Dynamical Patterns in the Development of Clapping

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Dynamical patterns in the development of clapping is modeled using a formal, explicit model of coupled oscillator dynamics. Even though this behavior manifests a good deal of nonstationarity and high variability within and across subjects, results indicate that these properties may be dynamically modeled quantitatively as well as qualitatively. Results suggest that clapping goes through a less stable period of relative coordination between 3 and 7 years before more stable absolute coordination is achieved. Nevertheless, in that the clapping behavior is affected in highly predictable ways by inertial loading of the limbs, the same underlying dynamic seems responsible for the coordination of both the younger and older children. Developmentally, the behavior of the coordination variable (relative phase) changes from a nonconstant magnitude in younger clappers to a constant magnitude in older clappers. These results suggest that development of proficiency in rhythmic motor skills displays developmental changes that can be understood well in dynamical terms.

There has been a growing interest recently in using dynamical theory as a means for understanding and modeling developing systems (Fitzpatrick, in press; Thelen, 1995; Thelen & Smith, 1994; Turvey & Fitzpatrick, 1993). A defining feature of developing systems is that they change behavioral modes. Dynamical theory is particularly well suited for modeling developing systems due to its reliance on general principles of stability and change to explain the emergence of new behavioral organizations. In broad strokes, a biological organism is a complex physical system. Its behavioral patterns can be thought of as attractive states that arise from an interplay of forces and mutual influence of the very many components of this system. Under certain circumstances, particular patterns are preferred and act as attractors in the sense that they are stable and chosen most often. Changes in circumstances (e.g., task, intention, environment, age) can alter the stability characteristics of those behavioral patterns and result in the appearance of new behavioral modes.

In the dynamical modeling of behavioral systems, rhythmic interlimb coordination patterns have been a main focus on the formal modeling efforts. This is due in part to the fact that coordination patterns in which the two limbs move at a common frequency are basic to many everyday activities. Proficiency in rhythmic behaviors seems to be intimately tied to the ability to bring simple motor rhythms (repetitive patterns with fixed temporal structure) under voluntary control to produce coordinated behaviors with complex temporal sequences (e.g., von Hofsten & Rönnqvist, 1993; Rob-
erston, 1993; Thelen, 1981, 1991; Thelen et al., 1993; Wolff, 1967, 1968, 1991). It has been argued (Kelso, 1994) that coupled oscillator dynamics are essentially the only coordination option for achieving such coordination patterns. In this sense, coupled oscillator dynamics are an elementary coordination dynamic—a simple organizing principle found over and over in the dynamics of behavioral systems. The generality of the these coordination principles is supported by a brief sampling of the very many different types of movements that have succumbed to such modeling: oscillations of an individual’s two index fingers (e.g., Kelso, 1984), an arm and a leg (Jeka, Kelso, & Kiemel, 1993; Kelso & Jeka, 1992), pendulums held in each hand (e.g., Schmidt, Shaw, & Turvey, 1993), pendulums held by two individuals (e.g., Schmidt & Turvey, 1994), the legs of two individuals (Schmidt, Carello, & Turvey, 1990), juggling (Beek & Turvey, 1992), finger tapping (Peper, Beek, & van Wieringen, 1991), and clapping (Fitzpatrick, Schmidt, & Carello, 1996).

If coupled oscillator dynamics are indeed elementary, then developmentally one should expect to see evidence of coupled oscillator dynamics underlying the ontogenetic change of interlimb coordination patterns. Given the generality and power of the principles of coordination dynamics established in the adult literature, the present study proposes to use interlimb patterns as an entry point for the formal dynamical modeling of coordination in a developing system. Since the behavior of children is very noisy and variable by its nature, a robust coordination task or model system is essential for successful modeling. Elsewhere, the very robust dynamical basis of a naturally occurring rhythmic behavior—clapping—has been established (Fitzpatrick et al., 1996). Clapping is a behavior exhibited beginning at a relatively young age (between 8 and 12 months; Kaye & Marcus, 1981) and one known to adhere, in adults, to coupled oscillatory dynamics. This basic behavior has been chosen as a window through which to view the development of coordination dynamics.

In developmental work, coordination research has predominantly been limited to investigations of infant behaviors that can be characterized as rhythmic or oscillatory. For example, manual behaviors such as banging, shaking, and waving have been investigated (Lockman & McHale, 1989; Palmer, 1989; Ramsay, 1985). The goal of such research efforts has been to determine whether infants use these behaviors in a discriminatory or goal-directed manner. It is only recently, however, that investigators have begun to examine how young children harness the oscillatory properties of the limbs in performing skilled actions. In this connection, investigators have attempted to model the dynamics that underlie infant interlimb coordination patterns.

For example, von Hofsten and Rönnqvist (1993) have shown that the spontaneous arm movements of infants 3–5 days old are clearly coupled, demonstrating either a strong positive or strong negative correlation. Corbetta and Thelen (1994), in an investigation of the development of reaching, report that initially bimanual reaches predominate and are characterized by a strong coupling between the arms. Later, when control of the contralateral arm is gained, the two arms can be controlled independently, and unimanual reaches appear in the behavioral repertoire. Additionally, Thelen and Fisher (1983) have shown that early leg movements, although not generally goal directed, are well coordinated. In particular, they demonstrate that the leg joints of a single limb move in synchrony and the movements between limbs are well-coordinated, usually in an alternating pattern. Later, infants begin to decouple the whole leg movements to allow the leg joints within a single limb to move independently to accomplish such tasks as crawling or walking (Jensen, Ulrich, Thelen, Schneider, & Zernicke, in press). Similarly, Clark, Whitall, and Phillips (1988) demonstrate that the interlimb coordination between the two legs is very tight soon after the onset of walking. Indeed, given the rather severe task constraints involved in walking, this strong coupling may be important in defining the gait pattern as walking rather than some other locomotory pattern.

In sum, these studies suggest that babies are born with strong interlimb and intralimb coupling in spontaneous movements and demonstrate a preference for moving the arms in an inphase pattern and the legs in an antiphase. Further, the stability of the coupling within and between the limbs does not appear to be static but seems to wax and wane throughout the first year, and perhaps into childhood. Understanding the circumstances surrounding these changes in interlimb coupling could be important in understanding how interlimb coordination unfolds in developmental time. Extending
Coupling of $\theta_1$ and $\theta_2$

![Diagram](image)

**FIG. 1.**—One cycle of each of two oscillators is represented as closed orbits in a coordinate system defined by position and velocity. $\theta$ represents the position of an oscillator in its cycle. In the figure, the oscillator on the right is slightly ahead in its cycle of the oscillator on the left, as indicated by a larger angle at $\theta_2$ than at $\theta_1$. In this case, relative phase ($\phi$) would be less than 0.

