Rhythmic coordination dynamics in children with and without a developmental coordination disorder
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Bimanual rhythmic tapping in children:
Age related and practice induced changes in coordination stability

Abstract
Age related and practice induced changes in the intrinsic dynamics of bimanual rhythmic coordination in school age children are examined following a dynamic pattern approach. Fifty-two children aged 6, 8, and 10 years old performed inphase and antiphase coordination tasks (finger tapping). Coordination stability was measured by (i) the variability of the relative phase, and (ii) the critical frequency (i.e., loss of stability when frequency is increased). An age related decrease in relative phase variability, and an increase in critical frequency indicated that bimanual rhythmic coordination stability increased as a function of age. Ten children of the same group (6, and 8 years old) were trained on the antiphase tapping task at a subcritical frequency level. Training resulted in an increase in critical frequency towards an age-related maximum, indicating that the intrinsic dynamics were constrained by an age related physical limitation.

3.1 Introduction
In the course of development, children learn to perform many different rhythmic coordinated actions, such as walking, hopping, bicycling, bouncing a ball, skipping, tapping, clapping, dancing, and playing music. The emergence of an adequate timing control mechanism is essential to the development and learning of such rhythmic coordinated actions (Parker, 1992; Thelen, 1991). A lack of timing control may result, for instance, in poor rhythmic movement skills as have been found in children with clumsy behavior (Geuze & Kalverboer, 1987; Williams, Woollacott, & Ivry, 1992). Frequently used tasks to study the development of timing control in children are unimanual rhythmic limb movements (Smoll, 1974; Thomas & Moon, 1976), or unimanual rhythmic finger tapping (Knights & Moule, 1967; Wolff & Hurwitz, 1976; Peters & Durding, 1978; Sugden, 1980; Roth, Wündrich, & Pögelt, 1985; Fagard, 1987; Carlier et al., 1993; Greene & Williams, 1993). These studies have suggested that tapping speed, which was
found to increase with age, and intertap interval (ITI) variability, which was found to
decrease with age, are relevant indicators of the development of timing control in children
aged 5 to 12 years. A problem with most of these studies is that they lack an explicit
theoretical model of how rhythmic movements are organized and how they develop. In an
information processing perspective on movement control, such developmental changes in
tapping speed and ITI-variability may be associated with an increase in the information
processing capacity of the central nervous system (CNS) (cf. Thomas, 1980). In one of the
studies mentioned above (Greene and Williams, 1993) an explicit timing control model was
applied to investigate whether the decrease of ITI-variability with age was due more to
‘central’ or ‘peripheral’ processes in the CNS, using Wing-Kristofferson’s (WK)
timekeeper model (Wing & Kristofferson, 1973). The timekeeper model divides the
temporal variance into a central clock or timekeeper component and a motor
implementation component. Greene and Williams (1993) found that the decrease of ITI-
variability was due mainly to the timekeeper component, leading them to the conclusion
that the decrease of ITI-variability with age resulted from an improvement in timekeeper
processes rather than from an improvement in motor execution processes.

The aim of the present study is to examine developmental changes in the relative timing
of bimanual rhythmic finger tapping in children. Not the ITI-variability of individual
limbs, but the relative phase between the limbs is the variable of interest. Although it is
widely accepted that interlimb coordination plays an important role in the performance of
many rhythmic skills (Turvey, 1990), not much is known about children’s development of
relative phase in rhythmic interlimb coordination, or its role in clumsy behavior (see
chapter 5). Two studies have examined developmental changes in interlimb coordination of
the lower limbs (Roberton & Halverton, 1988; Whitall, 1989). Whitall (1989) found a
gradual decrease in relative phase variability in running and galloping with age in 4 to 9
year old children. Roberton and Halverton (1988) found a stage-like increase with age in
the entrainment of the ‘swing’ limb to the ‘support’ limb in hopping in children between 3
to 15 years of age. Developmental studies on bimanual rhythmic coordination in childhood,
however, are largely lacking.

