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Joint drumming: Social context facilitates synchronization in preschool children

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ABSTRACT

The human capacity to synchronize body movements to an external acoustic beat enables uniquely human behaviors such as music making and dancing. By hypothesis, these first evolved in human cultures as fundamentally social activities. We therefore hypothesized that children would spontaneously synchronize their body movements to an external beat at earlier ages and with higher accuracy if the stimulus was presented in a social context. A total of 36 children in three age groups (2.5, 3.5, and 4.5 years) were invited to drum along with either a human partner, a drumming machine, or a drum sound coming from a speaker. When drumming with a social partner, children as young as 2.5 years adjusted their drumming tempo to a beat outside the range of their spontaneous motor tempo. Moreover, children of all ages synchronized their drumming with higher accuracy in the social condition. We argue that drumming together with a social partner creates a shared representation of the joint action task and/or elicits a specific human motivation to synchronize movements during joint rhythmic activity.

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Introduction

Humans have the ability to entrain their movements to an external rhythm such as a beating drum (Wallin, Merker, & Brown, 2000). Such *rhythmic entrainment* of periodic body movements to rhythmic sound patterns is a fundamental component of music and dance, themselves integral elements of natural human behavior (Clayton, Sager, & Will, 2004).

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Many animals move their limbs in a metrical alternating fashion, but the underlying motor pattern generators are mostly automatic and refer only to the animals' own bodies (Marder & Bucher, 2001). Yet in a few arthropod and anuran species, the males use periodic movements to create acoustic courtship signals and can synchronize these sounds to the signals of other nearby males (Gibson & Russell, 2006; Greenfield, 1994; Kotiaho, Alatalo, Mappes, & Parri, 2004). However, *Homo sapiens* is the only known species where both sexes engage in spontaneous synchronization of periodic body movements to acoustic rhythmic pulses (Patel, 2006). Furthermore, this rather unusual skill among primates develops relatively early in human ontogeny, long before sexual maturity (Fitch, 2006).

Patel, Iversen, Chen, and Repp (2005) further emphasized the complexity and flexibility of human "beat perception and synchronization," as they called it. For example, adults can synchronize the movements of various body parts to external rhythms over a great range of tempi, also at rates that are multiples or fractions of the same underlying pulse (Drake, Jones, & Baruch, 2000; Large & Palmer, 2002; Snyder & Krumhansl, 2001). The special relationship between the auditory system and rhythmic body movement is evidenced by the finding that visual rhythms induce only very poor rhythmic entrainment in humans (Patel, Iversen, Chen, & Repp, 2005; Repp & Penel, 2004).

Within the first year of life, human infants learn to discriminate acoustic rhythmic patterns and can discern the metrical structures that underlie musical pieces (for a review, see Trehub & Hannon, 2006). Infants as young as 7 months infer different meters from the same auditory rhythm when they get bounced at different periodic accents, illustrating the multisensory interactions between rhythm perception and movement (Phillips-Silver & Trainor, 2005). However, infants at that age do not actively synchronize their movements to an external beat (Longhi, 2003, cited in Patel, 2006). According to the tapping literature, such *sensorimotor synchronization* (Repp, 2005) is not clearly present in young children until around 4 years of age (McAuley, Jones, Holub, Johnston, & Miller, 2006). The testing paradigms used to infer this developmental shift were basically the same as those used in adult studies, where participants are asked to tap their finger or hand in synchrony with an auditory stimulus (for reviews, see Aschersleben, 2002; Repp, 2005). Nevertheless, although 4-year-olds are quite competent in this sensorimotor synchronization task, their range of accessible tempi is smaller than that of adults and, significantly, the best results are yielded by *interstimulus intervals* (ISIs) of approximately 400 ms (equating to 150 beats/min), which is in the range of the *spontaneous motor tempo* of children of this age (Drake et al., 2000; Fitzpatrick, Schmidt, & Lockman, 1996; McAuley et al., 2006; Provasi & Bobin-Bègue, 2003).

There is very little research on rhythmic entrainment in children before 4 years of age. First, Fitzpatrick and colleagues (1996) reported that 3-year-olds were basically unable to clap their hands in time with a metronome. Second, Provasi and Bobin-Bègue (2003) found that 2.5-year-olds sometimes managed to tap in synchrony with an isochronous beat (occurring at equal intervals), but only when the tempo was at an ISI of 400 ms—again, a beat within the range of their spontaneous motor tempo. In that study, participants needed to tap on a horizontal touch screen in phase with a short sound of an animal's call that occurred at 400, 600, or 800 ms ISI (equivalent to 150, 100, or 75 beats/min, respectively). The taps caused a picture of the corresponding animal to appear on the screen, but only when tapping occurred in time with the sound (as a nonverbal reinforcement). The same participants who were successful at an ISI of 400 ms, however, failed to slow down their tapping so as to synchronize with the call sequence at 600 and 800 ms ISI. In contrast, many of the 4-year-olds managed to tap in phase with the stimulus at all tempi presented. Third, Eerola, Luck, and Toivainen (2006), focusing on whole-body dancing movements, found a similar developmental pattern for children of 2 to 4 years of age. Although the younger children showed periodic movements that were at times in synchrony with the original piece of music, they did not adjust the period of their hopping, swaying, or circling to the song played at tempi much slower than 150 beats/min.

However, none of these studies with younger children used a social context to elicit sensorimotor synchronization. In our view, successful research on the origins of rhythmic entrainment must take into account the natural environment in which this behavior most likely evolved (e.g., Bispham, 2006; Fitch, 2006; Huron, 2001; McNeill, 1995; Merker, 2000). Specifically, before the invention of sound recording and reproduction devices during the 1870s, every musical context involving synchro-

nized motor movements implied some form of social activity (Chanana, 1995). There was only live music with the performers present. Furthermore, the members of most human cultures do not apply the sharp distinction between performer and audience typical of music in Western societies. Instead, they practice music in groups, often in association with dance and ritual (Nettl, 2005). Natural musical behavior that includes rhythmic entrainment can thus be regarded as a fundamentally cooperative activity (see Brown & Volgsten, 2006). It naturally involves complex joint actions (for a review, see Sebanz, Bekkering, & Knoblich, 2006), with the individual sharing the intention and motivation to actively sing, dance, or play along with the other participants (see Tomasello, Carpenter, Call, Behne, & Moll, 2005).