The Dynamical Modeling of Clapping Behavior

As a result of the mass-spring and oscillatory properties of rhythmic coordination patterns (Kandel, Schwartz, & Jessel, 1991; Kugler, Kelso, & Turvey, 1989), rhythmically moved limb segments have been treated as self-sustained physical oscillators. Such an oscillator has its own preferred frequency of oscillation, or eigenfrequency ($\omega$)—it prefers to complete one cycle of its behavior at a certain rate (Kadar, Schmidt, & Turvey, 1993; Kay, Saltzman, & Kelso, 1991; Kelso, Holt, Rubin, & Kugler, 1981). Interlimb coordination patterns have been formally modeled by two such oscillators interacting across a coupling medium (Haken, Kelso, & Bunz, 1985). If the oscillators have different preferred frequencies ($\omega$), the coupling requires that each oscillator modify its intrinsic frequency so the two oscillators can become coordinated at a common frequency.

The dynamics of an oscillator can be graphically understood by representing its change of position and velocity during its cycle. As seen in Figure 1, each oscillator traces a closed orbit in such a coordinate system defined by its position and velocity. The location of an oscillator in its cycle is represented as a phase angle $\theta$ which changes from 0 to $2\pi$ rad from the start to the end of an oscillation cycle. The variable that has been used to capture the coordination of the two oscillators (the collective variable or order parameter) is the relative phase angle, $\theta_1 - \theta_2$, namely, the difference between the two oscillators' individual phase angles. Using this coordination measure, one can determine whether the two oscillators are in the same parts of their cycles at the same time (i.e., $\theta_1 = \theta_2$), or whether one oscillator is ahead of the other. If the two oscillators are perfectly in phase, then $\phi = 0$ rad. If they are perfectly in antiphase, $\phi = \pi$ rad.

Clapping is an inphase coordination pattern by definition since homologous muscle groups are extending or flexing at the same time during the clapping movements. (For example, when the palms are together, the flexor muscle group of each arm is at peak flexion.) Relative phasing in clapping can be illustrated with a simple demonstration. Stand facing a partially open door and clap each hand on either side of the door at a comfortable tempo. The hands will contact the door at precisely the same time and one bang or "clap" will be heard. In other words, each hand will achieve peak flexion (when hitting the door) at the same time, indicating a relative phase of 0 rad between the two hands. In this case, the phasing between the limbs is very stable and would be constant from one clap to the next. Now, clap at a faster tempo or strap a light wrist-weight on one arm. You will notice that one hand will hit the door slightly before the other. In other words, one hand will lag slightly behind the other. If one continues to increase the clapping tempo or add more and more mass to the hand, the lag between the two hands contacting the door will continue to increase. This demonstration illustrates that it becomes more difficult to maintain a relative phase relation of precisely 0 when clapping frequency increases or the mass imbalance between the limbs increases. Under these circumstances, the inphase mode becomes less stable and less precise.¹

These kinds of systematic changes in the behavior of relative phase $\phi$ which are seen in even this casual demonstration have

¹ It is worth keeping in mind that the deviation of limb phasing from exactly 0 is subtle and most likely would go unnoticed in the normal course of events. Merely looking at someone clapping with a mass strapped on the arm is not likely to result in the impression that the phasing between the hands is imperfect.
been formally modeled by a coupled oscillatory system with stable modes at $\phi = 0$ and $\pi$ rad (Haken et al., 1985; Kelso, Delcolle, & Schöner, 1990; Kelso & Jeka, 1992): 

$$\dot{\phi} = \Delta \omega - a \sin(\phi) - 2b \sin(2\phi) + \sqrt{Q}\epsilon. \quad (1)$$

This equation indicates that three parameters influence relative phase behavior: $\Delta \omega$, the difference in the uncoupled (preferred) frequency of oscillation of the two oscillators; $-a \sin(\phi) - 2b \sin(2\phi)$, a periodic coupling function that captures the effect of the behavior of one oscillator on that of the other; and $\sqrt{Q}\epsilon$, a stochastic noise process generated by the many interacting subsystems underlying the coordination (Haken, 1983; Schöner, Haken, & Kelso, 1986). $\Delta \omega$ is equal to $\omega_1 - \omega_2$, namely, the preferred frequency of oscillator 1 minus the preferred frequency of oscillator 2. It captures the differences between the two oscillators and is an index of the amount of competition between the oscillators that results from each trying to maintain its preferred intrinsic frequency. When the two oscillators prefer to oscillate at the same frequency, $\Delta \omega = 0$. When oscillator 1 has a faster intrinsic frequency $\Delta \omega > 1$ and when oscillator 2 has a faster intrinsic frequency $\Delta \omega < 1$. The coupling term, $-a \sin(\phi) - 2b \sin(2\phi)$, reflects the processes underlying the coordination of the two oscillators and as such indexes the degree of cooperation that attempts to bring the oscillators to a common tempo in spite of their intrinsic differences. The coupling function includes two terms whose coefficients ($a$ and $b$) determine the relative strength of the cooperation between the oscillators, and hence, the coordination pattern.

When the magnitudes of the competitive ($\Delta \omega$) and cooperative processes [$-a \sin(\phi) - 2b \sin(2\phi)$] are equal, the coordination and (hence, the relative phase $\phi$) is stable. These balanced situations correspond to solutions of Equation 1 (i.e., situations where $\phi = 0$ excluding $\sqrt{Q}\epsilon$). Importantly, the properties of such solutions provide predictions about the patterns of interlimb coordination to be expected if they are governed by such a dynamical regime under different circumstances.

Consider first the special case situations for which $\Delta \omega = 0$. When $b$ is large with respect to $a$ (e.g., the ratio $b/a > 1$), the system has two stable states at $\phi = 0$ and $\pi$ rad (in-phase and antiphase modes). This means there are two behavioral patterns available to this system that are defined by equilibria or attractors. Since for clapping we are only concerned with an inphase coordination, the model will be discussed only in terms of the stable state at $\phi = 0$. The strength of the inphase behavioral pattern is determined by strength of the cooperative processes, which are a function of the magnitude of the coupling function coefficients. The greater the coupling strength, the more stable the relative phasing. What this means behaviorally is that greater coupling strengths should have less variable relative phasing. Hence one can predict that experimental manipulations that decrease the coupling strength should increase the variability of relative phase. Haken et al. (1985) proposed, and later studies (Kelso, Scholz, & Schöner, 1986; Schmidt et al., 1993; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, in press; Schöner et al., 1986; Turvey, Rosenblum, Schmidt, & Kugler, 1986) have verified, that increasing the frequency of oscillation $\omega$, decreases of the strength of the coupling terms and increases the relative phase $\phi$ standard deviation observed. In particular, Fitzpatrick et al. (1996) affirmed this prediction of the dynamical model for clapping behavior in adults.