With respect to different perspectives on timing control in rhythmic actions, we can
make a rough distinction between the timekeeper perspective in which the timing is
regulated by an internal timekeeper or central clock, and the dynamic systems perspective
in which timing emerges from the intrinsic dynamics of the system. The WK timekeeper
model has been applied mainly to children’s unimanual rhythm production (e.g., Greene &
Williams, 1993; Williams, Woollacott, & Ivry, 1992). For bimanual rhythmic coordinated
movements, modified versions of the WK model for unimanual rhythmic tapping have
proposed that the relative timing between the hands is regulated by a single timekeeper with dependent motor delays for left and right hand, or by two timekeepers that are coupled at a central level of organization (e.g., Wing, 1982; Vorberg & Hambuch, 1984; Stucchi & Viviani, 1993). Alternatively, it has been suggested that bimanual coordinated finger tapping is controlled by two coupled neural oscillator networks (Yamanishi et al., 1980). Empirically, some dynamic characteristics of coupled oscillator systems were found. Among the many possible relative phase (\(\phi\)) relations between the oscillating limbs, only the coordination patterns at \(\phi = 0\) (inphase) and \(\phi = \pm \pi\) (antiphase) appeared to be stable attractors (Yamanishi, Kawato, & Suzuki, 1980; Kelso, 1981, 1984). Furthermore, spontaneous transitions from antiphase to inphase coordination were observed when the movement frequency was increased. It was suggested that such stable coordination patterns arise from the temporary assembly of neuromuscular components in a task-specific coordinative structure, or, following a synergetic or dynamic pattern approach, that the patterns and their switching behavior emerge in a self-organized fashion from cooperative coupling between the individual components (Kelso & Schöner, 1988).

There are good theoretical reasons for approaching timing control from a dynamic pattern perspective. Firstly, from a timekeeper perspective, timing is regulated a priori by a central timekeeper (i.e., a motor program), while in a dynamic pattern perspective timing is emergent property of the system itself. As such, dynamic models provide a more parsimonious solution with respect to the control of redundant degrees of freedom in coordinated actions. Secondly, dynamic models account for inherent stability characteristics of biological coordination systems, such as the resistance to external perturbations, and loss of stability in transitions from one stable coordination pattern to another. Timekeeper models do not account for such inherent stability properties. The timekeeper perspective, therefore, focuses mainly on the maintenance of timing invariance, whereas the dynamic pattern perspective focuses on maintenance (i.e., stability), breakdown (i.e., loss of stability), and the emergence of new stable coordination patterns (Zanone & Kelso, 1991).

In the present study, we will study developmental changes in children’s bimanual rhythmic coordination patterns from a dynamic perspective, focusing on both pattern stability and the loss thereof.

Bimanual rhythmic coordination dynamics
Kelso’s studies (1981, 1984) demonstrated that the relative phase \(\phi\) between the rhythmically moving limbs captures the stable states of the coordination system at \(\phi = 0\) (inphase), and \(\phi = \pm \pi\) (antiphase), and that a transition from antiphase to inphase
coordination occurs when movement frequency is increased. In the sense of synergetics (Haken, 1978), the relative phase is a relevant order parameter or collective variable, and frequency is a control parameter. Theoretical (Haken, Kelso, & Bunz, 1985; Schöner, Haken, & Kelso, 1986) and empirical studies (Kelso, Scholz, & Schöner, 1986; Scholz, Kelso, & Schöner, 1987) have shown that the observed transition from antiphase to inphase is caused by a loss of stability (as indicated, for instance, by critical fluctuations of the relative phase) due to an instability in the relative phase dynamics. Haken, Kelso and Bunz (1985) (hereinafter HKB) modeled these dynamics, using a potential function $V(N)$ to express the rate of change of the relative phase $N$

\[
\frac{dV(N)}{dt} = \frac{d\phi}{dt} = a + \sqrt{Q} \xi
\]

where $V(\phi) = -a \cos \phi - b \cos 2\phi$, and $\sqrt{Q} \xi$ is a stochastic force of strength $Q$ that accounts for observed fluctuations of the collective variable arising from random influences of the underlying subsystems (Schöner, Haken, & Kelso, 1986). Methodologically, fluctuations are a measure of stability, and the magnitude of these fluctuations can be measured by the standard deviation (SD) of the relative phase $\phi$. $a$ and $b$ are coupling constants. The ratio $b/a$ is inversely related to frequency. The attractor strength of the stable coordination modes at $\phi = 0$, and $\phi = \pm \pi$ decreases as $b/a$ is scaled from 1 to 0 (Figure 3.1). At a critical ratio $|b/a| = 0.25$ (i.e., the critical frequency) the attractor at $\phi = \pm \pi$ disappears. The critical frequency represents the frequency where loss of stability occurs. In the present study we used variability of the relative phase SD$\phi$ and critical frequency ($f_{\text{critical}}$) to measure the (loss of) stability of bimanual coordination patterns.