From this social perspective on rhythmic entrainment, asking children to clap along with a metronome, tap on a touch screen to animal calls, or dance to a song played on a loudspeaker might be familiar to the children based on their previous experience, but none of these situations is in fact “natural” in an evolutionary sense. Instead, a more natural situation would be a joint rhythmic activity with a human play partner such as during joint drumming. We hypothesized that in this kind of situation, even children younger than 4 years would synchronize their body movements to an isochronous drum beat other than their spontaneous motor tempo. The presence of a play partner should increase the motivation of the children to join in with the shared activity of drumming (Tomasello et al., 2005) and/or facilitate the understanding of the joint action task by sharing its mental representation with the experimenter through *joint attention* (Sebanz et al., 2006).

However, better synchronization during drumming with a live partner compared with tapping with a metronome could also be due simply to the multisensory input through the combination of sound production and periodic hand movement. To distinguish between such processes that affect synchronization only on the basic perceptual level and processes that affect synchronization on the more social–cognitive level, a reasonable control condition would provide a similar audio–visual input as a human drummer but without any social cues.

In the current study, therefore, we encouraged children of 2.5, 3.5, and 4.5 years of age to drum together with (a) an adult in a playful setting (*social condition*), (b) a machine that provided similar audio–visual stimuli but no social–motivational or joint attentional cues (*audio–visual condition*), and (c) a loudspeaker that provided only acoustic cues by playing previously recorded samples of human drumming (*acoustic condition*). Because we were interested in the developmental origins of *spontaneous* sensorimotor synchronization, we did not verbally instruct the participants on how to drum and did not ask them to drum in synchrony; they were simply invited to join in the game of drumming. The second factor that we manipulated was the tempo. We assumed that synchronizing with a beat at 400 ms ISI (150 beats/min) would be an easy task for children because it lies in the range of their spontaneous motor tempo during clapping or tapping (Fitzpatrick et al., 1996; McAuley et al., 2006; Provasi & Bobin-Bègue, 2003). In contrast, we assumed that a drum beat at 600 ms ISI (100 beats/min) would be more difficult to synchronize with because it is approximately 1.5 to 2.0 times slower than the children’s spontaneous motor tempo.

Method

Participants

A total of 36 children, divided into three age groups, were included in the final sample: 12 each of 2.5 years ($M = 30$ months 9 days, range = 28 months 4 days to 32 months 22 days), 3.5 years ($M = 42$ months 11 days, range = 40 months 0 days to 44 months 6 days), and 4.5 years ($M = 53$ months 14 days, range = 52 months 1 day to 55 months 11 days). Each age group contained 6 boys and 6 girls. Children were recruited from urban day care centers. Children came from mixed socioeconomic backgrounds, and all were native German speakers. Another 12 children took part in the study but were not included in the final sample because of experimenter errors ($n = 4$) or absence on the second testing day ($n = 8$).

Design

The study had a $3 \times 2 \times 3$ mixed design, with one between-participants factor (Age) and two within-participants factors (Speed: 400 or 600 ms ISI; Condition: social, audio–visual, or acoustic). Each child was tested by the same experimenter (first author, with no change of experimenter throughout data acquisition) in a quiet room of the day care center during two sessions on consecutive days. Each session included three test trials of the same speed but differing in condition. Both the order of conditions within sessions and the order of speed between sessions were counterbalanced across participants.

Materials

Fig. 1 shows the materials and experimental setup. We constructed two identical red floor drums (40 cm high) with a white synthetic drum skin of 25 cm diameter. Inside each drum, a unidirectional condenser microphone recorded the stimulus and response beats. All sessions were filmed with a digital video (DV) camera.

For the social condition, the left-handed experimenter knelt behind the stimulus drum and played an isochronous beat with the flat palm of his left hand. Hidden earphones, which played click sounds from a digital metronome, constantly paced his drum beat, keeping it independent of the child's drumming. In addition, the earphones served as earplugs to decrease the experimenter's audio perception of the child's drumming. To minimize the interference that the child's drumming might have on the experimenter's isochrony, the experimenter went through numerous training sessions with an adult drum partner who purposely caused interferences. His precision in keeping isochrony during data acquisition was always monitored; trials with a standard deviation of ISIs greater than 20 ms were counted as an experimenter's error. For further prevention of experimenter bias, see the "Data Processing" subsection.

For the audio–visual condition, we constructed a drumming machine in the shape of a blue box ($25 \times 30 \times 50$ cm) that was placed behind the drum. At the top of the box was a lever (25 cm) that protruded from the side with a sponge attached at its farthest end, which hung over the surface of the drum. The lever and sponge were yellow to contrast the moving parts of the machine from its static body. A switch caused the protruding lever to move up and down at an angle of approximately 45° . With the stimulus drum placed beneath this lever, the sponge produced a continuous isochronous movement and sound similar to that made by a human hand during drumming. The machine's precision in keeping isochrony during testing was monitored (standard deviation of ISIs < 20 ms).

In the acoustic condition, a portable MP3 player played prerecorded drum beats amplified via a speaker hidden in a blue box (20×30 cm). The drum beat was recorded using the same drum as used in the other conditions except that it was digitally sampled and strung together in an isochronous beat with either 400 or 600 ms ISI. In all conditions, the stimuli were played at the same volume. To record the stimulus and response signals separately, we used the left and right audio channels of the DV tape (see wiring scheme in Fig. 1).

Procedure

During both sessions (10 min each), the child sat in a small seat while the experimenter knelt approximately 1 m in front of the child. All participants first took part in a warm-up task to familiarize themselves with the experimenter and to establish a natural game play situation. Both the child and the experimenter played successively with various plastic toy animals on three different apparatuses (slide, rocker, and carousel) in a turn-taking game.