Consider next the predictions of Equation 1 when there exists some competition between the oscillators and $\Delta \omega \neq 0$. Given a constant strength of the coupling, $\Delta \omega \neq 0$ causes the competitive and cooperative processes to balance at some deviation from perfect inphase. That is, the solutions to Equation 1 when $\Delta \omega \neq 0$ will be near but not equal to 0 rad. In short, the position of the relative phase attractor has moved and consequently creates a “phase lag” such that the oscillator with the slower intrinsic frequency $\omega_1$ lags behind that with the faster intrinsic frequency. Further, the equation predicts that increasing the amount of competition ($\Delta \omega$) increases the magnitude of this phase lag and concomitantly decreases the stability of the behavioral pattern as the phase lag grows. Consequently, the experimental scaling of $\Delta \omega$ should increase the deviation of mean relative phase $\phi$ from 0 rad and increase its variability.

Experiments investigating adult clapping (Fitzpatrick, Schmidt, & Carello, 1996) and the bimanual coordination of hand-held pendulums (see Schmidt & Turvey, 1995, for a review) have manipulated the preferred frequencies of the oscillatory limbs by vary-
ing the inertial loading of the limbs. (Limbs with greater inertia have slower intrinsic frequencies and limbs with lower inertia have faster intrinsic frequencies.) Using this methodology, the difference in preferred frequencies $\Delta \omega$ of the oscillators can be manipulated by changing the inertial loadings of the two limbs differentially. This research has empirically verified the above predictions of Equation 1 for interlimb coordination, namely, that the unit with the slower preferred frequency lags behind the unit with the faster preferred frequency, and that the magnitude of this phase lag and the variability of $\phi$ increase as the magnitude of $\Delta \omega$ deviates from 0. This research has also verified another prediction of Equation (1) that combines the manipulation of $\Delta \omega$ and frequency of oscillation $\omega_c$. Given a constant $\Delta \omega \neq 0$, the weakening of the coupling function by increasing the frequency of oscillation $\omega_c$ will amplify the phase lag and the variability of $\phi$. In brief, the balancing of the competitive and the cooperative processes is weaker and this consequently creates a greater deviation from perfect inphase and higher fluctuations.

To summarize, the coupled oscillator model is composed of competitive ($\Delta \omega$) and cooperative ($-a \sin(\phi) - 2b \sin(2\phi)$) terms. The magnitude of processes can be manipulated in the laboratory (by frequency of oscillation and differential inertial loading of the limbs, respectively), and predictions of the model regarding how the two processes should balance can be verified in interlimb coordination experiments. Past research has verified these coupled oscillator predictions for adult clapping behavior. If the same dynamics underlie the coordination of clapping in children, we should also expect to see experimental support of these predictions in their relative phase patterning.

**Relative Coordination**

Up to this point, we have been discussing instances of Equation 1 in which the competitive and cooperative terms balance and stable relative phase patterns are formed. However, we need to countenance the possibility that in some systems, particularly immature systems, the competitive processes may not be balanced by the cooperative ones. When these two processes balance, the relative phase over time is centered around a constant value, and the system is phase-locked. Von Holst (1939/1973) referred to such stable coordination as absolute coordination. As demonstrated above, this kind of coordination can be quantified by summary measures of its mean state and its variability (e.g., mean $\phi$ and standard deviation of $\phi$), and using such measures model predictions can be tested. Bear in mind, however, that such measures are only appropriate for characterizing steady-state or stationary behavior. If the competitive and cooperative processes do not balance, relative phase will not be constant—every possible phase relation will be exhibited. However, if the systems are still exerting an influence on each other, they can still be coordinated. Von Holst (1939/1973) referred to this less stable kind of coordination as relative coordination. In order to evaluate whether relative coordination exists (rather than no coordination at all), alternative measures of the behavioral patterning are required.

Importantly, the coupled oscillator model of Equation 1 makes predictions not only about stationary absolute interlimb coordination but also about nonstationary relative interlimb coordination. Kelso and colleagues (Kelso & Ding, 1994; Zanone & Kelso, 1990; Zanone, Kelso, & Jeka, 1993) have pointed out that such relative coordination can be produced by dynamical systems with weak attractors and intrinsic noise. This kind of system would demonstrate the property of intermittency: An attraction to certain regions in spite of a constant change in state. Hence, a system demonstrating relative coordination governed by Equation 1 would exhibit intermittent attraction to weak attractor regions near 0 and $\pi$ rad in spite of a nonconstant relative phase. Intermittent attraction in interlimb coordination can be evaluated in two ways. First, the rate of change of relative phase, $\phi$, should be less for regions that are more attractive (near 0 and $\pi$ rad). Because the magnitude of $\phi$ is determined by the relative strength of the attractive region, the weaker the attractor, the larger the magnitude of $\phi$. Second, intermittent attraction to 0 and $\pi$ rad would be indicated by a distribution of relative phase across all phase relations, but with a concentration of states near these magnitudes. Such concentrations would represent the dwell time of the attractive regions.

From the above discussion of the coupled oscillator model, one can predict how the magnitude of intermittent attraction should change with the experimental manipulations of frequency and $\Delta \omega$. Past research suggests that the strength of the behavioral patterns decreases with increasing frequency and as $\Delta \omega$ deviates from 0. Hence,
one can predict that with increasing frequency of oscillation or the deviation of $\Delta \omega$ from 0, $\phi$ should increase and the distribution of relative phase should be more or less concentrated at 0 and $\pi$ rad.

**Current Experiment and Predictions**

In the current experiment, we will evaluate the appropriateness of coupled oscillator dynamics in modeling the clapping patterns displayed by children and the development of these patterns. Support for this model will be evaluated both in terms of predictions regarding measures indicative of absolute coordination (characteristic changes in mean relative phase and its variability) and relative coordination ($\phi$—the rate of change of relative phase and the distribution of relative phase) as enumerated below.

**Absolute Coordination Predictions**

Prediction 1. For $\Delta \omega \neq 0$, $\phi$ should deviate from 0 such that the rhythmic unit with the slower preferred frequency should lag behind the unit with the faster preferred frequency.

Prediction 2. The magnitude of this phase lag depends on how much $\Delta \omega$ deviates from 0.

Prediction 3. For $\Delta \omega \neq 0$, deviation of $\phi$ from 0 increases with increasing frequency.

Prediction 4. SD $\phi$ increases with increasing frequency.

Prediction 5. SD $\phi$ increases as the magnitude of $\Delta \omega$ deviates from 0.

**Relative Coordination Predictions**

Prediction 6. $\phi$ should be distributed across all relative phases but concentrated near 0 and $\pi$ rad.

Prediction 7. The distribution of $\phi$ should be more disperse as frequency increases.

Prediction 8. The distribution of $\phi$ should be more disperse as $\Delta \omega$ deviates from 0.

