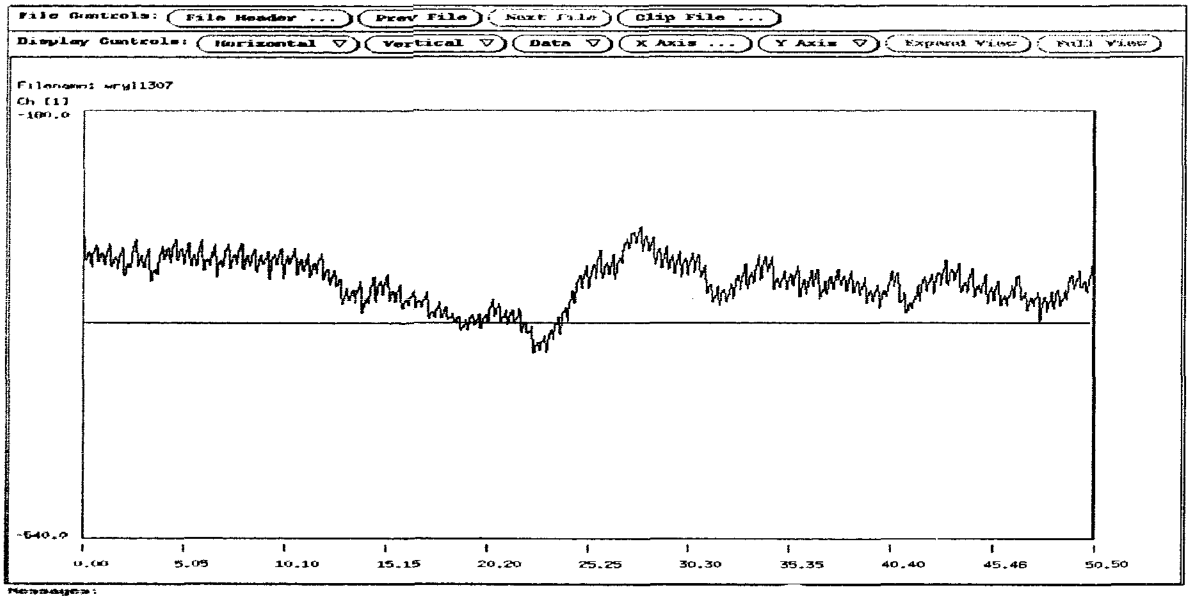
Ch. [1]

C: yl/mr mapping - 0°→180° - 1.5 Hz



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Ch [1]

D: yl/mr mapping - 180°→0° - 1 5 Hz

Figure 7.5 A-D: Examples of relative phase time series illustrating deviation of mean relative phase from intended coordination pattern.

The mean deviations of relative phase from the intended pattern is plotted in Figure 7.6 as a function of mapping, orientation, and frequency. Analysis of these data revealed an influence of oscillation frequency, *F*(3, 15) = 27.06, *p* < .001, confirming, as evident in Figure 7.6, an increase in mean phase drift with increasing oscillation frequency. There was also an interaction of mapping and orientation, *F*(6, 30) = 9.41, *p* < .001. As illustrated in Figure 7.7, when the intended coordination pattern was ml/yr, drift of the equilibrium point was, on average, lower at an orientation of 180°, at which the combination of mapping and orientation yielded in-phase motion. Phase drift increased as the display was rotated through to 0°, at which mapping and orientation yielded anti-phase motion. The converse trend is apparent for the yl/mr coordination mapping. For this mapping, a display orientation of 0° yielded in-phase motion and 180° yielded anti-phase motion. Post-hoc analyses (Tukey HSD, *p* < .05) also revealed a significant difference between intended coordination mappings at orientations 0° and 180°. That is, at 0° and 180°, the mapping and orientation combinations which yielded in-phase motion exhibited less overall relative phase drift than that which yielded anti-phase motion.

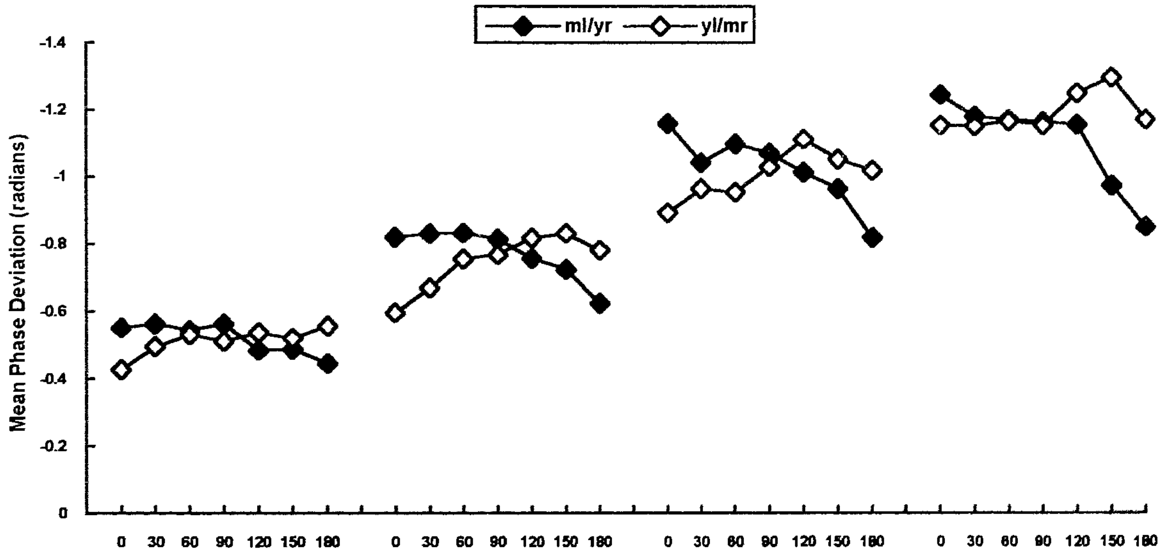

Figure 7.6 Mean deviations of relative phase from phase value of intended pattern, collapsed across direction of orientation change, plotted as a function of mapping, orientation, and frequency. Levels of oscillation frequency proceed from left to right: 1.0, 1.25, 1.5, 1.75 Hz. Negative deviation indicates that movement lags behind display.