After each apparatus was played with for approximately 2 min, the experimenter led the child over to the test trials, saying, "Hey, I brought another game with me; it's called drum king. Do we want to play that now?" Then the experimenter placed the two drums in a direct line between him and the child and introduced two plastic crowns as part of the game that followed. He put one of the crowns on his head and offered the other to the child, saying, "The game is called drum king. You are the small

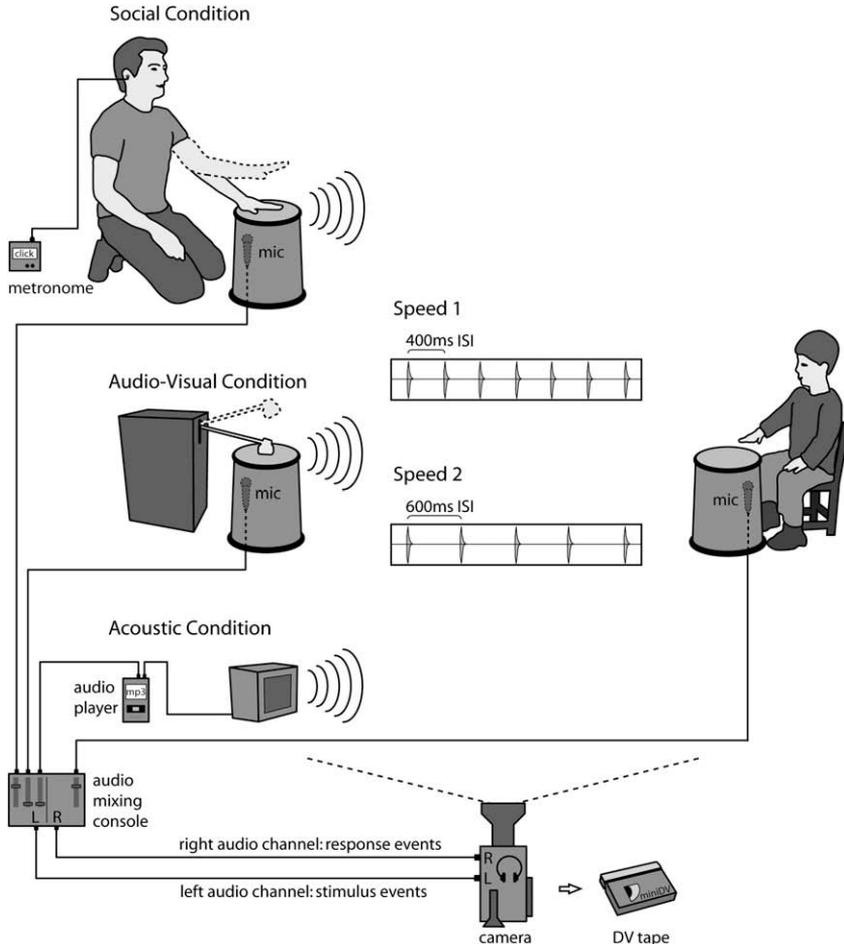


Fig. 1. Materials and experimental setup. The study included three conditions differing in the way the drum beat was presented: by a human play partner (social condition), by a drumming machine (audio-visual condition), and by drum sounds coming from a speaker hidden in a box (acoustic condition). In addition, in each condition the beat was presented twice: one day at a presumably easier speed with a 400-ms ISI and another day at a presumably more difficult speed with a 600-ms ISI. To capture both the stimulus and the response signal independently, but without losing their temporal relationship, we recorded both signals separately on the left and right audio channels of the same DV tape with the help of a portable audio mixing console (see wiring scheme).

drum king, and I am the big drum king.” To familiarize the child with the task of single-handed drumming during the first session, the experimenter demonstrated a sequence of three beats in the appropriate ISI of that session while saying, “Can you also drum this way?” All 36 participants answered this question by imitating the experimenter’s behavior and hitting their drum a few times with only one hand. Then the experimenter sequentially introduced the different tasks by saying the following:

- *In the acoustic condition:* “Look, this is a radio. Listen. There are drum sounds coming out of the radio. Can you drum along with the radio?”
- *In the audio-visual condition:* “Look, this is a drumming machine. Listen to how the machine drums. Can you drum along with the drumming machine?”
- *In the social condition:* “Now I want to drum together with you. Listen to how I drum. Can you drum with me?”

After the introduction, the appropriate stimulus was played for 20 s. All participants reacted by playing their own drum with a continuous quasiperiodic movement of either their left or right hand throughout the whole trial. All children stopped drumming immediately after the stimulus ended. Because the drumming time of 20 s was kept the same for both speed conditions, the actual number of stimulus beats per trial differed; at 400 ms ISI each trial consisted of 50 stimulus beats, whereas at 600 ms ISI each trial consisted of 33 stimulus beats. Six participants temporarily paused their drumming to inspect the radio or drumming machine but returned to their drumming after no longer than 5 s. Depending on those pauses and individual differences in drumming tempo, the number of response beats that went into further analysis varied between 25 and 48 events per trial ($M = 39$) at the 400-ms ISI speed and between 20 and 40 events per trial ($M = 34$) at the 600-ms ISI speed.

During playing time in the nonsocial conditions, the experimenter knelt away from the child at an angle of 90° while looking and smiling at the radio or machine. In contrast, during playing time in the social condition, the experimenter knelt in line with the child and looked and smiled at the child's face.

Data processing

We extracted all taped sections with successful trials using Adobe Premier CS2 software. From each video clip, we isolated the content of the left and right audio channels—containing either the stimulus or the response signals—as separate audio files. To receive the precise time of the drum beats, we ran a custom-written script using Praat 4.5.16 (Boersma & Weenink, 2007) that scanned each audio file for events occurring above a fixed volume threshold and subsequently marked the time of the peak amplitude within each event with a point that was always between 7 and 10 ms after the event onset time (a complete drum beat event lasted approximately 50 ms). The program produced a list of points (a Praat text grid) that returned both the order and time of all the drum beats measured from the onset of the recording. The detection accuracy of the Praat script reached approximately 90%, and the remaining 10% of misdetected or missing points were adjusted or filled in manually via a parallel visual inspection of each of the 216 audio files and the corresponding text grids.

Minimizing potential experimenter's bias

The time sequences of stimulus beats from the social condition underwent an additional conversion before they were included in the final data analysis. Tapping experiments with adults have shown that error correction mechanisms in response to small shifts in the metronome signal are not always under conscious control (Repp & Keller, 2004). Regarding our study, despite the numerous training sessions and the use of ear plugs simultaneously producing the isochronous pacing signal, the experimenter could still hear and see the child's drumming and might have unwittingly and unconsciously adjusted his drumming phase to the child's own rhythm. Because later the synchronization accuracy was calculated *relative to* the driving rhythm, the results in the social condition might have been biased by small occasional adjustments of the experimenter's drumming phase toward the child's drumming phase.

To avoid this potential bias, we computer generated a strictly isochronous sequence of stimulus events of either 400 or 600 ms ISI and aligned it with the stimulus sequence from the tape recordings. This alignment was done by an automatic procedure, written in R (R Development Core Team., 2008), such that the sum of the absolute divergences between the experimenter's beats and the closest corresponding beats from the generated sequence was minimized. For all further analyses, this aligned isochronous stimulus sequence was taken as the reference for the calculation of the children's synchronization accuracy.