Development and learning of coordination dynamics

From a dynamic pattern perspective, the development and learning of movement coordination involves the assembly of subsystems into functional task-specific action systems, and the modification (i.e., parametrization) of the initial intrinsic dynamics in the direction of optimal stability (Smith & Thelen, 1993; Schmidt et al., 1992). It has been suggested that the intrinsic dynamics are ‘channeled’ by physical properties of the body (e.g., biomechanical, neuromuscular-skeletal) and by informational constraints (e.g., task,
Development of Bimanual Rhythmic Coordination

**Figure 3.1.** In the potential $V(\phi) = -a \cos \phi - b \cos 2\phi$, the dynamical “landscape” or “attractor lay-out” of $\phi$ changes as a function of the coupling ratio $b/a$. Black balls represent stable points, and white balls represent unstable points in the potential (adapted from Haken, Kelso, & Bunz, 1985).

On the time scale of learning, the relation between information and coordination dynamics was explicitly addressed by Schöner, Zanone, and Kelso (1992). They defined learning as the modification of the intrinsic dynamics in the direction of a ‘to-be-learned’ pattern, which is specified by behavioral information (i.e., perceptual, learned, intentional, memorized). Information in this context is meaningful and specific only to the extent that it contributes to the collective variable dynamics. Competition between behavioral information and intrinsic dynamics results in a less stable intrinsic pattern and a more stable ‘to-be-learned’ pattern. This was shown in an experiment where subjects had to learn a 90° out-of-phase pattern, which resulted in a stability increase of the $\phi = \frac{1}{2} \pi$ attractor, and a concurrent decrease of stability of the $\phi = \pi$ attractor (Zanone & Kelso, 1992).

Cooperative interaction between behavioral information and intrinsic dynamics will enhance the stability of the intrinsic pattern. The present study investigates whether the intrinsic dynamics of school age children can be modified in the direction of increasing stability by training an intrinsically stable pattern. To understand the role of development, we will focus on gradual changes in children’s coordination stability of intrinsic patterns as a function of age. It should be noted that, from a dynamic perspective, the development and learning of timing control in rhythmic coordinated actions result from changes in intrinsic coordination dynamics, as influenced by physical constraints of the body and behavioral informational (i.e., learning history), rather than being imposed on by changes in some central clock device (Thelen, 1991).
Stability as a function of development and learning

According to the HKB-model, the degree of concavity \( \frac{d^2 V(\phi)}{d\phi^2} \) of the potential wells of the potential function \( V(\phi) = -a \cos \phi - b \cos 2\phi \) decreases as the ratio \( b/a \) decreases (Figure 3.1). This means that \( \frac{d^2 V(\phi)}{d\phi^2} \) determines the attractor strength or stability of the attractor modes at \( \phi = 0 \) and \( \phi = \pm \pi \) (cf. Schmidt et al., 1992; Kelso, Ding, & Schöner, 1994). If the stochastic force strength \( Q \) remains constant, \( \frac{d^2 V(\phi)}{d\phi^2} \) completely determines the magnitude of relative phase fluctuations. An increase in \( \frac{d^2 V(\phi)}{d\phi^2} \) results in a decrease in relative phase fluctuations (Figure 3.2). Note, however, that a decrease in \( Q \) may have the same effect. We assume that an increase in the stability of inphase and antiphase patterns on the time scale of development and learning reflects an increase of \( \frac{d^2 V(\phi)}{d\phi^2} \) and the ratio \( b/a \). If, for example, behavioral information \( c \) is acting on the intrinsic dynamics in a cooperative way, then the potential function \( V(\phi) \) will be modified following \( V(\phi) = -a \cos \phi - (b + c) \cos 2\phi \) (cf. Schöner, Zanone, & Kelso, 1992). For \( b' = b + c \), the ratio \( b'/a \) and the degree of concavity \( \frac{d^2 V(\phi)}{d\phi^2} \) will increase. Hence, the intrinsic pattern will become more stable. For the present study, this leads to the following predictions with regard to changes in stability as a function of development and learning: (1) the variability of the relative phase will decrease; and (2) the critical frequency will
increase, because the control parameter has to be scaled over a greater range to reach the critical value of the ratio $b'/a$. Furthermore, we expect critical frequency and variability of the relative phase, being signatures of the same underlying dynamics, to correlate highly.