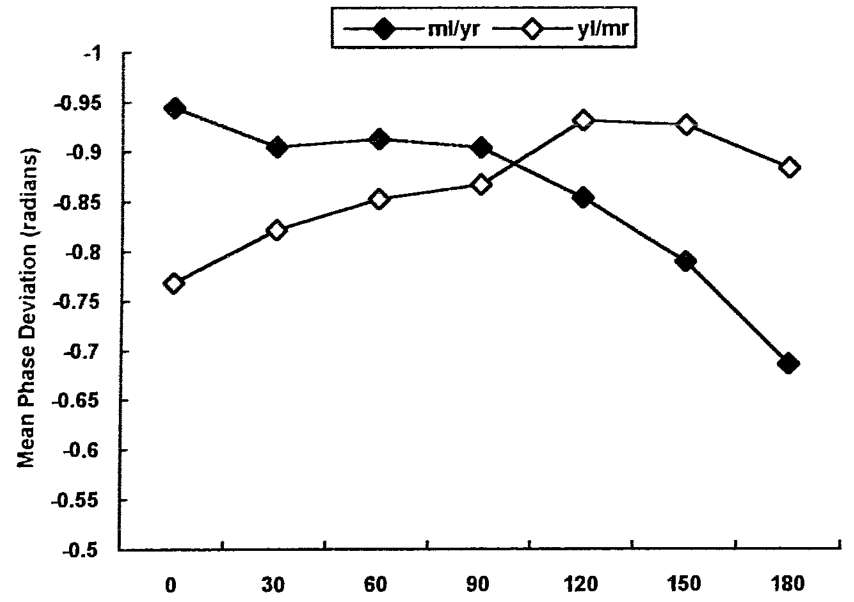

Figure 7.7 Mean deviations of relative phase from intended pattern plotted as a function of mapping and orientation.

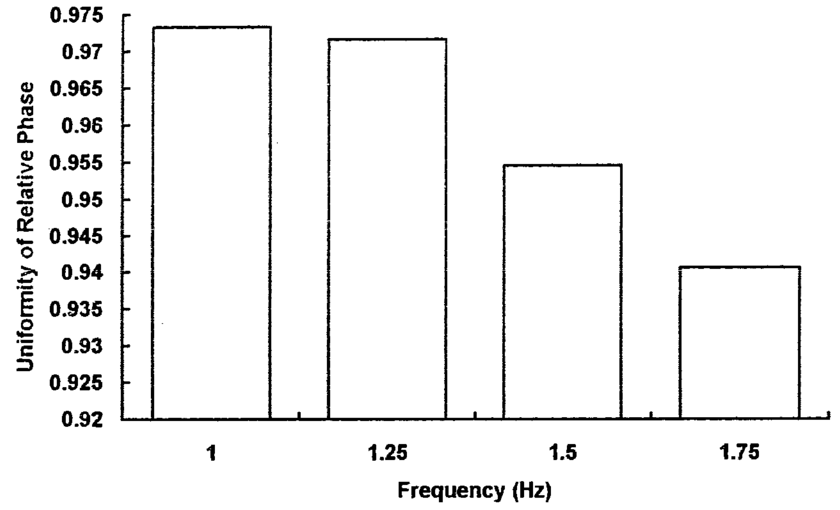

Figure 7.8 Mean relative phase uniformity as a function of oscillation frequency.

Analysis of relative phase uniformity revealed that the increase in mean phase deviation with oscillation frequency was accompanied by an increase in relative phase variability, $F(3, 15) = 9.11, p < .002$ (see Figure 7.8). There was also an interaction of mapping and orientation, $F(6, 30) = 3.13, p < .02$, which was further mediated by direction, $F(6, 30) = 2.63, p < .04$. As illustrated in Figure 7.9, the stability of the coordination patterns, revealed through the measure of uniformity, was influenced not only by the combination of the mapping and orientation, but also by the direction in which the orientation was changed. Consider, for example, the results for the ml/yr mapping, for which the effects were most evident (see Figure 7.9A). For the ml/yr mapping, the 180° orientation clearly yielded an in-phase pattern, and when a trial was began at the 180° orientation and subsequently rotated to 0° degrees, stability of relative phase was maintained until the orientation and mapping yielded an anti-phase pattern. In contrast, when a trial was began at 0° (anti-phase pattern) and rotated through to 180° (in-phase pattern), similar levels of uniformity were never quite realized. This hysteresis in relative phase uniformity was somewhat less evident for the yl/mr mapping. Finally, a Mapping x Direction interaction, $F(1, 5) = 8.48, p < .04$, indicated that, on average, trials prepared in a ml/yr mapping exhibited greater overall uniformity under a 180°→0° parameter scaling ($\bar{x} = .964$) than a 0°→180° scaling ($\bar{x} = .957$), whereas yl/mr trials exhibited a similar pattern in the opposite direction (0°→180 = .964; 180°→0° = .955).

Analyses of phase attraction, quantified as the proportion of the plateau duration spent within regions corresponding to ml/yr and yl/mr coordination, revealed effects generally consonant with those observed for mean phase deviation and uniformity. Specifically, analysis of phase attraction to a ml/yr coordination pattern, when prepared in this mapping, revealed that attraction decreased with increasing oscillation frequency, $F(3, 15) = 25.34$, $p < .001$, as well as with orientation from 180° to 0°, $F(6, 30) = 3.66, p < .008$. Analysis of attraction to a yl/mr coordination pattern, when prepared in this mapping, also decreased with increasing oscillation frequency, $F(3, 15) = 23.71, p < .001$, and with orientation from 0° to 180°, $F(6, 30) = 3.46, p < .02$ (see Figure 7.10 and 7.11).