Measures of synchronization

Our predictions focused on three variables of the children's drumming behavior: *adjustment of tempo*, *synchronization accuracy*, and *phase preferences*. Regarding tempo, we expected that children of all three ages should be able to adjust their drumming tempo to a beat at 400 ms ISI regardless of stimulus type. However, at the slower beat of 600 ms ISI, the 2.5-year-olds should have problems in adjust-

ing their drumming tempo in the acoustic condition (in line with the results from Provasi & Bobin-Bègue, 2003) but might perform better in the audio–visual condition and/or social condition. However, according to previous findings, most of the 4.5-year-olds should be capable of accurately tracking the tempo at 600 ms ISI in the acoustic condition as well.

Regarding synchronization accuracy, we expected the *variance of asynchronies* between stimulus and response beats to be smaller if children were actively synchronizing to the driving rhythm (according to Repp, 2005). Likewise, if the speed or nature of the stimulus had any effect on the children's phase preferences (e.g., whether they preferred to drum with or off the beat), the *mean asynchrony* should differ between conditions.

Analysis part 1: adjustment of tempo

To assess tempo changes between conditions, we calculated the median interresponse interval from each trial. Because we wanted to observe the children's natural behavior, we refrained from any event exclusion criteria as are commonly used in adult tapping research. Consequently, regarding our data, sequences of interresponse intervals from children who paused their drumming for a few seconds included some extreme outliers. To diminish the impact of such interval outliers on the tempo analysis, we calculated the median of interresponse intervals instead of the mean. In addition, we asked whether the speed or nature of the stimulus would have any effect on the *tempo variance* of the children's drumming. Therefore, we calculated the median absolute deviation (described in Quinn & Keough, 2002) of all interresponse intervals from a particular trial.

To test for effects of age, speed, and condition on the median and median absolute deviation of interresponse intervals, we refrained from a repeated-measures analysis of variance (ANOVA) because both a Levene's test of variance homogeneity and visual inspection of plots of residuals against predicted values indicated clear deviations from the assumption of homogeneity of error variances. Instead, we used corresponding permutation tests (described in Manly, 1997) based on 1,000 permutations (with permutation algorithms implemented as described in Anderson, 2001).

Analysis part 2: synchronization accuracy and phase preference

Why circular statistics?

The standard method to assess the degree of synchronization during tapping experiments is to align the stimulus and response sequences on a linear time scale, take the relative deviation or *asynchrony* of each response tap from the corresponding metronome click, and finally calculate the mean and variance of all asynchronies per trial. However, such linear statistics require rather small asynchrony values to assign each response event to one particular stimulus event. As expected, the drumming behavior of our young participants was much more diverse, with many children drumming continuously out of phase. Because it was not straightforward to associate the children's taps with the stimulus beats on a one-to-one basis as is required in linear statistics, we chose circular statistics (Fisher, 1993; Mardia & Jupp, 2000; Zar, 1999) as the appropriate method to calculate mean and variance of the asynchronies (e.g., Large & Palmer, 2002).

The basic idea of applying circular statistics to our data is to take advantage of the repetitiveness and isochrony of the stimulus signal and the natural periodicity of the circle. We transformed all ISIs from a single trial onto a circular scale (in degrees: 0–360°; in radians: 0–2 π) with all stimulus beats aligned at 0° (see example scatter diagram in Fig. 2). The relative time at which a particular response tap occurs within the current ISI can then be represented by a specific point on the circumference of the unit circle. Each data point is mathematically defined by a "direction" (angle in degrees or radians, also referred to as *phase*). For example, in the 400-ms ISI condition, a response tap with a positive asynchrony that occurred 100 ms after its preceding stimulus beat would result in a point at 90° or 0.5 π on the circumference. Instead, a response tap with a negative asynchrony of 100 ms would result in a point at 270° or 1.5 π .

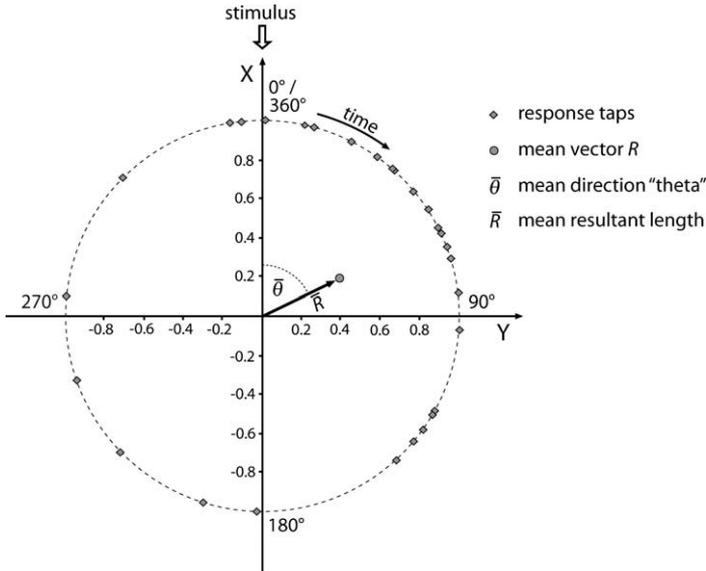


Fig. 2. Example scatter diagram of the circular statistics of a particular trial. Each ISI is normalized to the 360° of the circular scale. Now the relative time at which a response tap occurred within the current ISI can be defined by a specific direction or angle on this circle (marked by square-shaped dots on the circumference). For example, in the 400-ms ISI condition, a response tap that occurred exactly in time with a stimulus will result in a direction of 0°, a tap with a 50-ms delay in a direction of 45°, and another tap preceding the stimulus by 50 ms in a direction of 315°. Subsequent calculation of the mean vector R (round dot) summarizes the child's performance during that trial. The direction of R returns the *mean direction* $\bar{\theta}$ (theta) of all response beats, equivalent to the mean asynchrony in linear statistics. The length of R termed *mean resultant length* \bar{R} , goes from 0 to 1 and is an inverse measure for the variance of asynchronies during that particular trial; the higher the \bar{R} , the smaller the variance of asynchronies, indicating higher synchronization accuracy.

The major advantage of converting the drumming responses into circular data is that each response event can now be included in the calculation of the degree of synchronization without concerning its attribution to either the preceding or following stimulus beat. This way, we can detect and compare the variance of asynchronies from different trials regardless of whether an individual child was drumming in synchrony with the beat or was in any manner off phase. Again, this is particularly important for our study because we did not instruct the participants to drum downward on the stimulus beat and thus found a large variation between individual phase preferences.