Prediction 9. $\phi$ should increase with increasing frequency.

Prediction 10. $\phi$ should increase as $\Delta \omega$ deviates from 0.

**Method**

**Participants**

The final sample consisted of 20 participants (12 males, 8 females), five in each of four age groups—3 (mean age = 41.6 months, range = 30–47 months), 4 (mean age = 54.8 months, range = 49–60 months), 5 (mean age = 67.4 months, range = 63–71 months), and 7 (mean age = 93.6 months, range = 90–98 months) years old. All children were right handed based on parental report. Children were recruited from nursery schools, day-care centers, and elementary schools in New Orleans. The older children (5 and 7 years) were compensated $5 for their cooperation. Participants came from both middle-income and low-income populations and were primarily either African-American or Caucasian. Sixteen 3-year-olds came to the lab; six cooperated, 10 refused, and data from one subject were unusable due to equipment problems. Nine 4-year-olds came to the lab; five completed the experiment, and four either refused to clap or tired before the end of the session. Five 5-year-olds participated in the experiment; data from all participants were usable. Seven 7-year-olds participated, but the data from two children could not be used due to equipment malfunction.

**Materials**

Wrist weights constructed of lead shot sewn inside terry cloth wrist bands were used to manipulate inertial loading of the limbs, and hence, $\Delta \omega$. The masses were chosen to be analogous to wrist weights used in a previous study with adults (Fitzpatrick et al., 1996), but scaled to body mass—0.0075 * body mass for the “light” mass condition and 0.015 * body mass for the “heavy” condition. Table 1 lists a range of mean body masses appropriate for the children participating in the study (Brandt, 1979; Haywood, 1986) as well as the corresponding dimensions of the appropriate wrist weights. Wrist weights were selected on the basis of body mass. Six Styrofoam balls wrapped in reflective tape (3M) were used as joint markers for a video digitizing system (described below) required to analyze the unconstrained clapping of children. One marker was placed on

<table>
<thead>
<tr>
<th>MEAN BODY MASS (kg)</th>
<th>Wrist Weight Dimensions (kg)</th>
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<td>&quot;Light&quot;</td>
<td>&quot;Heavy&quot;</td>
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<tr>
<td>13</td>
<td>0.98</td>
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<tr>
<td>15.25</td>
<td>1.14</td>
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<td>17.25</td>
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<td>19.5</td>
<td>1.46</td>
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<td>21.5</td>
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<td>24.5</td>
<td>1.84</td>
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<td>28</td>
<td>2.10</td>
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each fingertip, wrist, and elbow. These markers become very bright by reflecting light from a source.

Apparatus

A Peak Performance Video Motion Measurement System (Peak Performance Technologies, Englewood, CO) was used to record and digitize the movement trajectories. Two Panasonic D5100 video cameras (frame rate of 60 Hz) with the high-speed shutter set to 1/250 were used to videotape the experimental session; each camera was connected to a Panasonic 7400 VCR. One camera was placed in front of the subject, 1.2 m away, on a tripod approximately 2.3 m high; the other camera was placed at approximately a 90° angle from the first, off to the right-hand side of the subject, 3 m away atop a tripod 1.9 m high. Video floodlights with 250 W bulbs were positioned next to each camera. The two cameras were genlocked to synchronize the two views in time. To further ensure that the video fields of the cameras matched (since the VCRs were not genlocked), a synchronization light was recorded onto each video image. Longitudinal time code was written to audio channel 2 of each VCR using a SMPTE (Society of Motion Picture and Television Engineers) time-code generator. The time code simplifies trial selection and synchronization.

The peak standard calibration frame with eight control points was digitized and used to determine the image space of the video chips in the system. The three-dimensional coordinates of any movement within the image space can then be calculated using the least-squares method to determine the best fit. Three-dimensional coordinate data were obtained from the two two-dimensional views by the Direct Linear Transformation Method (DLT).

A metronome pulse generated on a Macintosh computer specified the frequency of oscillation.

Design and Procedure

Children were tested one at a time, seated on a child-sized chair (on a platform 22 cm high) centered within the view of the video cameras. Children were simply instructed to clap their hands (e.g., “imagine you are at a birthday party or movie”). Children in the three younger groups were told to look at a puppet one of the experimenters was controlling while they were clapping. The children were told that the puppet (a wolf named “Loopy”) would get very happy and excited if they clapped their hands for him. The children were given as little instruction as possible in order to allow them to clap in a natural manner. Although individual styles of clapping are possible (Repp, 1987), clapping style was neither restricted nor analyzed here. Before beginning the experimental trials, the experimenter demonstrated clapping and asked the child to clap with her. No demonstration occurred during the experimental trials. At the start of each trial, the children were asked to begin clapping and continue until instructed to stop. The experimenter attempted to obtain 10 seconds of continuous clapping for each condition.

Five inertial loading ($\Delta$\omega) conditions were created by differentially loading the two wrists. In two conditions, the heavy and light weights were on the left wrist; in two conditions, the light and heavy weights were on the right wrist; in the final condition, neither wrist was weighted. Because the preferred frequency of oscillation was not measured or could not be estimated (as in wrist-pendulum studies), an ordinal index of $\Delta$\omega was employed that captured the relative left-right loadings. Further, $\Delta$\omega > 0 indicates that the right limb is loaded, while $\Delta$\omega < 0 indicates that the left limb is loaded. The inertial loadings and $\Delta$\omega values are provided in Table 2.

Children were asked to clap at one of three tempos—at a self-chosen pace, or in time to a metronome set to .88 Hz or 2.09 Hz. Children in the youngest age group (3-year-olds) did not complete the metronome-paced trials because pilot testing indicated (a) they could not keep the metronome beat, and (b) they would become tired and distracted before the end of the session. All children clapped very quietly and therefore had no difficulty hearing the metronome during the metronome-paced trials.

For the 3-year-olds, the experimental design consisted simply of the five $\Delta$\omega condi-

<table>
<thead>
<tr>
<th>$\Delta$\omega INDEX FOR FIVE INERTIAL LOADINGS OF THE LIMBS</th>
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<tr>
<td>Left Limb</td>
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<td>&quot;Heavy&quot;</td>
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tions at a self-chosen pace (a total of 5 experimental conditions). The experimental design for the three older groups was a repeated-measures design in which the three frequencies (self-chosen pace, 0.88 Hz, 2.09 Hz) were completely crossed with the five Δω conditions, for a total of 15 experimental conditions. Each condition was given only once. Presentation of trials occurred in blocks, with the self-chosen pace block always occurring first; whether a block of slow metronome trials or a block of fast metronome trials was the second or third block was randomized across subjects. Order of presentation of Δω conditions was randomized within each frequency block, with the exception that the unweighted self-chosen pace trial was always first. This trial was repeated again at the end of the first block to reduce any biasing due to practice. Each session lasted approximately 20–30 min.