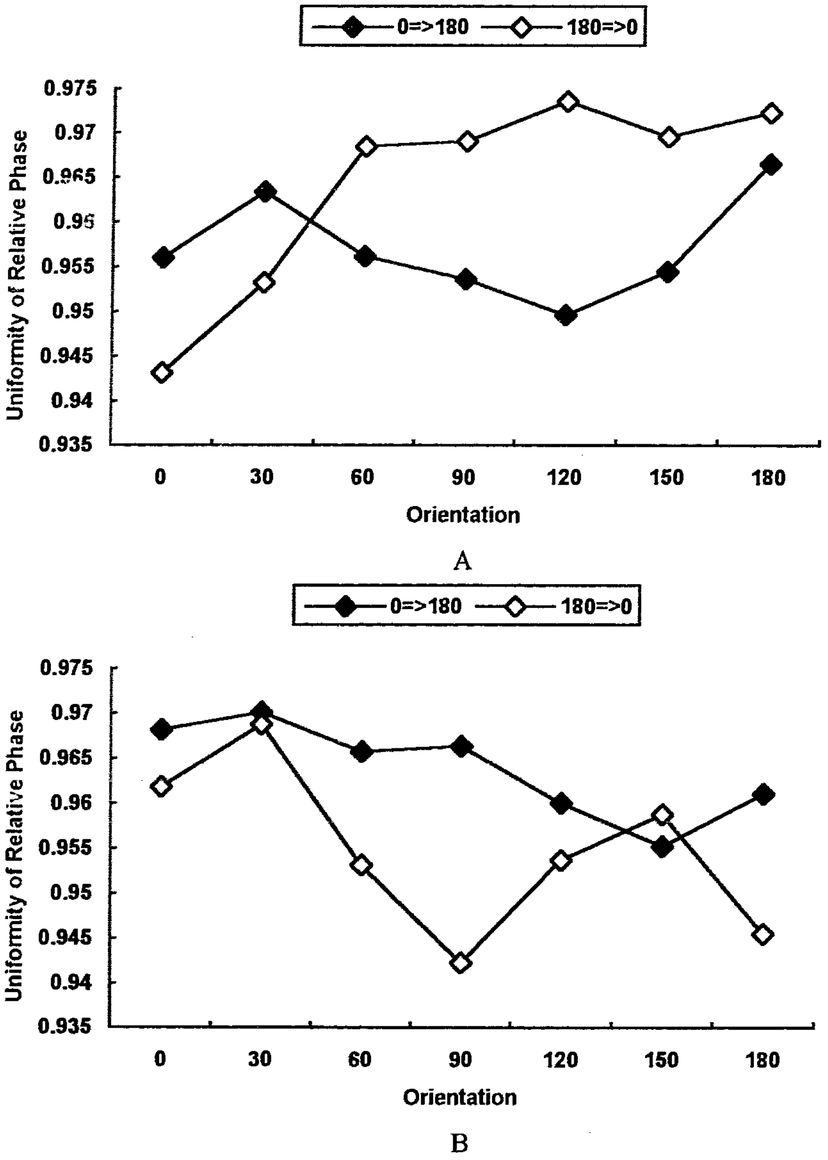

Figure 7.9 Mean relative phase uniformity as a function of direction of orientation change and display orientation: (A) ml/yr mapping; (B) yl/mr mapping.

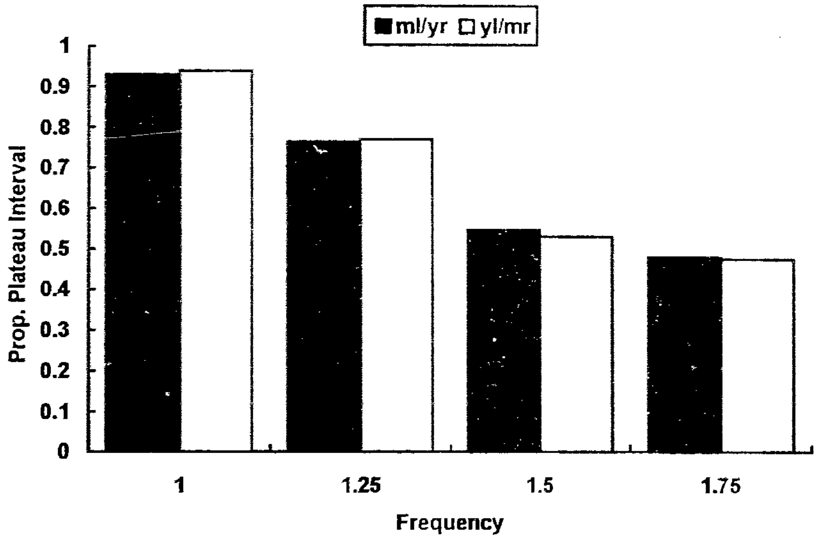

Figure 7.10 Phase attraction as a function of frequency: ml/yr mapping refers to attraction to this coordination pattern when prepared in this mapping; yl/mr mapping refers to attraction to this coordination pattern when prepared in this mapping.