For clarity, we followed Fisher (1993) and Zar (1999) in using a “clock” or “compass” convention for plotting polar coordinates. This familiar convention incorporates the direction of a data point by giving it an angle relative to 0° at the top of the circle (noon or true north), moving clockwise around the circle. Converting such polar coordinates into Cartesian coordinates entails a vertical x axis and a horizontal y axis. The radius of the circle is standardized to 1.

Mean direction and mean resultant length

The next step is to summarize the directions of points on the circle's circumference to infer the mean and variance of the asynchronies of all the response taps from one trial. Consider that one fundamental property of circular data is that the beginning and end of the scale coincide, that is, 0° = 360°. This implies that the classic arithmetic mean gives a rather poor summary; for example, the mean of 30° and 350° cannot sensibly be 190° but should be 10°. The solution is to calculate the mean vector R (for calculation, see Fisher, 1993; Mardia & Jupp, 2000; Zar, 1999). The mean vector can be broken down into two nonparametric components: the vector's *mean direction* $\bar{\theta}$, which is analogous to the mean asynchrony in linear statistics and can be used as a measure of the participant's phase prefer-

ence, and the vector's *mean resultant length* \bar{R} . The latter varies between 0 and 1 and is the inverse analogue of the variance of asynchronies in linear calculation.

An \bar{R} of 1.0 implies that all response taps are coincident at the same time relative to the stimulus beats (i.e., perfect synchronization). However an \bar{R} of 0.0 does not necessarily imply the opposite—a uniform distribution around the circle (also referred to as isotropy or randomness) and thus no synchronization. For example, a bimodal dispersion of data points in opposite directions around the circle would also result in an \bar{R} close to 0. Regarding our data, we predicted that if a participant was actively synchronizing his or her drumming to the isochronous driving rhythm, any phase shift should be more or less stable throughout the trial, resulting in a unimodal distribution of points on the circle. Thus, in our case, the reverse assumption was that a small \bar{R} results from a rather uniform distribution of points, reflecting a high variance of asynchronies of response taps and thus a rather low synchronization accuracy.

Statistical tests on mean resultant length \bar{R}

To decide whether a child was significantly synchronizing his or her drumming to the driving rhythm during a particular trial, we used Rayleigh's test, which tests the null hypothesis of circular uniformity against the alternative hypothesis of a unimodal distribution of circular data points (Fisher, 1993). Rayleigh's null hypothesis can be rejected if \bar{R} gets too large and thus $p \leq .05$. If the live drumming partner has any positive effect on the children's synchronization accuracy, the number of children who reach significance in Rayleigh's test should be higher in the social condition than in the two nonsocial conditions.

Rayleigh's test works for finding a significant concentration of response taps for a single trial. However, our study had a three-way repeated-measures design, and we wanted to compare \bar{R} between conditions and age groups. Because \bar{R} ranges from 0 to 1 on a linear scale, we could use a three-way ANOVA to test for the effects of age, speed, and condition on \bar{R} , after arcsine transformation, because visual inspection of plots of residuals against predicted values clearly indicated homogeneity of error variances. Considering \bar{R} as a measure of how accurate participants were synchronizing their drumming, it should be higher in the social condition than in the nonsocial conditions. Likewise, \bar{R} should be higher at the faster, presumably easier driving rhythm of 400 ms ISI than at the slower speed at 600 ms ISI.

Statistical test on mean direction $\bar{\theta}$

To our knowledge, there is no available statistical test for circular data (comparing $\bar{\theta}$ and \bar{R} between conditions and age groups) analogous to the multiway analysis of linear data. Nevertheless, to be able to use repeated-measures ANOVA of $\bar{\theta}$, we transformed the mean vectors \bar{R} of each trial into two linear scales. Consider that any vector \bar{R} on the plane of the circle (see dots and squares in Fig. 4) can be described either by its polar coordinates (angle $\bar{\theta}$ and distance from the center \bar{R}) or by its Cartesian coordinates (x and y). Their relation is as follows: $x = \bar{R} \cos(\bar{\theta})$ and $y = \bar{R} \sin(\bar{\theta})$. We calculated the x and y coordinates of each mean vector \bar{R} separately and treated the whole data set as if it were a sample of linear data with one additional within-participants factor (i.e., xy coordinate). Interactions of the xy coordinate with any of the other factors (age, speed, and condition) indicated by a repeated-measures ANOVA would indicate changes in either $\bar{\theta}$, \bar{R} , or both. To differentiate among these three possibilities, we needed only to refer to the visual inspection of the circular plots shown later in Fig. 4.

Significance level

For all tests, we considered p values $\leq .05$ as significant. Because we tested four different variables, an error level correction was required to control the family-wise error rate. We did this using the equation $p_{ck} = 1 - (1 - p)^k$, which we derived from conversion of the Dunn-Šidák method (Sokal & Rohlf, 1995). In our equation, p_{ck} returns the p value corrected for the number of tests and k equals the number of tests. We denote such corrected p values as p_{c4} . Significance of main effects from repeated-measures analyses were considered only if interactions between factors were not significant (Zar, 1999).

Results

Adjustment of tempo

The permutation test on effects of age, speed, and condition on the median of interresponse intervals revealed a significant Age \times Speed \times Condition interaction, $p_{C4} < .05$, $p_{rep} > .98$. Visual inspection of the data (Fig. 3A) indicated that children of all age groups adjusted their drumming tempo to the