To summarize, the aim of this study is to investigate changes in the stability of intrinsic bimanual rhythmic coordination patterns (i.e., inphase, antiphase) in school age children as a function of both development and learning (i.e., training). We will test stability and the loss thereof by measuring the variability of the relative phase $SD\phi$ and the critical frequency $f_{critical}$, respectively. We hypothesize that $SD\phi$ decreases and $f_{critical}$ increases as a function of age and training. To test these hypotheses, a cross-sectional developmental study and a training study were carried out. Since left- and right-handed subjects may differ in rhythmic motor performance (Peters, 1987), the role of handedness on children’s coordination stability was included in this study.

### 3.2 Method

**Subjects**

Fifty-two children of 6, 8, and 10 years of age from two regular elementary schools participated in the developmental study. Subject characteristics are presented in Table 3.1. Because experience in tasks similar to that of rhythmic coordinated tapping may positively influence task performance in our experiments, children who had been learning to play piano, keyboard or drums for more than one year were labeled ‘rhythmic experienced’. Five 6-year-old children, and five 8-year-olds without ‘rhythmic experience’ were randomly selected to participate in the training study, which was carried out two months after the developmental study.

**Table 3.1** Subject characteristics.

<table>
<thead>
<tr>
<th></th>
<th>Developmental study</th>
<th>Training study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>group 1</td>
<td>group 2</td>
</tr>
<tr>
<td>N</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Age (years; months)</td>
<td>6; 7</td>
<td>8; 9</td>
</tr>
<tr>
<td>Sex (boys / girls)</td>
<td>7 / 8</td>
<td>7 / 9</td>
</tr>
<tr>
<td>Handedness (R / L)</td>
<td>2 / 3</td>
<td>14 / 2</td>
</tr>
<tr>
<td>Rhythmic experience</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>
Apparatus
Two touch-sensitive buttons (diameter 1.5 cm; force-threshold 0.013 N) were used to register the tap-events of the index finger of left and right hand. The buttons were embedded in two boxes (20 x 40 x 6 cm) with tilted surfaces, which provided support for forearms and hands. Tap-events were recorded on a PC (accuracy 1 ms) when the threshold was exceeded. Tapping was paced by beeps from the PC (duration 50 ms, pitch 1000 Hz).

Procedure
Subjects were instructed to tap rhythmic coordination patterns on the buttons with their index fingers, while their hands remained lying on the box surface. Tasks were paced in such a way that each beep corresponded to one tap of the index finger of the preferred hand. We defined the preferred hand as the hand that was used for writing.

Developmental study. Subjects were asked to tap with their index fingers in two different coordination modes: (i) inphase, i.e., tap synchronously with both fingers; (ii) antiphase, i.e., tap 180° out-of-phase. These tasks were performed under two pacing conditions: (1) a constant frequency condition at 1.5 Hz (30 cycles; duration 20 seconds); and (2) a scaled frequency condition, in which the frequency was set at 1.5 Hz for the first 12 stimuli, then gradually increased by 0.05 Hz per stimulus, and finally remained constant at the maximum frequency for the last four stimuli. The scaled frequency range was individually matched. First, subjects were asked to tap in inphase coordination as fast as possible for 10 seconds. The mean maximum frequency $f_{\text{max}}$ in this 10 second-task was used to set the upper limit for the scaled frequency range. The purpose was to limit the trial duration to avoid attentional or physical fatigue effects as much as possible. The scaled frequency range was then chosen from the following ranges: 1.0 - 2.4 Hz; 1.5 - 2.8 Hz; 1.5 - 3.2 Hz; 1.5 - 3.6 Hz; 2.0 - 4.0 Hz; 2.0 - 4.4 Hz. In the constant frequency condition, 1 practice trial and 1 experimental trial were given for each coordination mode. In the scaled frequency condition, 2 practice trials and 3 experimental trials were given. If a subject could not perform the task at 1.5 Hz, then the frequency was decreased to 1.0 Hz. Subjects were instructed not to return to the initial pattern if they had noticed that the pattern had changed. It sometimes happened that subjects did not increase their rate of tapping sufficiently to induce a loss of stability of antiphase coordination. If subjects lost the
Development of Bimanual Rhythmic Coordination

The coordination between a rhythmically moving limb and periodic perceptual events is in itself an interesting phenomenon that has been studied in a developmental context, using the relative phase as a collective variable (see chapter 4).

synchronization with the pacing signal and were too slow, they were verbally encouraged by the experimenter to further increase their tapping rate. If no loss of stability was observed the trial was repeated.