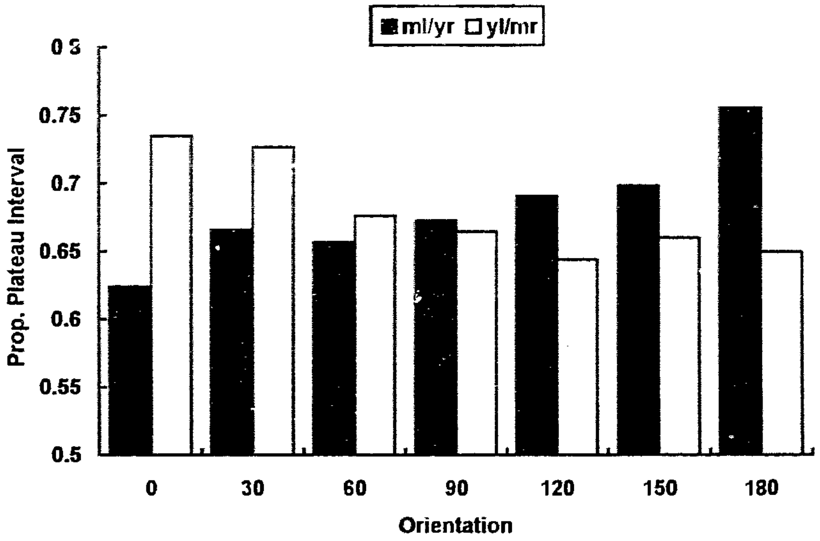

Figure 7.11 Phase attraction as a function of orientation: ml/yr mapping refers to attraction to this coordination pattern when prepared in this mapping; yl/mr mapping refers to attraction to this coordination pattern when prepared in this mapping.

7.4 Summary and Discussion

The present study examined the coordination dynamics of a unilateral, visually coupled perception-action system, under the scaling of a spatial and frequency parameter. Subjects were required to coordinate their movements with a visual display according to a prescribed mapping of information to action. The system under study was characterized by broken symmetry; that is, the components in coordination were non-identical in nature. Therefore, I expected to observe features of asymmetric dynamical systems, such as fixed point drift, as predicted by Equation (7.2).

In the present coordination task, the $\delta\omega$ term in Equation (7.2) can be taken to refer to the difference between the frequency of the visual display and the eigenfrequency of the limb. On the basis of the results, it may be assumed that $\delta\omega \neq 0$. At all oscillation frequencies employed, mean relative phase deviated from the intended coordination pattern and, moreover, increased as expected with increasing frequency. The frequency parameter also led to increasing instability in relative phase. Therefore, the impact of oscillation frequency on the coordination dynamics were as predicted by Equation (7.2).

An interesting feature of the present study was the scaling of a spatial parameter which influenced the phase attractive dynamics of the coupled system (see also Buchanan & Kelso, 1993). The stability and attraction to an intended coordination pattern were affected by the spatial orientation of the visual information. Depending upon the spatial orientation, a given coordination mapping could result in either an in-phase relation or an anti-phase relation. An in-phase relation was expected to stabilize and reduce drift from the intended coordination pattern, whereas an anti-phase relation was expected to lead to less stability and greater phase drift from the intended pattern. The present findings were generally in support of these expectations. Combinations of mapping and orientation which clearly yielded an in-phase relation between the visual information and the movement resulted in less overall deviation of relative phase from the intended coordination pattern. As the spatial parameter was scaled, such that the in-phase relation was transformed into an anti-phase relation, accompanying increases in phase deviation were also observed. Combinations of mapping and orientation which clearly yielded an anti-phase relation led to greater overall deviation of relative phase from the intended coordination pattern.

The variability of relative phase was similarly influenced by the scaling of spatial orientation. In general, there was less phase variability when the mapping and orientation combination yielded an in-phase pattern, relative to when it yielded an anti-phase pattern. Although the direction in which the spatial parameter was scaled did not influence the deviation of mean relative phase from the intended pattern, hysteresis was observed with respect to relative phase variability. That is, the variability observed was, to a certain extent, influenced by whether scaling of spatial orientation resulted in a gradual transformation of an in-phase pattern to an anti-phase pattern, or of an anti-phase pattern to an in-phase pattern. Less variability was generally observed when the phase relation proceeded from an initially more stable phase relation (in-phase) to a less stable relation (anti-phase). Since no direction-dependence was found for phase drift, these results suggest that mean relative phase was sometimes maintained at the expense of variability.

The findings from Experiments 1, 2, and 3 (this volume) suggest that the spatial relation between information and action, whether it be at the level of the mapping, configuration, or global relation, may have strong influences upon the dynamics of perception-action coordination. As in Experiment 3, the present results suggest that the spatial constraints imposed by the information-action configuration impact upon the coordination dynamics under a particular information-action mapping. Recall that subjects' intentions were to produce a given coordination mapping and not a specific phase relation per se. That is, subjects were not instructed to perform an in-phase or an anti-phase pattern. Indeed, due to the scaling of the spatial parameter, what begins clearly as in-phase becomes arbitrary as the parameter is scaled, then is transformed into an anti-phase pattern. In contrast, an intended coordination pattern based on a prescribed information-action mapping (in this case, a mapping of display colour to movement endpoint), remains invariant through the scaling of the spatial parameter. What the present findings reveal is that, whenever the combination of a given mapping and configuration yield an anti-phase relation, the less stable nature of this relation impinges upon the coordination dynamics. Specifically, the greater fixed point drift and variability associated with the anti-phase state is manifested in the greater deviation from, and variability of, the intended coordination mapping. When the phase relation is an in-phase pattern, the characteristics of this state also influence the coordination dynamics. The lesser degree of phase drift and variability associated with this state is manifested in less deviation from, and variability of, the intended coordination mapping. The differential stabilities of the in-phase and anti-phase equilibrium states are consonant with the predictions of Equation (7.2). In asymmetric systems, less stable states are expected to exhibit larger deviations and greater variability as the symmetry of the coordination dynamics is broken, relative to their more stable counterparts.