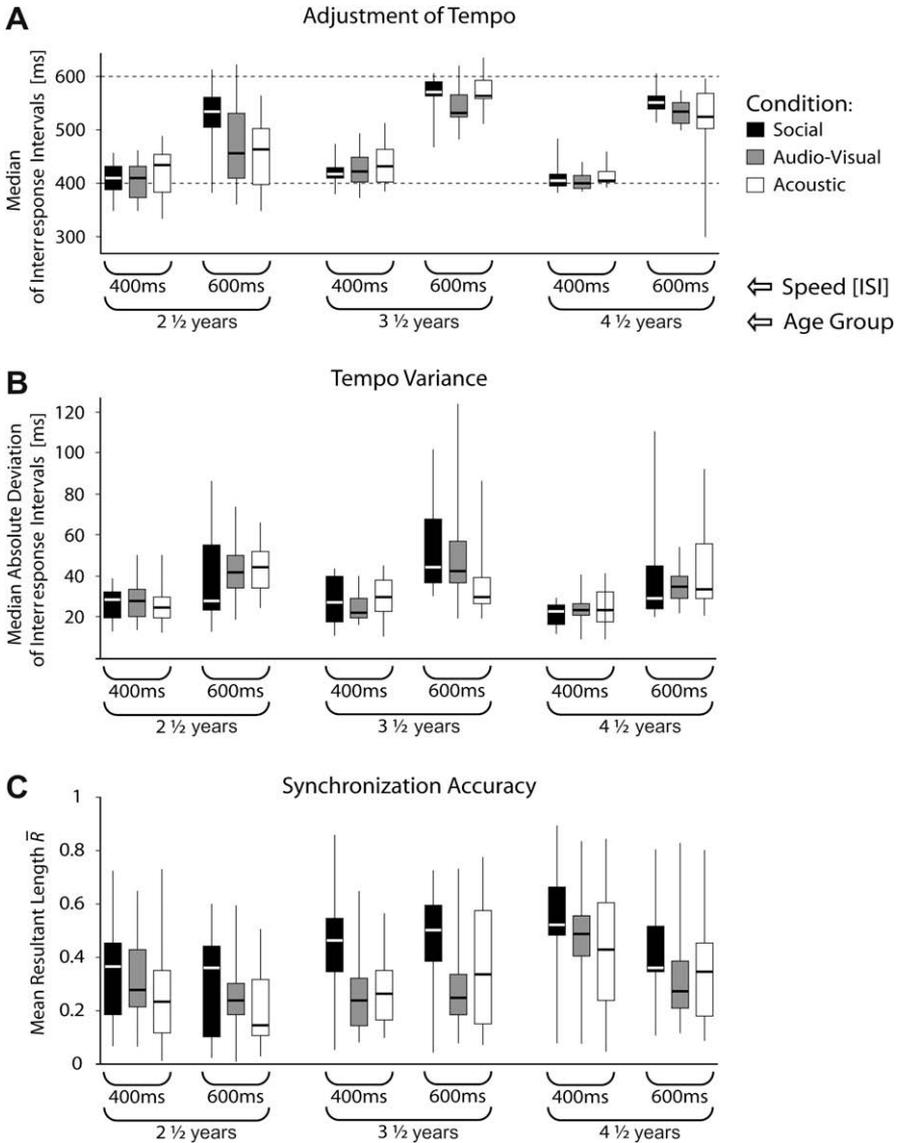


Fig. 3. Median (A) and median absolute deviation (B) of the children’s interresponse intervals as measures of tempo adjustment and the mean resultant length \bar{R} as a measure of synchronization accuracy (C). Each cell summarizes 12 data points. Distributional information shown is the median of a cell (crossbar), the range from the 25th to 75th percentiles (shaded box), and the minimum and maximum values (thin line). Results are sorted by age and speed. The dashed lines in panel A mark the optimal tempo adjustment depending on the stimulus tempo (40- or 600-ms ISI).

driving rhythm at 400 ms ISI with no difference between conditions. However, at the slower driving rhythm of 600 ms ISI, the 2.5-year-olds behaved differently from the older children. Within-age-group comparisons indicated that the 3.5- and 4.5-year-olds significantly decreased their tapping tempo toward the slower driving rhythm, $p \leq .01$, $p_{\text{rep}} \geq .99$, across all three conditions (no significant difference in tempo between conditions, $p \geq .12$, $p_{\text{rep}} \leq .92$). But in contrast, among the 2.5-year-olds, the drumming tempo varied significantly between conditions. Pairwise post hoc tests among the 2.5-year-olds revealed significant Speed \times Condition interactions when comparing the social condition with the acoustic condition, $p < .01$, $p_{\text{rep}} > .99$, and the social condition with the audio–visual condition, $p = .04$, $p_{\text{rep}} = .97$, but not when comparing the two nonsocial conditions with each other, $p = .48$, $p_{\text{rep}} = .65$. In other words, in the two nonsocial conditions, most 2.5-year-olds failed to adjust their tempo and drummed with a median interresponse interval shorter than 500 ms, whereas in the social condition, the same participants slowed down their drumming toward the driving rhythm, comparable to the tempo adjustment of 3.5- and 4.5-year-olds.

However, we found no effect of condition on the tempo variance (Fig. 3B). The permutation test revealed no differences between conditions, $p_{C4} = 1$, $p_{\text{rep}} = .16$, or age, $p_{C4} = .76$, $p_{\text{rep}} = .79$, and found no significant interactions, all $p_{C4S} \geq .99$, $p_{\text{rep}} \leq .38$. But children did show a smaller tempo variance when drumming with the fast stimulus beat compared with the slow one. Across all ages, the median absolute deviation of interresponse intervals was lower at 400 ms ISI than at 600 ms ISI, $p_{C4} < .01$, $p_{\text{rep}} > .99$. This is not surprising because drumming at larger interbeat intervals should admit larger variation in the interval length.

Synchronization accuracy

Across all ages and speeds, the number of children who reached significance in Rayleigh's test ($p \leq .05$) was highest in the social condition, as presented in Table 1. Fig. 4 summarizes all mean vectors R per trial. R vectors from trials with a significant unimodal distribution of response taps are marked by squared dots, whereas all R vectors from those trials where Rayleigh's null hypothesis of uniform distribution could not be rejected are marked by round dots.

Supporting the findings from Rayleigh's test, the ANOVA on effects of age, speed, and condition on mean resultant length \bar{R} (Fig. 3C) revealed no significant interactions (all $p_{C4S} \geq .33$, $p_{\text{rep}} \leq .76$), but a main effect of condition, $F(2, 32) = 6.41$, $p_{C4} = .02$, $p_{\text{rep}} > .98$, $\eta^2 = .16$. However, we found no significant effects of age, $F(2, 33) = 4.25$, $p_{C4} = .09$, $p_{\text{rep}} = .94$, $\eta^2 = 0.21$, or speed, $F(2, 33) = 1.72$, $p_{C4} = .59$, $p_{\text{rep}} = .56$, $\eta^2 = .05$.