Training study. Subjects were given eight training sessions (two 20-minute sessions a day) on the antiphase pattern within one week. In each session they performed eight antiphase trials (trial duration 30 seconds) at a submaximal frequency-level, i.e., 0.5 Hz below the \( f_{\text{critical}} \), which was determined in a pretest. In this pretest, and after each training session, \( \Delta f \phi \) (one experimental trial) and \( f_{\text{critical}} \) (two experimental trials) were measured using the same method as in the developmental study. At the 3rd, 5th, and 7th training session the submaximal frequency level was increased by 0.2 Hz.

Data reduction

Discrete estimates of the relative phase between the ‘preferred’ (\( P \)) and ‘non-preferred’ (\( N \)) index finger were calculated from the times of the successive tap-events (\( t_i \)) following

\[
\phi_i = (\frac{t_i^N - t_i^P}{t_i^P - t_i^P}) \times 360.
\]

In the constant condition tasks, three dependent measures were then calculated over the last twenty tap cycles: (1) the mean relative phase (\( \phi \)); (2) the variability of the relative phase (\( \Delta \phi \)); and (3) the absolute error or deviation of the relative phase (\( AE \phi \)) from the intended inphase (\( AE \phi = \phi = 0^\circ \)), or intended antiphase mode (\( AE \phi = \phi = 180^\circ \)).

In the scaled frequency task, a moving average of \( \Delta f \phi \), based on four successive relative phase points, was calculated for each tap-cycle. Loss of antiphase stability (i.e., critical fluctuations of \( \phi \)) was determined by detecting large and sudden enhancements of \( \Delta f \phi \) in the produced taps (cf. Kelso, Scholz, & Schöner, 1986). We defined \( f_{critical} \) as the average frequency of the four taps of the index finger of the preferred hand just before the first distinct enhancement of \( \Delta f \phi \) occurred.

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1 The coordination between a rhythmically moving limb and periodic perceptual events is in itself an interesting phenomenon that has been studied in a developmental context, using the relative phase as a collective variable (see chapter 4).
3.3 Results

3.3.1 Developmental study

Relative phase
Age related changes for the average relative phase, the relative phase variability, and the absolute deviation of the relative phase from the intended phase are presented in Table 3.2.

**Table 3.2.** Age related differences in average relative phase φ, the absolute deviation of the relative phase from the intended phase AEφ, and the relative phase variability SDφ (in degrees).

<table>
<thead>
<tr>
<th>Age</th>
<th>Inphase</th>
<th>Antiphas</th>
<th>Inphase</th>
<th>Antiphas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>φ</td>
<td>AEφ</td>
<td>SDφ</td>
<td>φ</td>
</tr>
<tr>
<td>6</td>
<td>-5.8</td>
<td>8.9</td>
<td>16.1</td>
<td>174.7</td>
</tr>
<tr>
<td></td>
<td>(8.8)</td>
<td>(5.5)</td>
<td>(4.7)</td>
<td>(14.5)</td>
</tr>
<tr>
<td>8</td>
<td>-4.2</td>
<td>6.1</td>
<td>10.5</td>
<td>175.4</td>
</tr>
<tr>
<td></td>
<td>(6.9)</td>
<td>(5.3)</td>
<td>(2.2)</td>
<td>(8.4)</td>
</tr>
<tr>
<td>10</td>
<td>-2.9</td>
<td>5.8</td>
<td>8.2</td>
<td>182.1</td>
</tr>
<tr>
<td></td>
<td>(6.5)</td>
<td>(4.1)</td>
<td>(1.7)</td>
<td>(10.3)</td>
</tr>
</tbody>
</table>

Note. Within-group standard deviation between brackets.

A 3 Age x 2 Gender x 2 Handedness ANOVA was applied. A significant effect of age was found on SDφ for inphase, $F(2,49) = 28.54$, $p < .001$, and antiphase coordination, $F(2,49) = 9.76$, $p < .001$, showing that SDφ decreased with age. Tukey HSD comparisons revealed that 6- and 8-year-old children differed significantly ($p < .05$), while 8- and 10-year-old children did not. No significant effect of age was found on AEφ. No significant effects for gender and handedness or any interaction effect were found. A paired T-test showed that the two phase modes (antiphase, inphase) differed significantly for SDφ, $T(51) = 10.47$, $p < .001$, but not for AEφ, indicating that inphase tapping was more stable than antiphase tapping, but not more precise with respect to the deviation from the intended relative phase.
Critical frequency
In the scaled frequency task, transitions from antiphase to inphase occurred when subjects were prepared in antiphase mode. In a number of trials, subjects typically decreased their movement frequency immediately after the antiphase pattern switched to inphase, and returned to the antiphase pattern to comply with the initial task instruction. They then noticed that they were tapping too slowly and increased frequency again, often resulting in a second phase switch. In such trials we used the first loss of antiphase stability to determine the critical frequency.
Table 3.3. Age related differences in maximum frequency, and critical frequency.