The present study has provided evidence for the intrusion of spatial constraints in the dynamics of perception-action coupling, through the manipulation of a spatial control parameter. Recently, Buchanan and Kelso (1993) have shown a similar spatial constraint in multijoint limb coordination. A salient finding in multijoint coordination has been the direction-dependence of the coordination dynamics. Specifically, it is much easier to coordinate joints of the same limb (e.g., Kelso, Buchanan, & Wallace, 1991) or different limbs (e.g., Kelso & Jeka, 1992) when the joints are rotated in the same direction. Buchanan and Kelso (1993) studied the coordination dynamics of single limb, multijoint coordination, under the scaling of limb orientation. In this study, subjects were required to coordinate rhythmic flexion and extension of the elbow and wrist under different forearm orientations. Subjects began a trial either by coordinating wrist flexion/extension with elbow flexion/extension with the forearm supine, or coordinating wrist flexion/extension with elbow extension/flexion with the forearm prone. Forearm orientation was varied during a trial. Transitions from one pattern to the other were observed at a critical forearm angle. Moreover, the critical angle depended upon the direction of the rotational change. In addition to the transition point, hysteresis was also observed in the variability of relative phase between wrist and elbow.

In the study by Buchanan and Kelso (1993), the coordination pattern was defined on the basis of a mapping of wrist and elbow flexion/extension. Whether or not the coordination mapping was stable depended upon the spatial configuration of the limb. Thus, a spatial parameter is shown to be an important system parameter, in that it induced fluctuations and switching in coordination. The present study has provided an analogue of this spatial constraint in a paradigm of perception-action coupling. Although an examination of phase transitions was not performed, the coordination dynamics, in terms of stability, phase drift and attraction, were nonetheless found to be influenced by the relation between the mapping and configuration between information and action. Further, the observation of spatial constraints in within-person coordination (e.g., Buchanan & Kelso, 1993) suggests that the intrusion of spatial constraints in coordination is not limited to coordinative systems which entail a coupling of perception and action.

In the present context, broken symmetry is embodied in the nature of the coupled system under study, which consisted of differing components, and the asymmetric dynamics expressed by Equation 7.2. The symmetry breaking referred to here is not equivalent to the usage of the term in Experiment 2, in which I spoke of a symmetry in terms of the stability of particular coordination mappings and of the informational constraints imposed by the interaction between specific information-action mappings and configurations. Symmetry breaking then referred to breaking an apparent equistability observed between mappings under orthogonal configurations.

The present findings are consistent with the predictions of the asymmetric form of the HKB model (Equation 7.2) and with previous work examining the influence of eigenfrequency differences between components (see Turvey & Schmidt, 1994, for review). Studies that have employed the pendulum paradigm (Kugler & Turvey, 1987) have been able to systematically manipulate the magnitude of the symmetry breaking term, $\delta\omega$, by varying the physical characteristics of pendula. In accordance with Equation 7.2, for example, increasing $\delta\omega$ leads to a systematic increase in mean phase drift and variability (e.g.., Schmidt & Turvey, 1995). In the present study, I have not been able to manipulate the magnitude of $\delta\omega$. From the results, I can only infer that $\delta\omega \neq 0$. In addition, however, the present study has shown that a spatial parameter may influence the symmetry breaking dynamics.

The study of phase attractive, symmetry breaking dynamics, has been carried out in within-person interlimb coordination (Kugler & Turvey, 1987; Schmidt et al., 1993), multijoint coordination within the same (Kelso et al., 1991; Buchananan & Kelso, 1993) and different limbs (Kelso & Jeka, 1992), between-person coordination (Schmidt & Turvey, 1994; Schmidt et al., 1994), and person-environment coordination (Kelso et al., 1990). The present study extends this to a situation in which action is unilaterally coupled to visual information (see also Byblow et al., 1995). The similarity of the dynamics which emerge in these coupled systems strengthens the idea that the principle of coordination dynamics are very general, applying across different levels of biological organization and physical realization (Schmidt & Turvey, 1995).

8. General Discussion

8.1 Overview

The primary goals of the present work were to investigate informational constraints in perception-action coupling through the study of spatial constraints, and to extend the study of perceptual-motor compatibility to coordinative actions. Two dominant perspectives in perceptual-motor behaviour were brought to bear on the topic of interest. The information processing framework provided a platform for the issue of perceptual-motor compatibility. The dynamical systems approach provided theoretical and analytical strategies, as well as tools, used to examine coordination dynamics.

I began by sketching a dynamical systems framework to the study of perceptual-motor behaviour, leading to a discussion of the coordination dynamics of perception-action coupling. The application of the principles and tools of nonlinear dynamics to the study of perception-action coupling provided an avenue through which informational constraints — specifically, spatial (compatibility) constraints, in coordination could be considered. Previous studies of visual perception-action coupling brought to light the spatial dependence inherent in visual coordination dynamics. As a complement to more traditional definitions of S-R compatibility, a framework was proposed to capture those perceptual-motor interactions in which some form of coordination is required between information and action.

A key aspect of the approach taken in the present work was the examination of compatibility relations at levels appropriate for the study of coordination. Rather than investigating variables typical in studies of response selection, observables that captured the coordination between information and action were selected. This entailed moving from measures of response times to indices of coordinative stability, which allowed the possibility of distinguishing preferred, or compatible, information-action relations from less compatible relations. In sum, compatibility effects were expected to emerge in the degree of coordinative stability that characterized a given information-action relation.

An underlying assumption of the above approach was that, just as the study of compatibility has provided a window into processes involved in response selection, the study of dynamical compatibility may provide insights into an informational constraint on perception-action coordination. Moreover, I also believed that research interests in the compatibility literature on dynamic S-R situations may be extended through a consideration of the dynamics of coordination.

In the present examination of the coordination dynamics of perception-action coupling, I employed a paradigm of person-environment coordination, in which action was unilaterally coupled to a rhythmic visual stimulus. A series of four experiments were performed to examine spatial constraints in coordination. I began in Experiment 1 with an examination of basic spatial constraints in perception-action coupling, through the study of the relation between information-action mappings and configurations and their impact on coordination dynamics. In Experiment 2, I proceeded with an investigation of whether the global spatial relation between information and action mediated the interaction between configuration and mapping. In Experiment 3, I extended the investigation of the influence of spatial configurations on coordination dynamics. Finally, I concluded with Experiment 4, in which I studied the asymmetric dynamics of perception-action coupling under the scaling of a spatial parameter.