Pairwise comparisons of conditions revealed that the above effect of condition was caused by a significant increase of \bar{R} in the social condition compared with the audio–visual condition, $F(1, 33) = 9.49$, $p = .02$, $p_{\text{rep}} = .99$, $\eta^2 = .22$, and compared with the acoustic condition, $F(1, 33) = 9.26$, $p = .02$, $p_{\text{rep}} = .99$,

Table 1

Number of participants per age group, speed, and stimulus condition who reached significance in Rayleigh's test for circular uniformity ($p < .05$)

	2.5 years	3.5 years	4.5 years	Total
<i>Speed 1: 400-ms ISI</i>				
Social condition	6	9	10	25
Audio-visual condition	4	3	9	16
Acoustic condition	3	4	6	13
Total	13	16	25	
<i>Speed 2: 600-ms ISI</i>				
Social condition	8	9	9	26
Audio-visual condition	3	3	4	10
Acoustic condition	1	5	6	12
Total	12	17	19	

Note. In each age group, 12 participants were tested; thus, the possible range for each cell was 0 to 12. Rayleigh's test for circular uniformity asks whether the distribution of response taps during a single trial significantly differs from a uniform distribution on the circle, indicating an active synchronization relative to the driving rhythm.

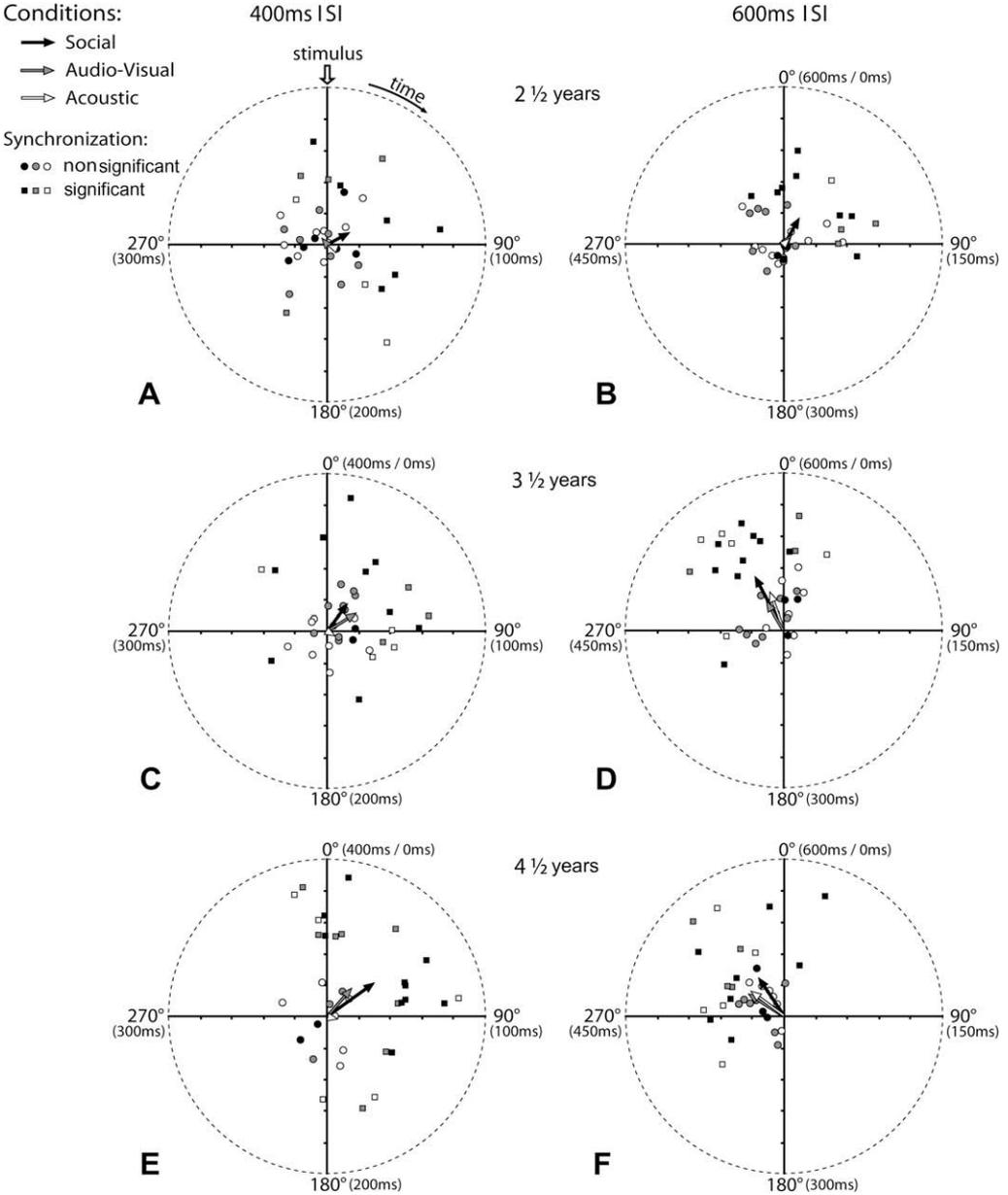


Fig. 4. Comparison of the mean vectors \bar{R} from the circular analysis between different conditions. We plotted the mean vectors \bar{R} from all 216 trials as dots onto the six circles (A–F), with each circle combining the results at a particular age and speed. The three different shadings of the dots (black, gray, and white) represent the three conditions (social, audio–visual, and acoustic, respectively). For those trials that reached significance in Rayleigh’s test of uniformity, the dots are square-shaped. The nonsignificant mean vectors are represented by round dots. In addition, the grand mean vector of all 12 dots per condition is indicated by an arrow in the respective shading.

$\eta^2 = .22$. However, \bar{R} did not differ between the two nonsocial conditions, $F(1, 33) = 0.13, p = .99, p_{rep} = .03, \eta^2 < .01$. The significant increase of \bar{R} in the social condition implies smaller variance of asynchronies, which can be interpreted as the result of a higher synchronization accuracy.

Phase preferences

The ANOVA on effects of age, speed, and condition on the x and y coordinates of the mean vectors \bar{R} revealed a significant xy Coordinate \times Speed \times Age interaction, $F(2, 33) = 10.49$, $p_{C4} < .01$, $p_{rep} > .99$, $\eta^2 = .39$, whereas the interaction among all four factors was not significant, $p_{C4} = 1$, $p_{rep} = .04$. Visual inspection of R vectors (dots in Fig. 4) indicated that this interaction was caused by primarily positive mean asynchronies (delayed drumming) at the 400-ms ISI speed across all three ages (Fig. 4A, C and E) but a shift with growing age at the 600-ms ISI speed from slightly positive to mainly negative mean asynchronies (cf. Fig. 4B, D and F).

