Rhythmic coordination dynamics in children with and without a developmental coordination disorder
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Chapter 4

Stability in unimanual rhythmic tapping ‘on’ and ‘off the beat’: A developmental study

Abstract
Age related differences in unimanual rhythmic perception-action coupling were examined from a dynamic pattern perspective. Thirty-six children, ages 7, 9, and 11 years, attempted to synchronize rhythmic finger taps to the beats of an auditory metronome, either ‘on the beat’ (i.e., inphase coordination), or ‘off the beat’ (i.e., antiphase coordination). Temporal stability of these perception-action patterns was measured by the variability of the relative phase between taps and auditory events, and by the critical frequency, i.e., the frequency at which a loss of stability was observed when the metronome frequency was increased. Age-related differences in temporal stability were found for both relative phase variability and critical frequency. These findings indicate a developmental change in the relative phase dynamics underlying the observed perception-action patterns in the direction of increased temporal stability.

4.1 Introduction

One of the games played by music teachers and their pupils is clapping halfway in time between the beats of a metronome (in music terminology this is called a syncope) while the frequency of the metronome is increased. The child who stays ‘off the beat’ the longest wins (Kelso, 1995). Such a game gives the teacher some information about the rhythmic ability of children. The ability to synchronize or syncopate one’s limb movements to
regularly occurring environmental events plays an important role in movement behavior, such as in playing music, dance, sports, and other daily life skills (Shaffer, 1982). Synchronization is one of the experimental paradigms that has been frequently used to study perceptuomotor timing mechanisms (e.g., Bartlett & Bartlett, 1959; Michon, 1967; Wing & Kristofferson, 1973; Hary & Moore, 1987; Ascherleben & Prinz, 1995). Synchronization tasks have also been applied in the field of child development to gain more insight to the development of rhythmic abilities in children, either by using discrete synchronization (e.g., Thackray, 1972; Smoll, 1975) or tracking tasks (Dunham, Allen, & Winter, 1985; Mounoud et al., 1985; Zanone, 1990). Insight into the timing mechanisms underlying rhythmic abilities could also be helpful in understanding difficulties in the timing of rhythmic movements in children with a developmental coordination disorder (e.g., Geuze & Kalverboer, 1987; Williams, Woollacott, & Ivry, 1992; see also chapter 5 and 6).

Two early studies on the development of rhythmic ability already reported that children’s ability to synchronize their finger taps with auditory stimuli increased between the ages of 6 and 12 years (Sievers, 1932; Williams, 1933). In a series of studies by Smoll (1974a, 1974b, 1975), children aged from 5 to 11 years attempted to synchronize rhythmic single limb movements (i.e., arm swinging) to auditory stimuli (frequency 0.55 Hz). These studies found that temporal accuracy increased linearly with age. Young children had difficulty synchronizing their arm movements to the stimuli. Such synchronization difficulties were also found in another investigation (Thomas & Moon, 1976), in which the same movements were studied in 5-year-old children using different stimulus modalities (i.e., auditory, visual, or auditory-visual stimuli). Children performed best under the auditory condition. No sex differences in synchronization were found (Smoll, 1974a, 1974b, 1975; Thomas & Moon, 1976). Although these studies provided insight into the age-related changes in the ability of children to synchronize, they were empirically motivated rather than theoretically based. No account was given of a timing mechanism underlying this synchronization ability and its developmental change.

The purpose of the present study was to examine age related differences in the synchronization and syncopating abilities of school age children. Syncopating abilities have been studied in adults (Fraisse & Voillaume, 1971; Kelso, Delcolle, & Schöner, 1990), but as far as we know not in children. The theoretical approach we applied in the present study was different from the predominant approach in this area of research, i.e., the temporal information processing approach. This approach postulates that synchronization is basically regulated by two mechanisms. An internal timekeeper mechanism, which produces a reference interval, accounts -a priori- for period-based corrections (i.e., internal resetting of the tap interval for timing of the next tap). A sensory feedback mechanism accounts -a
posteriori - for phase-based corrections to reduce the time gap between the onset of tap and metronome event (i.e., the synchronization error) (Hary & Moore, 1987; Mates, 1994).