<table>
<thead>
<tr>
<th>Age</th>
<th>Inphase  f \text{max} (Hz)</th>
<th>Antiphase  f \text{critical} (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.04 (.32)</td>
<td>2.46 (.37)</td>
</tr>
<tr>
<td>8</td>
<td>3.54 (.46)</td>
<td>2.81 (.27)</td>
</tr>
<tr>
<td>10</td>
<td>3.90 (.41)</td>
<td>2.98 (.40)</td>
</tr>
</tbody>
</table>

Note. Within-group standard deviation between brackets.

Table 3.3 shows age related changes for the maximum frequency \( f_{\text{max}} \) (inphase task), and critical frequency \( f_{\text{critical}} \) (antiphase task). A 3 Age x 2 Gender x 2 Handedness ANOVA was applied. Significance for age was found on \( f_{\text{max}}, F(2,49) = 15.50, p < .001 \), and on \( f_{\text{critical}}, F(2,49) = 8.25, p < .001 \), showing an increase of the inphase and antiphase stability range with age. Tukey HSD comparisons showed that the 6- and 8-year-old children differed significantly \( (p < .05) \), while 8- and 10-year-old children did not. No significant effects were found for gender and handedness.

A Pearson’s correlation analysis, applied over all subjects \( (N = 52) \), revealed that \( f_{\text{critical}} \) was significantly correlated with SD\( \Phi \), both in the antiphase task \( (r_p = -.521, p < .001) \), and in the inphase task \( (r_p = -.504, p < .001) \), showing that a high critical frequency corresponded with a low relative phase variability.

Rhythm ‘experience’

Eight children (two 8-year-olds, and six 10-year-olds) were ‘experienced’ piano or keyboard players having followed lessons for more than one year. In comparison with the mean age-group scores (8-year-olds: \( f_{\text{critical}} = 2.81, \text{SD}\Phi = 17.6 \); 10-year-olds: \( f_{\text{critical}} = 2.98, \text{SD}\Phi = 15.4 \)), the scores of the ‘rhythmic experienced’ children were above the age related average for critical frequency, and below the average for relative phase variability (8-year-olds: \( f_{\text{critical}} = 3.16, \text{SD}\Phi = 11.6 \); 10-year-olds: \( f_{\text{critical}} = 3.08, \text{SD}\Phi = 14.3 \)), indicating that their coordination patterns were more stable. Because the number of ‘experienced’ children was rather small this was not tested statistically.
In sum, significant changes in $f_{\text{critical}}$ and $\text{SD } \varphi$ indicate that the stability of the performed patterns increased with age, especially between 6 and 8 years of age, while non-significant changes of $\text{AE } \varphi$ indicate that older children did not perform the patterns more accurately with respect to the intended relative phase.

### 3.3.2 Training study

Relative phase

The effect of training on $\text{AE } \varphi$, and $\text{SD } \varphi$ was evaluated using a 2 Age x 9 Session one-way ANOVA with a polynomial trend analysis. For session a significant linear trend was found on $\text{SD } \varphi$, $F(1,8) = 8.15; p < .05$, showing that training resulted in a decrease of $\text{SD } \varphi$ (Figure 3.3). However, this significant effect seemed to be caused mainly by two subjects who showed a distinct decrease of $\text{SD } \varphi$, while in the other eight subjects the decrease of $\text{SD } \varphi$ was rather small. A significant effect on $\text{SD } \varphi$ was also found for age, $F(1,8) = 15.17; p < .01$, revealing that the relative phase variability was smaller in the 8 year old group than in the 6 year old group. The relative phase variability curves of both age-groups showed rather large fluctuations. These fluctuations were also observed in the individual curves. No significant effects were found on $\text{AE } \varphi$. 