8.2 Dynamics of Perception-Action Coupling

The perception-action system under study was composed of a rhythmic forearm movement coupled to a discrete, periodic visual stimulus. The coordination between components was captured by the order parameter, relative phase. The coordination dynamics was examined under the scaling of a control parameter, namely, oscillation frequency. Moreover, the visual coupling, person-environment paradigm was chosen because it allowed the study and manipulation of spatial parameters in the coupling between perception and action. Spatial parameters therefore also emerged as candidate control parameters.

I expected that coordination dynamics similar to those observed in within-person (e.g., Kelso, 1984; Byblow et al., 1994) and between-person (Amazeen et al., 1995; Schmidt et al., 1990) coordination would emerge in a unilateral, visually coupled system. For example, I expected that differential stabilities of the in-phase and anti-phase modes, when clearly defined, would be evident. In addition, because the components in coordination were non-identical in nature, the system was expected to be characterized by broken symmetry and subsequently exhibit asymmetric dynamics, as expressed in Equation 7.2 (asymmetric form of HKB model). Dynamical features of broken symmetry included fixed point drift, phase slippages, and phase wandering.

In accordance with previous work (e.g., Byblow et al., 1994, 1995; Schmidt et al., 1990; Wimmers et al., 1992), coordination modes corresponding to in-phase and anti-phase patterns were differentiated on the basis of stability (at present time, discussion is limited to situations in which in-phase and anti-phase patterns are clearly defined — i.e., under parallel configurations) (Experiment 1 & 2). As expected, in-phase patterns were generally found to exhibit less variability than anti-phase patterns. Attraction to in-phase regions, as well as the average time of maintenance of the pattern, were also greater for in-phase compared to anti-phase patterns (see also Byblow et al., 1995). These findings corroborate not only previous work on visual coordination (Amazeen et al., 1995; Byblow et al., 1995; Schmidt et al., 1990; Wimmers et al., 1992), but also work on within-person coordination (Byblow et al., 1994; Kelso, 1984; Schmidt et al., 1993). The similarity of the intrinsic dynamics of visual coupling to cases of within-person coupling speaks to the generality of the principles that underlie coordination dynamics.

The difference in stability of the $\phi = 0°$ and $\phi = 180°$ attractors is predicted by the HKB model of coordination dynamics (Haken et al., 1985; Kelso et al., 1990). The respective stability of each attractor is captured in the topology of the potential landscape around each attractor (e.g., see Figure 7.2 & 7.3). It has been postulated that the differential stability of the two attractors is a consequence of differences in the availability of information, or informational constraints, for the two coordination modes (Kugler, 1990). Specifically, it may be the case that information regarding whether the components are coordinated is available only at the endpoints for the anti-phase mode, but continually available for the in-phase mode (Kugler, 1990). Kugler's suggestion arises in a context in which coupling information is potentially continuous, such as, for example, in cases of within-person coordination or between-person coordination. However, in the present paradigm, coupling information, or possible synchronization points, was available only at endpoints for both coordination modes, given the discrete nature of the visual information. Therefore, it seems unlikely that the differences in stability between in-phase and anti-phase modes were a consequence of information availability, at least in terms of information regarding points of synchronization.

In the dynamical system described by the HKB model (Haken et al., 1985), coordination patterns are described by a low-order equation of motion in which the state of the system depends on the level of a control parameter. The control parameter is nonspecific with respect to the patterns that emerge but guides the system through its collective states. Oscillation frequency has been identified as a control parameter in human coordination, in that scaling of the parameter leads to qualitative changes in system state (e.g., Kelso, 1981; Schmidt et al., 1990). For example, as captured in the HKB model, scaling of oscillation frequency leads to the annihilation of the attractor at $\phi = 180^\circ$ and a shift from a bistable to a unistable regime.

In the present preparations of perception-action coupling, scaling of oscillation frequency led to changes in the stability of the system and the regime in which the system was situated (Experiment 1, 2, 3). Specifically, scaling of frequency resulted in an increase in mean phase drift (Experiment 4), increasing instability of the coordinative modes, and eventually a transition into a phase wandering regime (Experiment 1 & 2). Phase drift of the attractor point and phase wandering are features of systems characterized by broken symmetry and are theoretically not to be found in symmetric systems (compare Equations 7.1 and 7.2). Phase drift, phase attraction, and phase wandering are dynamical features of asymmetric systems which exhibit saddle-node bifurcations (Kelso, 1994). The presence of these features in the coordination dynamics of the present preparations of visual coupling are likely a reflection of the asymmetric nature of the coordinative system, namely, a system comprised of the coupling of external information and action.

The nature of the transitions observed in the present work (Experiment 1 & 2) were such that initially stable coordinative patterns, be they in-phase or anti-phase, gave way to phase wandering. Moreover, anti-phase patterns entered a phase wandering regime, usually without prior bifurcation to an in-phase pattern (see also Byblow et al., 1995; cf. Wimmers et al., 1995). This type of transition pathway, in which either in-phase or anti-phase enters phase wandering without prior bifurcation to another stable pattern, is not necessarily surprising. In the context of the asymmetric HKB model (Kelso et al., 1990), there are different transition pathways that the relative phase dynamics may take under the scaling of the control parameter, oscillation frequency. For example, taking Equation 7.2 and setting $\delta\omega = 1$, and independently varying the parameters a and b, different transition routes can be realized by taking different paths in the parameter space (a, b). These transition routes (outlined in Kelso et al., 1990), include those in which: a) an anti-phase state loses stability and gives way to an in-phase state, which subsequently also becomes unstable, giving way to unstable, wrapping solutions; b) only in-phase is stable, which enters phase wandering under further parameter scaling; c) a bistable regime enters a unistable regime in which only in-phase is stable; and finally, most relevant for the present results (Experiment 1 and 2), d) a path which leads directly to phase wandering from a bistable regime in which both in-phase and anti-phase states are stable. The dynamical features of the in-phase and anti-phase modes observed here are therefore consistent with those captured and predicted by a current theoretical model of coordination dynamics.