We examined synchronization and syncopation from a dynamic pattern perspective. This perspective assumes that stable coordination patterns, including perception-action patterns, arise from cooperative coupling between components of the system (Schöner & Kelso, 1988; Kelso, 1994; Kelso, 1995). Such patterns can be described in terms of the dynamics of a collective variable. A relevant collective variable to describe synchronization and syncopation appears to be the relative phase $N$ between a rhythmically moving limb and periodic events. Both synchronization (i.e., inphase coordination) and syncopation (i.e., antiphase coordination) are coordination patterns that correspond with the stable states (i.e., attractors) of the same underlying relative phase dynamics (Kelso, Delcolle, & Schöner, 1990), which read

$$\frac{d\phi}{dt} = \delta\omega - a\sin\phi - 2b\sin2\phi + \sqrt{Q}\xi$$

(1)

where $\delta\omega$ represents differences in the frequency of the metronome and the moving limb, $a$ and $b$ are constants, and $\sqrt{Q}\xi$ is a stochastic force of strength $Q$ that accounts for fluctuations of $\phi$ (Schöner, Haken, & Kelso, 1986). The ratio $b/a$ is inversely related to movement frequency. For $\delta\omega = 0$ the model is identical to the symmetric HKB model (Haken, Kelso, & Bunz, 1985) for bimanual coordination. The model predicts a number of empirical findings: (i) only two coordination modes are stable, i.e., at $\phi = 0^\circ$ (inphase) and $\phi = 180^\circ$ (antiphase); (ii) phase transitions from antiphase to inphase occur when frequency is increased towards a critical value; (iii) $\phi$ will phase shift for small values of $\delta\omega$; and (iv) $\phi$ will phase drift when $\delta\omega$ increases. Figure 1 shows the attractor landscape for different values of the ratio $b/a$ and $\delta\omega$. Phase drift is not only dependent on the difference in frequency $\delta\omega$, but also on the basic frequency of coordination, the ratio $b/a$. Phase drift will occur more easily at a higher frequency. At the level of the components of the system, the moving limb can be modeled as a nonlinear oscillator that is nonlinearly and unidirectionally coupled to an external oscillator (the metronome).

Signatures of the relative phase dynamics can be found in the stability and loss of stability of coordination patterns, which can be experimentally determined. While a timekeeper perspective focuses on relative timing invariance, a dynamic perspective on synchronization focuses on temporal stability and the loss thereof. In the present study, stability of perception-action patterns were measured by fluctuations of the relative phase (SD$\phi$) during steady state performance, and by the critical frequency, which is the frequency where loss of pattern stability occurs when the metronome frequency is increased. Loss of stability may be characterized by a phase transition from antiphase to
**Figure 4.1.** Attractor landscape of the potential function $V(\phi) = -\phi \delta \omega - a \cos \phi - b \cos 2\phi$ for different values of $b/a$ and $\delta \omega$. Black balls correspond to stable minima of the potential, white balls represent unstable states. As the difference between the movement frequency and the metronome frequency increases ($\delta \omega$ increases), the stable minima of the potential are changed into an unstable point, and synchronization is lost. For antiphase coordination this occurs at a lower frequency ($\delta \omega$ large, $b/a = 1$) than for inphase coordination ($\delta \omega$ large, $b/a = 0.25$). Antiphase patterns will switch to inphase. Inphase patterns will start to phase drift. During such phase drift, short periods of phase attraction (i.e., phase intermittency) may occur nearby the remnant of a previously stable minimum (the white ball in the lower-right panel) (adapted from Kelso, 1995).

Inphase coordination, or by phase drift (i.e., the 1:1 frequency relation between metronome and finger tapping is lost).