**Figure 3.3.** Polynomial trends in the relative phase variability (left panel), and critical frequency (right panel) as a function of training.
Critical frequency
A 2 Age x 9 Session one-way ANOVA with a polynomial trend analysis was applied on $f_{\text{critical}}$. A significant quadratic trend was found for session, $F(1,8) = 21.54$, $p < .01$, revealing an increase in $f_{\text{critical}}$ as a function of training (Figure 3.3). Furthermore, this quadratic trend shows that after 5 or 6 training sessions the critical frequency curve reached a level where little further progress was made. No significant effect was found for age. The two groups showed only small differences at the beginning of the training period. A significant interaction effect between age and session, $F(1,8) = 6.34$, $p < .05$, indicated that $f_{\text{critical}}$ increased more in the 8-year-olds than in the 6-year-olds. A Pearson’s correlation analysis, applied over all sessions and subjects ($N = 90$), showed that $f_{\text{critical}}$ and $SD\phi$ were significantly but not highly correlated ($r_p = -.373$, $p < .001$). Applying the same analysis over all sessions ($N = 9$) for every individual subject did not show significant correlations between $f_{\text{critical}}$ and $SD\phi$ for any of the subjects.

In short, training of antiphase coordination at a subcritical frequency level resulted in an increase in the frequency range in which the antiphase pattern remained stable, and a decrease in relative phase variability.

3.3.3 Comparison of developmental and training effects
A comparison of developmental and training effects on $f_{\text{critical}}$ and $SD\phi$ showed that the effect of training on $f_{\text{critical}}$ was much larger than the effect of development (Figure 3.4). For instance, antiphase training of the 6-year-olds improved their $f_{\text{critical}}$ up to the developmental level of the 10-year-olds, while the 8-year-olds clearly exceeded this level. In the group of 8-year-olds, a similar effect was observed on $SD\phi$. The $SD\phi$ level of the 8-year-olds after training was higher than the developmental level of the 10-year-olds (Figure 3.4). In the group of 6-year-olds, the training effect on $SD\phi$ was much smaller than the developmental effect. It should be noted, though, that the $SD\phi$ level before training was already much higher than the $SD\phi$ level in the developmental study.

3.4. Discussion
The purpose of this study was to investigate age related and practice induced changes in the intrinsic dynamics of bimanual rhythmic coordination patterns in children. Our main hypotheses were confirmed. Relative phase variability decreased and critical frequency
increased as a function of both age and training. These findings suggests that the
development and learning of timing control of rhythmic coordinated actions result from changes in intrinsic dynamics, rather than being the consequence of changes in some central timekeeper device (Greene & Williams, 1993). Such an interpretation is in line with other developmental (e.g., Whitall, 1989) and learning studies (e.g., Zanone & Kelso, 1992) on interlimb coordination.

Findings are in accord with the HKB model. The developmental increase in critical frequency and decrease in relative phase variability indicates that, at the level of relative phase dynamics, the ratio $b/a$ and the degree of concavity $d^2V(\phi)/d\phi^2$ of the potential $V(\phi)$ have increased. At the level of subsystems, this stability increase is due to an increase in the coupling strength between the coupled oscillators (i.e., the moving fingers). The decrease in relative phase variability, however, may also be due to a decrease in the force strength $Q$, that represents random fluctuations at the level of the individual oscillators (Figure 3.2). If we assume, for example, that the ITI-variability in unimanual tapping is related to the force strength $Q$ in the relative phase dynamics, then a decrease in ITI-variability with age, as reported in several developmental studies (Wolff & Hurwitz, 1976; Roth, Wündrich, & Pögelt, 1985; Fagard, 1987; Carlier, Dumont, & Beau, 1993; Greene & Williams, 1993), indeed suggests that $Q$ might have decreased during childhood development. Hence, the decrease in relative phase variability might be a combined effect of an increase in coupling strength and a reduction in the force strength $Q$. It should be

**Figure 3.4.** Comparison of developmental and training effects on the relative phase variability (left panel), and the critical frequency (right panel).
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noted, however, that the effect of ITI-variability on the variability of the relative phase has not yet been investigated systematically. The increase in critical frequency in the training study is due mainly to an increase in coupling strength. Such a practice induced increase in coupling strength has also been found in bimanual rhythmic coordination in adults (e.g., Schmidt et al., 1992; Peper, 1995). At the relatively short time scale of days, any contribution of Q to this increase in critical frequency is probably rather small.