Data Reduction

Digitized movement trajectories (i.e., the three-dimensional coordinates of the image space) were obtained post hoc from each videotaped experimental session. The Peak Performance Automatic Data Capture module was used to track contrasting bright markers (with image pixel values greater than a user-defined minimum) against a dark background, using a cubic spline search algorithm. Only the markers on the fingertips and elbows were tracked. The experimenter had to intervene manually whenever the Automatic Module failed to keep the fingertip markers distinct.

The 3-D raw data were filtered using a Butterworth filter with the optimal filtering parameter determined by the Jackson Knee Method (Jackson, 1989). The three-dimensional coordinates were then transformed so that the origin was at the left elbow and the primary angular excursion for each limb was calculated. The primary angle of excursion (α) was defined as the angle formed between two vectors originating at the biceps: A extending to the fingertip, and B extending to an arbitrary fixed point on the body as demonstrated in Figure 2.

\[
\alpha = \arccos \left( \frac{\mathbf{A} \cdot \mathbf{B}}{||\mathbf{A}|| \cdot ||\mathbf{B}||} \right).
\]

In other words, the primary angle represents the angle formed between the forearm segment of the arm and the vertical plane of the body. Thus, a 90° angle indicates the limb is straight out in front of the body; a 0° angle indicates the limb is flush across the body.

The frequency of oscillation of each limb and the ϕ times series of the two limbs were determined using software routines. The time of maximum extension of each limb was calculated using a peak picking algorithm. The frequency of oscillation was calculated using the peak extension times:

\[
f_n = 1 / (\text{time of peak extension}_{n+1} - \text{time of peak extension}_n). \tag{3}
\]

These cycle frequencies were used to calculate the mean frequency of oscillation of each limb for each trial and condition. Coupled frequency of the two-limb system was calculated as the mean of the frequency of oscillation of each limb. The phase angle of each limb (θ_i) was calculated at each sample (60/sec) to get a time series of θ_i. The phase angle of limb i at sample j (θ_ij) was calculated as

\[
θ_{ij} = \arctan \left( \frac{x_{ij}}{Δx_{ij}} \right), \tag{4}
\]

where \(x_{ij}\) is the velocity of limb i at sample j divided by mean trial frequency, and \(Δx_{ij}\) is the position of the time series of limb i at sample j minus the average trial position. ϕ between the right and left limbs was calculated as \(θ_{\text{left}_j} - θ_{\text{right}_j}\). Thus, if the right limb is ahead of the left in its cycle, ϕ will be negative (ϕ < 0); if the left limb is ahead of the right in its cycle, ϕ will be positive (ϕ > 0). In clapping, ϕ should be near 0 rad. That is, when the palms are together, the flexor muscle group of each arm is at peak flexion. The ϕ time series allows an evaluation of the stability of the coordination across the different conditions. This evaluation was accomplished by calculating the mean ϕ and standard deviation of ϕ (SDϕ) for each trial. Note that because the intended ϕ is 0 rad, the mean ϕ is equivalent to phase lag.
Results

Due to the fact that the 3-year-olds were only able to complete self-chosen pace trials, their data will be analyzed in an ANOVA separate from the data for 4-, 5-, and 7-year-olds. This will facilitate drawing conclusions with respect to frequency manipulations. Comparisons between the data of the 3-year-olds and the data of the older children’s self-chosen pace trials will be made as appropriate. Regressions of data across all age groups will be used to evaluate developmental trends. Frequency of oscillation will be evaluated first to determine whether the two hands move at the same frequency, to calculate actual clapping tempos, and to assess accuracy in metronome tracking. Predictions regarding absolute coordination—characteristic changes in relative phase and its variability—will be evaluated next. Finally, predictions regarding the rate of change of relative phase and the distribution of relative phase, indicative of relative coordination, will be assessed.

Frequency of Oscillation

Absolute interlimb coordination assumes that the two limbs oscillate at a common tempo, that is, are frequency locked (von Holst, 1939/1973). In order to confirm that frequency locking between the two hands was achieved, a $4 \times 2 \times 5$ ANOVA was performed with a between-subjects factor of age (3, 4, 5, 7) and within factors of hand and $\Delta \omega$ on the frequency of oscillation of the self-chosen pace only. The lack of a significant age effect, $F(3, 16) = .91$, indicates that children in all four age groups selected similar clapping tempos when instructed to clap in a natural manner ($M = 2.75, 3.05, 2.84$, and $2.69$ Hz for 3-, 4-, 5-, and 7-year-olds, respectively). The lack of a significant effect of hand alone, $F(1, 16) = .25$, suggests that the two limbs were oscillating at the same frequency (right = $2.79$ Hz, left = $2.88$ Hz). A significant hand $\times \Delta \omega$ interaction, $F(4, 64) = 2.95, M_Se = 1.34, p = .03$, however, suggests that the manner in which 1:1 frequency locking was achieved changed under manipulation of $\Delta \omega$ (Fig. 3). That is, when $\Delta \omega \leq 0$ (i.e., when the left limb was loaded), there was a tendency for the left limb to oscillate slightly faster than the right limb; when $\Delta \omega > 0$ (i.e., when the right limb was loaded), the right limb oscillated slightly faster than the left. Tests of simple effects reveal a significant effect of $\Delta \omega$ for the right limb, $F(4, 64) = 6.84, p < .01$, but not the left, suggesting that the right limb speeded up when it was weighted but the left limb tended to oscillate at the same tempo regardless of $\Delta \omega$.

In order to determine (a) whether children are able to clap in time to a metronome and (b) whether frequency locking is achieved when oscillating the limbs in time to a metronome, a $3 \times 2 \times 2 \times 5$ ANOVA with a between factor of age (4, 5, 7) and within factors of hand, metronome frequency (0.88 Hz, 2.09 Hz), and $\Delta \omega$ was performed on the frequency of oscillation of the metronome trials only. Significant effects were found for age, $F(2, 12) = 23.54, M_Se = .94, p < .01$; hand, $F(1, 12) = 4.65, M_Se = .86, p < .05$; metronome frequency, $F(1, 12) = 322.96, M_Se = .38, p < .01$; and $\Delta \omega$.

![Fig. 3.—The change in mean frequency and frequency standard error as a function of $\Delta \omega$ and hand](image-url)
4-year-olds were less accurate than the 5-
year-olds at tracking both the slow and the
faster than the prescribed tempos of .88 Hz
oscillator frequency indicates that participants were suc-
cessful in differentially tracking the slow
and 7-year-olds, respectively) metronomes, with
the difference between groups more pro-
nounced for the fast metronome than the slow.
The significant effect of Δω demonstrated a tendency to oscillate slightly
faster than the prescribed temps of .88 Hz
and 2.09 Hz. The interaction between metronome frequency and age reveals that the
4-year-olds were less accurate than the 5-
and 7-year-olds at tracking both the slow
(1.68 Hz, 1.01 Hz, and 1.12 Hz for the 4-, 5-, and 7-year-olds, respectively) and fast (3.21
Hz, 2.26 Hz, and 2.15 Hz for the 4-, 5-, and 7-year-olds, respectively) metronomes, with
the difference between groups more pro-
nounced for the fast metronome than the slow.