8.3 Spatial Constraints in Perception-Action Coupling: Compatibility Effects

One of the primary purposes of the present series of experiments was to examine spatial constraints in the dynamics of visual coordination. I expected compatibility effects to be manifested in terms of stability. Was there evidence of spatial constraints, or compatibility effects, in the coordination dynamics? Taken together, the results of the experiments suggest the affirmative, that there were indeed compatibility effects in the visual coordination of action.

In compatibility terms, the spatially defined in-phase and anti-phase patterns were classified as compatible and incompatible information-action mappings, respectively. As discussed in the previous section, the greater relative stability of the in-phase mapping corresponded to what would be expected for a spatially compatible relation. As well, the lesser degree of stability of the anti-phase mapping corresponded to expectations for a spatially incompatible relation. These expectations were based on work from both the coordination dynamics (e.g., Kelso, 1981) and S-R compatibility (e.g., Fitts & Seeger, 1953) literature. The results for in-phase and anti-phase mappings were most evident when these mapping relations were clearly defined. This was the case under conditions in which the information-action configuration was parallel (Experiment 1 & 2).

The intrinsic dynamics of the coordination mappings were influenced by the configuration between information and action. Under orthogonal configurations (Experiment 1 & 2), the coordination mappings, up-right/down-left and up-left/down-right, were arbitrary compared to in-phase and anti-phase mappings. This was essentially reflected in the general absence of stability differences between these orthogonal mappings (Experiment 1). This equistability was attributed to a symmetry in the informational constraints imposed by the orthogonal information-action mappings (cf. Wimmers et al., 1992). On the basis of previous examinations of orthogonal compatibility in the S-R compatibility literature (e.g., Michaels, 1989; Weeks & Proctor, 1990), I questioned whether a change in what is referred to as the information-action global relation could influence coordination dynamics in visual coupling (Experiment 2). I manipulated the global spatial relation between information and action in order to break the symmetry between orthogonal information-action mappings. The preferred orthogonal mapping (based on greater relative phase stability) changed as a function of the global relation. Indications were of an up-right/down-left preference for movements performed in ipsilateral space and a trend toward an opposite preference for contralateral space. These mapping preferences in coordination are consonant with those observed for discrete reaction time tasks (e.g., Michaels & Schilder, 1991; Weeks et al., 1995).

Experiments 3 and 4 further confirmed the intrusion of spatial constraints in visual coordination. Moreover, compatibility effects were noted even when the coordination mappings were defined independently of the spatial dimension of the visual information. Whereas in Experiments 1 and 2, coordination patterns were based explicitly on a spatially defined mapping, the mappings in Experiments 3 and 4 were only implicitly based on a spatial parameter. Specifically, coordination patterns (Experiments 3 & 4) were based on a mapping of an informational feature (display colour) to action (movement endpoint) and not based on both the spatial dimensions of the information and action. Nonetheless, the spatial dimension of the information, although essentially irrelevant to the prescribed information-action mapping, impinged upon the coordination dynamics. Interestingly, this compatibility effect mirrors the Simon effect (see Simon, 1990, for review), a variant of spatial compatibility observed in choice RT situations.

In summary, the results of the present work suggest that spatial constraints impinged upon visual coordination dynamics. The intrinsic dynamics of the coupled system may be influenced by the spatial relation between the driving visual information and the movement with which it is coupled. In the visual perception-action system under study, coordination patterns were spatially defined, either explicitly or implicitly. The stability of coordination patterns, from which I inferred compatibility effects, depended upon the spatial correspondence of the mapping between information and action. Moreover, this spatial dependence was mediated by the spatial configuration between information and action. Lastly, this interaction between mapping and configuration was further affected by the global spatial relation between information and action. Changes in these levels of spatial relations presumably led to changes in the informational constraints, which subsequently led to differences in stability, or compatibility.

8.4 Spatial Compatibility in Response Selection

Since the work of Fitts and Seeger (1953), the spatial dependence of choice reaction time to stimuli in a spatial array has been repeatedly demonstrated. S-R compatibility effects often arise when spatial relations, whether implicit or explicit, exist among stimuli and responses. Theoretical accounts of compatibility have been couched in the language of information processing (Proctor & Reeve, 1990, for review; cf. Michaels, 1988), an important feature of which is that stimuli and responses are represented by mental codes. Compatibility effects are attributed to cognitive processes that translate between stimulus and response codes and reflect the efficiency of the translation process. Compatible S-R mappings are said to be those in which stimulus and response codes are similar and which lead to greater relative ease in selecting the response assigned to a stimulus. Incompatible S-R mappings are those in which S-R codes conflict and interfere in selection of the response.

The wealth of research beginning with Fitts and Seeger (1953) has provided evidence to suggest that, for stimuli and responses arranged in a spatial array, translation is based on codes which are spatial (see Proctor & Reeve, 1990; Umiltà & Nicoletti, 1990, for reviews). Moreover, these codes are generally independent of the means by which stimulus information is presented and responses are effected (Proctor et al., 1993). When spatial relations are explicit, such as in a prototypical two choice task in which left and right stimuli are mapped onto left and right responses, spatial coding is based on the relative stimulus and response locations, and not actual physical locations. When spatial relations are implicit, such as when symbolic stimuli (e.g., left and right facing arrows) are used to denote left and right responses, coding may be based upon salient spatial features of the stimuli and responses (Reeve & Proctor, 1990). Briefly, salient features coding (Proctor & Reeve, 1986) is based on the principle that codes are based on the salient features of the stimulus and response sets, with translation being most efficient when the S-R mapping result in correspondence of these salient features.