Although relative phase variability and critical frequency were significantly correlated in both experiments, the correlation in the training study was rather low. Within-subject correlations of $\text{SD}\phi$ and $f_{\text{critical}}$ were also low and did not reach significance in any of the subjects. This is not in accord with the HKB model, which would predict a simultaneous decrease in $\text{SD}\phi$ and increase in $f_{\text{critical}}$ as a result of training. This was observed only in two subjects. In the other subjects, between-session variability and a small decrease in $\text{SD}\phi$ throughout the training sessions were responsible for the low within-subject correlations. We do not have an explanation for this, but it could be that training the antiphase pattern at a subcritical frequency level only weakly affected the relative phase variability, as the latter was measured at a much lower frequency level (i.e., 1.5 Hz). In other words, the transfer-effect of the training along the control parameter dimension might have been rather small. Further, more trials for each subject per session might have been necessary to get a more reliable estimation of $\text{SD}\phi$ throughout the training period.

In terms of constraints acting on the intrinsic dynamics, the age-related differences in stability found in the developmental and training study may be a consequence of differences in physical and informational constraints between the age-groups. Physical constraints refer to biomechanical and neuromuscular-skeletal properties of the body, such as finger mass, finger length, muscle strength of finger flexors and extensors, and neural connectivity. Informational constraints refer to behavioral information (e.g., instruction, learning history). An interesting question is, whether the age-related differences in critical frequency are due mainly to physical or informational constraints. Although finger mass, length and muscle strength increase during childhood, these changes are probably not responsible for the observed increase in critical frequency. While they probably influence the dynamics of the individual finger movements, they do not necessarily influence the coupling strength between the fingers. Moreover, an increase in inertial mass leads to a decrease in the eigenfrequency of the oscillations of individual limbs, which would result in a decrease rather than an increase in critical frequency. Is the increase in critical frequency, then, mainly a consequence of differences in behavioral information? Formally, we suggested that adding behavioral information to the intrinsic dynamics in a cooperative way will lead
to an increase in the ratio \( b/a \) to \( b'/a \), corresponding with an increase in critical frequency. The higher performance level of children who were experienced piano or keyboard players provides an example of the effect of behavioral information. Learning to play piano, keyboard or drums involves learning and practicing bimanual inphase and antiphase patterns. This ‘experience’ apparently enhanced the intrinsic pattern stability. The effect of behavioral information was explicitly addressed in the training study in the sense that the information here is embedded in the task-instruction, i.e., the intention to maintain a stable antiphase relation nearby the critical point in the movement frequency range. Indeed, this resulted in an increase in critical frequency. Interestingly, however, we found an age-dependent ceiling effect on critical frequency, suggesting that it is constrained by an age-related physical limitation. In terms of the dynamic model, this means that there is a limitation on further increases in coupling strength. Our interpretation of these findings is that the age-related differences in stability reflect differences in intrinsic dynamics, influenced as they are by both physical and informational constraints. Since the coupling in bimanual coordination has to be mediated by the nervous system, we assume that this physical limitation is related to certain neuromuscular system properties. An interpretation of these findings at the neuronal level would be that cooperation between the intrinsic dynamics and behavioral information will lead to a ‘Hebbian’ reinforcement of synaptic connections in the neural oscillator networks (Zanone & Kelso, 1993) until a maximum age-related critical level of the degree of interaction between neurons (i.e., mean synaptic strength) has been reached (cf. Rose & Siebler, 1995).

Whereas the relative phase variability decreased clearly with age, the effect of training on it is less clear. One reason may be that the task-instruction in the training was aimed at maintaining the antiphase pattern at a subcritical frequency level. Although it was expected that this would also influence the relative phase variability it is obvious that task-information specifying the phase relation between the hands might have had a much greater impact on the relative phase variability.

In conclusion, the present study showed age related and training induced changes in the intrinsic dynamics of bimanual rhythmic coordination in children. Coordination stability was larger in the older children than in the younger children, and increased with training. In the training study, the stability range of the antiphase pattern was modified by behavioral information (i.e., the intention to maintain the antiphase pattern at a subcritical frequency level) towards an age-related biophysical limitation. In the developmental study both physical constraints (e.g., neuromuscular) and behavioral information (e.g., learning
history) might account for the age-related intrinsic differences in stability. The present study provided insight into age-related changes in the intrinsic dynamics of bimanual rhythmic coordination patterns of normal children. In chapter 5, the intrinsic dynamics of such coordination patterns were studied in children with a Developmental Coordination Disorder. Our next step (chapter 4) was an investigation of developmental changes in the coordination dynamics of rhythmic perception-action patterns in normal children.

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