The significant effect of metronome fre-
quency indicates that participants were suc-
cessful in differentially tracking the slow
(1.27 Hz) and fast (2.54 Hz) frequencies, but
demonstrated a tendency to oscillate slightly
faster than the prescribed temps of .88 Hz
and 2.09 Hz. The interaction between metronome frequency and age reveals that the
4-year-olds were less accurate than the 5-
and 7-year-olds at tracking both the slow
(1.68 Hz, 1.01 Hz, and 1.12 Hz for the 4-, 5-, and 7-year-olds, respectively) and fast (3.21
Hz, 2.26 Hz, and 2.15 Hz for the 4-, 5-, and 7-year-olds, respectively) metronomes, with
the difference between groups more pro-
nounced for the fast metronome than the slow.

48) = 4.14, MSe = .22, p < .01. Signifi-
cant interactions were found between age
and metronome frequency, F(2, 12) = 4.13,
MSe = .38, p < .05, and age and Δω, F(8,
48) = 4.14, MSe = .22, p < .01.

Thus, they adopt a strategy of speeding up
as the hands come together and compensate
by slowing down (or stopping) at contact and
as the hands move apart. As seen in Figure
4, this strategy is more prevalent in younger
children than older children and for slow
metronome tracking as opposed to fast met-
ronome tracking.

Evaluation of Absolute Coordination Predictions

Relative phase.—An ANOVA with a
within factor of Δω was performed on mean
φ for each condition for the 3-year-olds. The
effect of Δω was not significant, indicating
that there was not a systematic change in
interlimb phasing under manipulation of
Δω. A 3 × 3 × 5 ANOVA with a between
factor of age (4, 5, 7 years) and within factors
of metronome frequency and Δω resulted in
a significant effect of Δω, F(4, 48) = 5.59,
MSe = .02, p < .01, in support of Prediction
2. Means for the 5 Δω conditions were −0.02,
−0.03, −0.07, and −0.05 rad, respectively.
The effect of Δω indicates that when the
right limb is loaded (Δω > 0), it lags in phase
(mean φ > 0), and when the left limb is
loaded (Δω ≤ 0), it lags in phase (mean φ < 0), in support of coupled oscillator model
Prediction 1 that the unit with the slower
intrinsic frequency should lag behind the
unit with the faster intrinsic frequency. While
we did expect to see the magnitude of the
deviation of φ from 0 rad to increase
with increasing frequency, as stated in Predic-
tion 3, this was not supported by the data
(frequency was not significant in any main
effects or interactions). This may be due in
part to the fact that metronome tracking
turned out to be a challenging task, and as
such was an added source of variability.
Mean φ was calculated for each Δω con-
dition of each participant and regressed on Δω
for each of the four age groups as a means of
exploring developmental changes. The re-
results (Table 3) suggest that the systemic
change in φ under manipulation of Δω is sig-
ificant for the 7-year-olds only. While the
small sample size (N = 5) warrants caution
in interpretation, the 7-year-olds neverthe-
less appear to be the only group to display
the predicted patterning of φ for absolute
coordination.

Variability of φ.—An ANOVA with a
within factor of Δω was performed on SDφ for
the 3-year-old self-chosen pace condi-
tions and did not result in a significant effect
of Δω (p > .05), indicating that overall vari-
ability was rather high but did not change
in a systematic manner under manipulation of
Δω. In other words, Prediction 5 was not
supported for the 3-year-olds. A 3 × 3 × 5
ANOVA as above was performed on SDφ for
the 4-, 5-, and 7-year-olds and resulted in a
significant effect of Δω only, $F(4, 48) = 2.55$, $MS_ω = .06$, $p < .05$. Mean variability for the five Δω conditions was .77, .70, .60, .70, and .71 rad, respectively. This indicates that as Δω deviates from 0 variability increases, and the magnitude of this variability increases with the magnitude of Δω as Prediction 5 states. There was no evidence for the predicted changes in variability as a function of increasing frequency (Prediction 4). Again, this is most likely due to the difficulty children had in tracking the metronome.

Summary of absolute coordination results.—Of the five predictions used to evaluate absolute coordination patterns of the
TABLE 3

<table>
<thead>
<tr>
<th>Age</th>
<th>Intercept</th>
<th>Slope</th>
<th>$r^2$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-year-olds</td>
<td>-.07</td>
<td>.01</td>
<td>.01</td>
<td>.68</td>
</tr>
<tr>
<td>4-year-olds</td>
<td>-.01</td>
<td>.03</td>
<td>.07</td>
<td>.21</td>
</tr>
<tr>
<td>5-year-olds</td>
<td>.02</td>
<td>.00</td>
<td>.00</td>
<td>.54</td>
</tr>
<tr>
<td>7-year-olds</td>
<td>.02</td>
<td>.04</td>
<td>.26</td>
<td>.01</td>
</tr>
</tbody>
</table>

NOTE.—Degrees of freedom are equal to (1, 23) for all regressions.

coupled oscillator dynamic, experimental support was found for four. In particular, the hand with the slower preferred frequency was shown to lag behind the hand with the faster preferred frequency, and both $\phi$ and $SD\phi$ increased with the magnitude of $\Delta \omega$. Neither $\phi$ or $SD\phi$ increased with increasing frequency as expected. This most likely is due to the difficulties children had in tracking the metronome. Regression analyses suggest that support for the model as summarized above was appropriate for the data of the 7-year-olds only. The expected patterning of relative phase was not found in the data of the younger children. Taken together, these results suggest that absolute coordination patterns are not evidenced in clapping before 7 years. The coupled oscillator predictions regarding relative coordination patterns will be evaluated next to determine whether those measures indicate that coupled oscillator dynamics underlie clapping patterns of younger children.

Evaluation of Relative Coordination Predictions

The relative phase standard deviation magnitude (near .7 rad) is rather large compared to those observed in adult clapping (near .16 rad; Fitzpatrick et al., 1996). Such a result suggests that the relative phase performed is not constant throughout a trial, and that the behavioral patterns are less like absolute coordination and more like relative coordination. Consequently, Equation 1's predictions for relative coordination will be evaluated in this section.