A cross-sectional design was applied to examine the ability of school age children to synchronize and syncopate their finger taps with an auditory metronome. The aim was to describe developmental changes in these perception-action patterns and their underlying dynamics. We hypothesized that the relative phase variability would be smaller, and the critical frequency would be higher for older children.
4.2 Method

Subjects
Teachers of grades 4, 6, and 8 at a regular elementary school were asked to select 6 boys and 6 girls at random from three age groups: 7 years, 9 years, and 11 years. The mean ages (years; months) of the three age groups were 7;3, 9;5, and 11;3. After informed consent from their parents, these children participated in the experiment that took place at school.

Apparatus
A touch-sensitive button (diameter 1.5 cm; force-threshold 0.013 N) that was built in the surface of a box (45 x 20 x 6 cm) was used to register finger taps. The box also served as support for underarm and hand. Auditory stimuli were generated by a PC (i.e., computer beeps; duration 50 ms, pitch 600 Hz). Tap events and auditory stimuli were recorded on the PC with an accuracy of one millisecond.

Procedure
Children were seated at a table. The arm and hand rested on the box, and the index finger of the preferred hand was placed on the button. The preferred hand was defined as the hand the children used for writing. Children were asked to tap with the index finger on the button, while their arm, hand, and other fingers remained resting on the box surface throughout a trial. They were instructed to coordinate their finger taps with the computer beeps in two different coordination modes: (i) inphase (tapping ‘on the beat’), i.e., tapping synchronously with the beeps (synchronization); and (ii) antiphase (tapping ‘off the beat’), i.e., tapping halfway in time between two successive beeps (syncopation). Children first performed a series of 18 ‘steady state’ trials, and -after a 5-minute break- another series of 12 ‘scaled frequency’ trials. In both task conditions, trial duration was limited to a maximum of 32 seconds to avoid attentional or muscular fatigue effects.

Steady state trials. The stimulus frequency was constant at 1.0 Hz. Each trial consisted of 30 auditory stimuli. On-the-beat and off-the-beat coordination patterns were demonstrated by the experimenter. Subjects were instructed to perform these patterns as precisely as possible throughout a trial. Subjects performed two practice trials and four experimental trials in each condition. The design was balanced across subjects for phase mode.

Scaled frequency trials. In this condition, the metronome frequency was constant at 1.0 Hz for the first 12 stimuli, and was then gradually increased to 3.0 Hz by 0.05 Hz per
stimulus. The task was presented in a game-like fashion, in which the children had to ‘follow’ the auditory stimuli -either in the on-the-beat or off-the-beat mode- as long as they could. Children performed two practice trials and four experimental trials in each coordination mode. The design was balanced across subjects for phase mode.

Data reduction
Discrete estimates of the relative phase $\phi$ between the tap-events and auditory stimuli were calculated following

$$\phi_i = \frac{t_{TAP_i} - t_{STIM_i}}{t_{STIM_{i+1}} - t_{STIM_i}} \times 360$$

where $t_{STIM_i}$ are the successive onset times of the auditory events, and $t_{TAP_i}$ the onset times of the corresponding tap events. In the ‘steady state’ trials, the relative phase $\phi$, the absolute error or deviation of the relative phase ($\text{AE}_\phi$) from the intended phase ($\phi = 0^\circ$, or $\phi = 180^\circ$), and the variability of the relative phase ($\text{SD}_\phi$) were calculated for the last 18 stimuli. Trials in which the relative phase drifted outside the range of $\pm 90^\circ$ from the intended relative phase for more than four successive taps were defined as unsuccessful and not used for further statistical analysis. In the scaled frequency trials, we determined the critical frequency, which we defined as the metronome frequency at which the relative phase drifted more than $90^\circ$ from the intended relative phase for at least four successive taps.

4.3 Results

Steady state trials
Table 4.1 shows the percentage of successfully performed trials (inphase: $-90^\circ < \phi < 90^\circ$; antiphase: $90^\circ < \phi < 270^\circ$) for the three age groups. There is a clear difference in the percentage of successful trials between the 7-year-old group and the two other groups. Further, a clear difference in the percentage of successful trials between inphase and antiphase coordination mode was found, in particular for the 7-year-old group. Three 7-year-old children were unable to produce a single successful antiphase trial.