Coding based on salient stimulus and response features has also been invoked in accounts of orthogonal compatibility effects (Weeks & Proctor, 1990; cf. Bauer & Miller, 1982; Michaels, 1988). On the basis of some evidence that suggests that up and down positions and left and right positions may be coded asymmetrically (e.g., Chase & Clark, 1971; Olson & Laxar, 1973), Weeks and Proctor (1990) have proposed that in orthogonal spatial configurations, the up and right positions may serve as polar referents for their respective dimensions. Coding is then based upon these salient referents for the vertical and horizontal dimensions, with the compatible mapping resulting in correspondence of the salient features. Accordingly, for orthogonal S-R configurations, a mapping of up-right/down-left has been found to yield faster responding than a mapping of up-left and down-right (Weeks & Proctor, 1990; Weeks et al., 1995).

This is not the entire picture presented for orthogonal compatibility effects. Weeks and colleagues (Weeks et al., 1995; cf. Michaels & Schilder, 1991) have also found that compatible mappings for orthogonal S-R configurations change as a function of what I refer to as the global spatial relation between stimulus (information) and response (action). Specifically, Weeks et al. found that an up-right/down-left mapping yielded faster responses when the response was located eccentrically to the right of a central stimulus display. This mapping advantage diminished as the response location was moved to the midline, and reversed in direction when the response was placed eccentrically to the left of the display. In the latter position, the up-left/down-right mapping yielded faster responses. Weeks et al. applied the salient features coding principle to these results by assuming that the response associated with the hemispace in which the response set is placed becomes the salient member of the response set. For response sets located in right hemispace, the right response becomes the salient member, whereas for response sets located in the left hemispace, the left response becomes the salient member. Again, response selection is facilitated when mapping yields correspondence of the salient features of the S-R sets.

8.5 Spatial Compatibility in Information-Action Coupling

The spatial compatibility constraints observed in the present series of coordination experiments mirrored effects found in work examining response selection. Due to the discrete nature of the visual displays employed in the experiments, information-action mappings, or coordination modes, were not differentiated in terms of the available information for synchronization (cf. Byblow et al., 1995). What proved to play a role in determining the dynamical stability of the information-action coupling was the spatial relation between information and action, independent of whether or not mappings were based explicitly on a spatial relation.

Greater stability of coordination was generally observed when the direction of stimulus motion corresponded with the direction of movement, or when the movement endpoints corresponded with the relative spatial position of the stimulus endpoints. This was most apparent under parallel configurations. The importance of direction of motion in determining coordinative stability in visual coordination has been well established (e.g., Byblow et al., 1995; Schmidt et al., 1990; Wimmers et al., 1992). Indeed, it was the spatiotemporal correspondence of the information and action motion that served as the basis for relative phase. Again, the in-phase relation emerged as being more stable than the anti-phase relation.

What about orthogonal information-action configurations? At the midline, the spatial correspondence of stimulus motion to movement, or of stimulus endpoints to movement endpoints, was less obvious. This ambiguity was reflected in the similar stability that emerged for the orthogonal mappings. Why, then, did differences in stability emerge when movements were made at locations eccentric to the midline and visual display? Why was the informational symmetry broken? Byblow et al. (1994) and Carson et al. (1994) have provided evidence that indicate that the temporal location of information relative to the movement cycle is important in the dynamics of the information-action couple. For example, these authors have shown that the presence of pacing information and its temporal location impinges upon the stability and dynamics of bimanual coordination. In the present work, the driving visual information was always present at the endpoints of the cycle, points at which synchronization tendencies were likely to occur. Thus, temporal location of the information was probably not a factor. However, the results suggested that the spatial location of the information relative to the movement played a crucial role.

For orthogonal configurations at the midline, the spatial positions of the information and movement endpoints were essentially neutral with respect to one another (Experiment 1 & 2), perhaps contributing to the equivalence of the two mappings. However, when the movement was performed eccentric to the midline and information, the spatial positions were no longer neutral due to the change in the global spatial relation. I suspect that as the movement was placed to the right of midline and eccentric of the central visual display, the spatial proximity of the down stimulus endpoint and the left movement endpoint yielded a salient information-action synchronization point. When the movement is placed to the left of midline, it was the right movement endpoint that becomes proximal to the down stimulus endpoint, thus yielding a salient down-right synchronization point. These synchronization points may have contributed to better coordinative stability and gave rise to the preferred information-action mappings.

8.6 Summary

In the present work, I examined the impact of spatial, informational, constraints in perception-action coupling. My framework relied on work from both the information-processing and dynamical systems approaches to perceptual-motor behaviour. There has been much debate between these two perspectives; however, it has not been the intent of the present work to comment on the complex "motor-action controversy" (Meijer & Roth, 1988). Inherent in the present approach taken has been a principle of complementarity (e.g., Pattee, 1977, 1982). The information-processing framework has provided the empirical platform for the study of compatibility while the dynamical systems framework has provided the analytical tools and principles for the study of coordination. For cognitive theorists interested in S-R compatibility, I have presented an approach to examine dynamic perceptual-motor interactions. For theorists interested in coordination, I have provided an example of how the study of spatial compatibility in coordination might provide some insights into informational constraints in coordination dynamics.

I believe that the complementary framework that I have employed is in keeping with what Fitts had envisioned. Although Fitts was responsible for the chronometric approach to the study of compatibility, he acknowledged that perceptual-motor behaviour may be assessed at other levels:

> . . . the same theory which has been developed for the analysis and synthesis of dynamic physical systems can, to a considerable extent, be applied directly to the description of human perceptual-motor learning and performance.
>
> Paul M. Fitts (1964)

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