Distribution of $\phi$.—The percentage of relative phase values falling within each of nine $\phi$ ranges was calculated for each trial of each participant and was entered into a $4 \times 9$ ANOVA with the between-subjects variable age (3, 4, 5, and 7 years) and within-subjects variable of $\phi$ range (.35, .70, 1.05, 1.40, 1.75, 2.09, 2.44, 2.79, and 3.14 rad). A significant main effect of $\phi$ range, $F(8, 1968) = 1027.72$, $p = .0001$, indicates that although $\phi$ was concentrated close to 0 rad, all phase relations did occur (M = .51, .24, .11, .05, .03, .02, .01, .01, and .02 for the nine $\phi$ ranges, respectively). A significant interaction between age and $\phi$ range, $F(24, 1968) = 5.5$, $p = .0001$, reveals that the distribution of relative phase changed developmentally (Fig. 5). In particular, $\phi < .35$ rad in-

![Fig. 5](image-url)
creased while the percentage of $\phi$ in all other ranges decreased as age increased. The concentration of $\phi$ near 0 rad supports Prediction 6 that $\phi$ should be concentrated closer to the points of weak attraction (0 rad in the case of an inphase coordination pattern like clapping). Additionally, the developmental trend for the concentration of $\phi$ nearer to 0 rad to increase suggests that the attractor at 0 is increasing in strength and, developmentally, clapping patterns are becoming more like absolute coordination patterns.

The proportion of the distribution of $\phi$ less than .35 rad was used as an index of the dispersion of $\phi$: As the distribution of $\phi$ moves outside of the stable region (<.35 rad), $\phi$ becomes distributed across phase relations rather dispersed from the attractor at 0. A $3 \times 3 \times 5$ ANOVA with between-subjects variable of age (4, 5, and 7 years) and within variables of frequency and $\Delta \omega$ was performed on the proportion of $\phi$ less than .35 rad. A significant effect of $\Delta \omega$ was obtained, $F(4, 48) = 4.92, MS_e = .02, p < .01$, and frequency approached significance, $F(2, 24) = 2.77, MS_e = .05, p = .08$. As Figure 6 demonstrates, as $\Delta \omega$ deviates from 0, the proportion of $\phi < .35$ rad decreases, with a tendency for the proportion of $\phi < .35$ rad to be greater at slower frequencies. Post-hoc $t$ tests of the frequency effect revealed that only slow and self-chosen are significantly different from each other ($p < .05$). A simple regression of the proportion of $\phi < .35$ rad on age group was significant, $r^2 = .31, F(1, 18) = 8.16, MS_e = .003, p = .01$. A positive slope (.024) suggests that the proportion of $\phi < .35$ rad may increase with age. Again, given the small sample size, interpretation of the regression results is a bit speculative. Overall, these results support model predictions (albeit modestly in the first case) that the distribution of $\phi$ should change with increasing frequency (Prediction 7) and as $\Delta \omega$ deviates from 0 (Prediction 8). A developmental trend for the proportion of $\phi < .35$ to increase again suggests that the oscillatory regime may become stronger developmentally, and hints that a transition from relative coordination in the direction of more strongly coupled absolute coordination may occur.

**Rate of change of $\phi$.**—In order to assess whether a constant phase relation was maintained while clapping, a $3 \times 3 \times 5$ ANOVA with between-subjects variable of age and within variables of frequency and $\Delta \omega$ was performed on the rate of change of $\phi$ ($\phi'$). A significant effect of frequency, $F(2, 24) = 13.32, MS_e = .01$, $p < .01$ indicates that $\phi'$ increases with increasing frequency (.09, .13, and .18 for the .88 Hz [slow], 2.09 Hz [fast], and 2.86 Hz [self-chosen] conditions, respectively) as predicted by the coupled oscillator model (Prediction 9). Post-hoc $t$ tests revealed that $\phi'$ at the slow tempo is significantly different from fast and self-chosen ($p < .01$), but fast and self-chosen are not significantly different from each other ($p > .05$). A significant effect of $\Delta \omega$, $F(4, 48) = 5.08, MS_e = .002, p < .01$, indicates that $\phi'$ increases as $\Delta \omega$ deviates from 0 (.14, .12, .11,
Coordination measures indicate that a coupling parameter and age group as the independent variable resulted in a significant regression, \( r^2 = .48 \), \( F(1, 18) = 16.65, MS_e = .0003, p = .0007 \), with a negative slope (−.01). This suggests (albeit modestly given the small sample) that developmentally \( \phi \) is decreasing. An inspection of mean \( \phi \) confirms this interpretation (\( M = .14, .15, .12, .11 \) for the 3-, 4-, 5-, and 7-year-olds, respectively). In sum, these results support the model predictions that \( \phi \) should increase as attractor strength decreases (increasing frequency, increasing deviation of \( \Delta \omega \) from 0). Additionally, a developmental trend hints at a decrease in \( \phi \), which suggests that strength of the attractor is increasing developmentally and moving in the direction of absolute coordination.

**Summary of relative coordination results.**—Of the five predictions used to evaluate relative coordination patterns of the coupled oscillator dynamic, strong support was found for four, and one prediction was modestly supported. In particular, \( \phi \) increased with increasing frequency, and as \( \Delta \omega \) deviated from 0, \( \phi \) was shown to be distributed across all phase relations with a concentration near 0, and the distribution of \( \phi \) became more dispersed (moved farther away from 0) as \( \Delta \omega \) deviated from 0. While the change in the distribution of \( \phi \) with increasing frequency was modest, it did demonstrate a trend toward increasing dispersion with increasing frequency as expected. Further, the regression analyses revealed several developmental trends—\( \phi \) decreased developmentally, and the distribution of \( \phi \) changed such that the distribution of \( \phi \) near 0 increased while all other phase relations became much less common. Concomitantly, these results suggest that the clapping patterns of children (particularly the younger groups) can be characterized as relative coordination abiding by coupled oscillator dynamics. Additionally, the results suggest that developmentally the coordination patterns are becoming more stable and less variable and begin to more closely approximate absolute coordination around 7 years.

**Discussion**

Generally, both absolute and relative coordination measures indicate that a coupled oscillator regime (Equation 1) is a viable model of the interlimb phasing found in children’s clapping at all stages of development. The clapping patterns of younger children can be characterized as relative coordination and are suggestive of an oscillatory system with weak attractors (i.e., a weakly coupled system) and considerable noise. In the younger children, the clapping patterns displayed more variability and did not demonstrate characteristic changes in relative phasing under manipulation of frequency and inertial imbalance. By about 7 years, however, clapping patterns more closely approximate absolute coordination patterns and are suggestive of a more strongly coupled oscillatory system. These clapping movements were less variable, more stable, and displayed changes in relative phasing characteristic of stable coupled oscillators. Thus, clapping behavior appears to demonstrate a developmental progression from relative coordination to absolute coordination.