Table 4.2 presents age related differences for the average relative phase $\phi$, the absolute deviation from the intended phase $\text{AE}_\phi$, and the relative phase variability $\text{SD}_\phi$. Negative values for $\phi$ in the inphase task indicate that children tapped in advance of the auditory
Table 4.1. Percentage of successfully performed trials.

<table>
<thead>
<tr>
<th>Age</th>
<th>Inphase</th>
<th>Antiphase</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>77%</td>
<td>56%</td>
</tr>
<tr>
<td>9</td>
<td>96%</td>
<td>85%</td>
</tr>
<tr>
<td>11</td>
<td>98%</td>
<td>82%</td>
</tr>
</tbody>
</table>

Table 4.2. Age related differences in average relative phase, the absolute deviation of the relative phase from the intended phase, and the relative phase variability (in degrees).

<table>
<thead>
<tr>
<th>Age</th>
<th>Inphase</th>
<th>Antiphase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>φ</td>
<td>AEφ</td>
</tr>
<tr>
<td>7</td>
<td>-21.1</td>
<td>22.3</td>
</tr>
<tr>
<td></td>
<td>(19.0)</td>
<td>(17.6)</td>
</tr>
<tr>
<td>9</td>
<td>-22.7</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td>(15.6)</td>
<td>(15.6)</td>
</tr>
<tr>
<td>11</td>
<td>-13.7</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>(13.1)</td>
<td>(11.8)</td>
</tr>
</tbody>
</table>

Note. Within-group standard deviation between brackets. A relative phase of 10° is equal to 27.8 ms.

stimuli (on average 38 ms to 63 ms), while in the antiphase task, they were tapping quite accurately at the intended relative phase of φ = 180°. A 3 Age x 2 Gender x 2 Phase ANOVA was applied on AEφ and Sdφ. A significant effect for age was found on Sdφ, F(2,57) = 22.83, p < .001, showing a decrease in relative phase variability with age. Tukey’s HSD comparisons revealed that all three age groups differed significantly from each other. No significant effect was found on AEφ. This shows that older children were less variable, but not more accurate in tapping on and off the beat than younger children. For phase, no significant difference was found on Sdφ, but a significant effect on AEφ, F(2,57) = 9.01, p < .01, revealed that tapping off the beat was more accurate (i.e., closer to the intended relative phase) than tapping on the beat (Table 4.2). No significant effects were found for gender. No significant interactions were found.
Rhythmic Coordination Dynamics in Children

A. RS (7 years) inphase

B. RS (7 years) antiphase

C. BD (11 years) inphase

D. BD (11 years) antiphase
F I G U R E 4.2 (L E F T). Examples of scaled frequency trials for a 7-year-old child (panel A and B), and 11-year-old child (panel C and D). In the inphase trials, phase drift occurs in the younger child, but not in the older child. In the antiphase trials, a phase transition from antiphase to inphase coordination can be observed in both children. After the transition, the inphase pattern of the older child remains stable, whereas the inphase pattern of the younger child starts to drift at the end of the trial. Note that the relative phase of the younger child is more variable.

Scaled frequency trials
In the inphase trials, loss of stability was characterized by phase drift (i.e., loss of entrainment) (Figure 4.2). No transitions from inphase to a stable antiphase coordination were observed. Seven 11-year-old, and six 9-year-old children were able to maintain the inphase coupling up to the maximum metronome frequency (i.e., 3.0 Hz) in all inphase trials. This indicates that the maximum metronome frequency was not high enough for these children to reach their critical frequency. In the antiphase trials, loss of stability was characterized by transitions from antiphase to inphase coordination. This inphase coordination pattern, in turn, did not remain stable because phase drift occurred when the frequency was further increased (e.g., Figure 4.2b). Three 7-year old children - the same children as in the steady state trials - could not produce a stable antiphase pattern during the steady state part of the trial (i.e., the first 12 stimulus intervals). Age-related differences in critical frequency are summarized in Table 4.3. A 3 Age x 2 Gender x 2 Phase ANOVA revealed that the critical frequency significantly increased as a function of age,