Dynamically speaking, such a progression suggests that the strength of the interlimb coupling is increasing developmentally. One way to model this change is to assume that age (or more more likely a variable associated with age—one that quantifies skill level, for instance) acts like a control parameter and alters the dynamical landscape, thereby modifying the stability of the interlimb coordination attractors. In particular, changes in age may result in changes of the magnitudes of the coupling processes which bring the limbs into a stable phasing pattern. To estimate the coupling strength of the dynamic, \( \Delta \omega \) was regressed on \( \sin (\phi) \) for each participant. The slope of such regressions is an estimate of the coupling strength of a coupled oscillatory dynamic (Schmidt & Turvey, 1995). Inspection of the coupling estimate means (\( M = 5.94, 6.59, 7.87, \) and 9.54 for the 3-, 4-, 5-, and 7-year olds, respectively; SD = 3.09, 3.79, 3.29, and 3.41, respectively) suggests a modest tendency for interlimb coupling to increase developmentally.

Another modeling alternative to account for the developmental changes that occur in the progression from relative coordination to absolute coordination is to add an additional dynamical term to the coupled oscillator model in Equation 1 that changes its strength with age. Such a developmental dynamic would reconfigure the initial clapping dynamic (without fixed points) to have an attractor state at the to-be-acquired coordination pattern. This is analogous to the modeling strategy adopted by Schöner and col-
leagues (Schöner, 1989; Schöner, Zanone, & Kelso, 1992; Zanone & Kelso, 1992) in modeling the dynamics involved in adult acquisition of a novel bimanual phasing pattern. This developmental dynamic may not only alter the strength of the attractors but also the location of the attractors. Further, such an additional term is likely one that accounts for the intentional aspects of clapping and the fact that the intentional resources needed to maintain coordination in all probability change with age. For example, it is possible that a stable coordination dynamic is assembled initially but cannot be maintained throughout a bout of clapping. This could occur if the intention to maintain the coordination pattern was not constant throughout a trial (i.e., the intention was “turned on and off”). A young child with a weak intentional term may initially concentrate on the clapping task, become distracted by something, and then return his or her attention to the task of clapping. Older children with a stronger intentional term, on the other hand, may assemble the dynamic and not have to actively monitor their intentional goals during the activity. Such an intentional term could have a value of 0 when attention is other-directed and intermediate values scaled to the magnitude of concentration on the task.

A combination of both modeling strategies is probably necessary in which there is an interplay between the intentional dynamic that “sets up” the attractor layout of the movement dynamic and the coupled oscillator movement dynamic itself. For example, initially the intentional dynamic may be weak and the oscillatory dynamic may have weak attractors associated with it. This combination of dynamics could result in the types of relative coordination patterns observed here in younger children. During a transitional period, one could imagine the intentional dynamic becoming stronger but the fixed points of the oscillatory dynamic remaining weak as optimal parameterization of coupling strength is explored. A period of skilled absolute coordination may result from a combination of an autonomous intentional dynamic coupled with an oscillatory dynamic with strong attractors. Such a progression from relative to transitional to absolute coordination may occur a number times as task, environmental, and intentional constraints change.

Given the findings presented here, the developmental course of rhythmic motor ability appears to have a rather protracted time scale. That is, even though infants begin clapping late in the first year and are capable of other forms of auditory-manual coordination, such as reaching to a sounding object (Clifton, Muir, Ashmead, & Clarkson, 1993), stable and highly predictable absolute coordination clapping patterns suggestive of strong interlimb coupling do not appear until well into childhood. This appears to contradict other findings that reveal very tight interlimb coupling in spontaneous movements of infants, for instance (Corbetta & Thelen, 1994; Thelen & Fisher, 1983).

However, a complete account of the development of coordination may reveal a developmental progression from stable absolute coordination to less stable relative coordination (Goldfield, 1995; Thelen & Smith, 1994) back to stable absolute coordination. It seems likely that while initial movements may be tightly coupled, such tight coupling may necessarily weaken as the infant explores new intentional behavioral patterns in producing goal-directed actions (e.g., reaching, walking). As proficiency is gained in producing the goal-directed actions, the coupling likely becomes stronger again. This type of weakening and strengthening of the coupling may indeed be a process that continues throughout childhood as body dimensions, motor competence, perceptual acuity, and task and intentional constraints continually vary. Coming to terms with the relation between rudimentary interlimb coupling (e.g., in spontaneous infant arm and leg movements) and the interlimb coupling involved in more complicated rhythmical behaviors with complex spatial and timing constraints and more explicit intentional goals (e.g., expressive or communicative functions, percussive functions) is important for a more complete dynamical account of the development of coordination.

It seems likely that the variability underlying relative coordination patterns as observed here in clapping may also be related to other variables, for example, explo-

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2 Comparisons between modeling strategies adopted in the learning domain are appropriate given the dynamical system’s proposal that general principles (e.g., change in stability) are responsible for changes in behavior. What distinguishes learning from development is the time scale over which the behavior unfolds (e.g., Saltzman & Munhall, 1992; Thelen, 1989; Zanone & Kelso, 1990); learning proceeds on the order of hours and days, while development unfolds on the order of months and years.
ration of different clapping styles. Transforming the initially rigid, stereotyped claps of very young children into the fluid, effortless applauding style seen in the absolute coordination of adults may require exploring how cupping the hands in different ways, aligning the hands in various positions, or altering the position of the limbs at contact affect the quality and loudness of the sound produced. Other factors may also be important contributors to the achievement of absolute coordination in clapping. One possibility is that children may need to master the coordination of each arm individually before they are able to couple both arms absolutely. Kaye and Marcus (1981), for instance, report that it is easier for babies to shake a toy twice than to clap four times in succession. Developmentally, little is known about the relation between skills that have both single oscillator and coupled oscillator components. Another possibility is that children may need to control not only the temporal but also the spatial aspects of clapping to achieve absolute coordination. For instance, absolute coordination may be more easily accomplished if the hands always collide at the same location than if they collide at different ones during a clapping bout. Although temporal measures were used primarily in the present work, future research might employ a combination of temporal and spatial measures (as well as single and coupled oscillator measures) to understand how absolute coordination develops.

Concluding Remarks

This research has made inroads into extending understanding of the development of coordination dynamics in several ways. First, an explicit, formal model has been applied and tested in examining the development of a complex interlimb rhythmical behavior. In this case, we have demonstrated the applicability of the Haken et al. (1985) coupled oscillator model to clapping of children and have further shown developmental changes in the parameterization of this model. Additionally, even though this behavior manifests a good deal of nonstationarity and high variability within and across young children, we have presented evidence indicating that quantitative dynamical modeling is possible nevertheless. Finally, the approach we have used suggests that clapping goes through a period of relative coordination before absolute coordination is achieved. These results suggest that developing systems can be understood in dynamical terms utilizing general principles of stability and change. Extension of these methods to the study of infant coordination patterns and other skills with rhythmical components should lead to more general insights into how motor coordination develops.

References


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