<table>
<thead>
<tr>
<th>Age</th>
<th>Inphase</th>
<th>Antiphase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f (Hz)</td>
<td>Range (Hz)</td>
</tr>
<tr>
<td>7</td>
<td>2.45</td>
<td>1.29 - 2.80</td>
</tr>
<tr>
<td></td>
<td>(.47)</td>
<td>(.23)</td>
</tr>
<tr>
<td>9</td>
<td>2.78</td>
<td>1.65 - 3.0</td>
</tr>
<tr>
<td></td>
<td>(.40)</td>
<td>(.24)</td>
</tr>
<tr>
<td>11</td>
<td>2.90</td>
<td>2.16 - 3.0</td>
</tr>
<tr>
<td></td>
<td>(.23)</td>
<td>(.43)</td>
</tr>
</tbody>
</table>

Note. Within-group standard deviation between brackets. The metronome frequency was increased from 1.0 to 3.0 Hz.

F (2, 57) = 8.30, p = .001. Tukey's HSD comparisons showed that for both coordination
modes only 7- and 11-year old children differed significantly. Differences between the age-groups for inphase coordination might have been larger if the upper metronome frequency range had been set to a higher value. A significant effect for phase, $F(2,57) = 206.01, p < .001$, showed that the critical frequency was higher in inphase than in antiphase coordination. No significant effects were found for gender. No significant interaction effects were found.

4.4 Discussion

The present study describes synchronization (inphase coordination) and syncopation (antiphase coordination) in terms of relative phase dynamics. It was found that both coordination patterns could be more or less stably performed by all children, except for three children who did not show a stable antiphase coordination. Phase transitions from antiphase to inphase were found, as well as phase drift of inphase coordination when frequency was increased. Loss of stability, phase transitions, and phase drift are not accounted for by the timekeeper models mentioned in the introduction. Multistability and phase transitions are considered important features of self-organization. The present study therefore supports the view that rhythmic perception-action coupling may be understood as a pattern formation process, in which self-organization plays an important role (cf. Kelso, Delcolle, & Schöner, 1990; Wimmers, Beek, & van Wieringen, 1992; Byblow, Chua, & Goodman, 1995). The main finding of the present study is that there are age-related differences for both relative phase variability and critical frequency, indicating that the stability of rhythmic perception-action coordination patterns increases with age. For antiphase coordination, the number of unsuccessful trials -including the three children who were not able to produce the antiphase pattern at all- was rather high. This finding suggests that the ability to syncopate emerges around the age of 7 years.

The observed negative phase shift (or synchronization error) in the inphase coordination mode is a phenomenon that has also been observed in adults, tapping about 20 to 50 ms in advance of auditory stimuli (Fraisse, 1966; Fraisse & Voillaume, 1971; Peters, 1989; Ascherleben & Prinz, 1995). The synchronization error decreases, and may even turn into a phase delay, when frequency is increased (Nagasaki, 1987; Peters, 1989). The negative phase shift found in children is not accounted for by the dynamic model. Although no significant age effect was found for tapping accuracy (i.e., AE$\phi$), the negative phase shift was much smaller in the 11-year-old group (Table 4.2). The phase shift in 7- and 9-year-old children is larger than in adults, but the phase shift of the 11-year-olds (average 38 ms)
was within the range reported in adult studies. Interestingly, children were more accurate in tapping off the beat than in tapping on the beat. This difference is mainly due to the fact that the negative phase shift found in inphase coordination seemed to be absent in antiphase coordination (Table 4.2). Although, to our knowledge, timekeeper models have not been applied to off-the-beat tapping, this absence of negative phase shift might be explained—in terms of timekeeper theory—by the fact that feedback processes (i.e., phase-based corrections aimed to reduce the time gap between the tap and auditory event) do not play a major role in tapping off the beat, i.e., halfway between two successive auditory events.

The finding that children had difficulty syncopating limb movements to a metronome, and, in particular, maintaining syncopation at a higher metronome frequency is in agreement with findings in adults. Fraisse and Voillaume (1971) found, for example, that 27 out 30 subjects were able to syncopate at a frequency of 1.0 Hz. This number decreased to 18 subjects at 2.0 Hz, and only 10 subjects at 3.65 Hz. This also indicates that children's critical frequency for syncopating (Table 4.3) is well below that of adults. Differences between syncopation and synchronization when frequency is increased have also been found in adults. Kelso et al. (1990) found that subjects (N = 7) were able to synchronize to an auditory metronome for frequencies between a range of 1 Hz and 3.5 Hz. Only in 20% of the trials was a phase drift at the highest frequencies found. However, most subjects were unable to syncopate at frequencies higher than 3.0 Hz.

Our findings are largely in accord with predictions from the coupled oscillator model, although some inconsistencies were found. As the model predicted, phase transitions from antiphase to inphase coordination, and phase drift of inphase coordination occurred when frequency was increased. Although the findings for critical frequency indicate that the inphase coordination mode was more stable than the antiphase mode, the relative phase variability did not differ between the two patterns. This is not in agreement with the model, which predicts larger relative phase fluctuations for antiphase than for inphase coordination under equal frequency conditions. A larger relative phase variability for antiphase coordination has been found in studies on rhythmic visual perception-action coupling (Schmidt, Carello, & Turvey, 1990; Wimmers, Beek, & van Wieringen, 1992; Byblow, Chua, & Goodman, 1995). No information about relative phase variability was given in two studies that have investigated inphase and antiphase auditory perception-action coupling (Fraisse & Voillaume, 1971; Kelso, Delcolle, & Schöner, 1990). Byblow et al. (1995) found that the relative phase variability was smaller in a condition in which visual information was displayed continuously than in a condition in which information was displayed discretely. Further, they found that the relative phase variability in inphase and antiphase coordination hardly differed in the discrete condition. These authors suggested that the availability of continuous information might explain the difference in relative phase
stability between inphase and antiphase visual perception-action coupling in the sense that continuous information ‘compresses’ the relative phase variability more in the inphase than in the antiphase mode, leading to a smaller variability for inphase coordination (Byblow, Chua, & Goodman, 1995). In the present study, the auditory events on which subjects had to synchronize or syncopate were discrete in nature, and this might explain why the inphase and antiphase tapping modes did not differ in relative phase variability.

The increase in critical frequency with age is consistent with the decrease in relative phase variability. Both indicate that the relative phase dynamics underlying these perception-action patterns changed in the direction of increased stability. In terms of the coupled oscillator model, such changes in stability as a function of age are due to an increase in the coupling strength between the oscillators. Apparently, this coupling is stronger in older children. With respect to the transition mechanism, it was suggested that the transition from antiphase to inphase might be linked to a threshold nonlinearity (Kugler, 1986). Since the perception-action coupling in the task used is essentially informational in nature, the threshold might be best understood as an informational limitation, in the sense that the antiphase organization breaks down when the perceptual limits on resolving the information that specifies the pattern are reached (Wimmers, Beek, & van Wieringen, 1992). The same explanation might apply for the observed loss of stability and subsequent phase drift in the inphase coordination patterns. Further, the lower critical frequency of the younger children might be explained by their lower perceptual threshold. More generally, this suggests that age related changes in critical frequency are probably constrained by perceptual information thresholds.

The present study shows that the relative phase dynamics underlying children’s ability to synchronize and syncopate limb movements to periodic auditory events change with age in the direction of an increasing stability. It should be noted, however, that longitudinal research is needed to describe the developmental dynamics of synchronization and syncopation more in detail. Relevant questions, such as at what age does the ability to syncopate emerge, or is the increase of stability of such perception-action patterns linear or non-linear, may then be addressed. Further, we think that it may be useful to apply such a dynamic approach to examine developmental coordination disorders in children (e.g., clumsiness), both at the level of perception-action coupling as well as at the level of interlimb coordination (see chapter 6).

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