Post hoc tests within age groups revealed significant xy Coordinate \times Speed interactions among the 3.5-year-olds, $F(1, 11) = 36.06$, $p < .01$, $p_{rep} > .99$, $\eta^2 = .77$, and the 4.5-year-olds, $F(1, 11) = 38.93$, $p < .01$, $p_{rep} > .99$, $\eta^2 = .78$, but not among the 2.5-year-olds, $F(1, 11) = 0.77$, $p = .40$, $p_{rep} = .71$, $\eta^2 = .07$. In other words, the above shift of phase preferences from positive to negative mean asynchronies when drumming with a 600-ms ISI occurred between the 2.5- and 3.5-year age groups.

However, the fact that we found no significant interaction involving the condition and xy coordinate factors suggests that participants did not change their phase preferences between the different kinds of stimuli. To better visualize this independence of mean direction $\bar{\theta}$ from the conditions in Fig. 4, we calculated the grand mean vector of each condition–speed–age combination and included them as arrows.

Discussion

The current study is the first to explore the early developmental origins of spontaneous sensorimotor synchronization from a social perspective. This perspective arises from current theories about the evolution of human beat perception and synchronization capacities in a social environment, with other humans providing the natural acoustic or audio–visual stimulus for spontaneous rhythmic entrainment of body movement during joint dancing, singing, or instrument playing (for reviews, see Fitch, 2006; McDermott & Hauser, 2005).

We found strong support for our original hypothesis that children spontaneously synchronize their tapping with higher accuracy when drumming together with a human in a playful setting instead of drumming along with a machine that simulates a human hand playing a drum or with a prerecorded beat that comes from a loudspeaker; at all three tested ages, participants decreased the variance of asynchronies significantly in the social condition compared with both nonsocial conditions. It would be interesting to test whether adults enjoy the same benefits in a similar setup. Because the variance of asynchronies did not differ between the two nonsocial conditions, we assume that the addition of a visual stimulus in the form of a moving “drumstick” to an acoustic signal does not improve synchronization in children. This observation reconfirms the special relationship between sensorimotor synchronization and the auditory system known from adult tapping research (Patel et al., 2005; Repp & Penel, 2004).

In further support of our hypothesis, we showed that children as young as 2.5 years spontaneously and voluntarily adjust their own drumming tempo to an isochronous beat at 600 ms ISI (150 beats/min), but only in the social condition. This finding contradicts the previous belief that children at this age are unable to synchronize their movements to an acoustic pulse at 600 ms ISI (100 beats/min) simply because they cannot stretch their tapping period too far outside the range of their spontaneous motor tempo (Eerola et al., 2006; Provasi & Bobin-Bègue, 2003). However, the results from our nonsocial conditions fit well with the results of Provasi and Bobin-Bègue (2003) and Eerola and colleagues (2006). Our findings simply reject their generalization.

There are a number of processes on different psychological levels that could explain the enhanced sensorimotor synchronization during joint drumming. Because children were not instructed to actually synchronize with the stimulus, it is important to distinguish between attempts on the social–cognitive level that try to explain *why* our participants *chose to* synchronize and attempts on the perceptual level that try to explain *how* our participants *were able to* synchronize better in the social condition.

A possible answer to the *why* question can be found by looking at the joint drumming task as a special case of cooperative activity, where both participants understand and share the intention to play the drums together. Tomasello and colleagues (2005) supposed that humans have a species-unique motivation to share emotions, experiences, and activities with other persons. We would like to put forward the idea that during joint rhythmic activities, this motivation includes an additional aspect, namely, the *desire to move in synchrony*. Several theoretical attempts have been made to account for the adaptive value of human musicality with special reference to rhythmic entrainment, for example, its role in male group signaling (Merker, 2000), mother–infant interaction (Dissanayake, 2000; Trevarthen, 1999/2000), or social bonding and group cohesion (Bispham, 2006; Huron, 2001; McNeill, 1995). However, each of these accounts implies that the participants are *motivated* to synchronize their voices or body movements. Tomasello and Carpenter (2007) further emphasized the importance of *shared intentionality* in early cognitive development because it enables humans to better learn through other persons and to collaborate with others in collective activities. Perhaps in the social context of joint drumming, children as young as 2.5 years infer and share the experimenter's intention not only to drum together but also to drum together in synchrony.

On the perceptual level, to answer the question of how the children in our study were able to synchronize better in the social condition, one could interpret the joint drumming task as a special form of joint action; the child and the experimenter share the same perceptual input and direct their attention to the same events. This process, called *joint attention*, creates a shared representation of the action that, according to Sebanz and colleagues (2006), allows an individual to better anticipate the behavior of the other. In the special case of joint drumming, the child's predictive simulation of the other's periodic action might have caused spontaneous coupling of perceived and self-produced movements (Hove, 2008). The possible role of action simulation in rhythmic entrainment was further discussed by Keller, Knoblich, and Repp (2007), who found that adult pianists synchronize better with audio recordings of their own playing rather than with audio recordings of others.

On the neurophysiological level, the human mirror neuron system has been proposed as playing an important role in the understanding and production of joint actions (Pacherie & Dokic, 2006). A recent electroencephalogram (EEG) study provided evidence that the mirror neuron system was activated during spontaneous synchronization between two people who observed each other's periodic finger movements (Tognoli, Lagarde, DeGuzman, & Kelso, 2007). Regarding our study, the question remains as to whether it was the shared *visual* representation of the drumming action, the shared *acoustic* representation of the beat, or the combination of both that might have enabled the children to better synchronize their drumming.

The most obvious difference from the tapping behavior of adults was that many children did not drum in phase with the stimulus signal. Instead, the differences in individual phase preferences during synchronous drumming were large. Because the children were not instructed to drum “down beat” with the stimulus, it remains unclear whether individual participants were unable or unwilling to tap down with the beat. However, individual phase preferences did not differ systematically between conditions, although the variance of asynchronies decreased systematically in the social condition.

In contrast, the phase preferences did change with age and stimulus tempo. When drumming along with a beat at 400 ms ISI, most participants' synchronous tapping showed delays of approximately 10 to 120 ms. This finding contrasts with the observation of a negative mean asynchrony in adults, where taps tend to unconsciously precede the clicks of an isochronous sequence by approximately 20 to 80 ms (see Aschersleben, 2002). However, in the 600-ms ISI condition, the older participants of 3.5 and 4.5 years tended to precede the stimulus beat by approximately 10 to 100 ms (similar to adults). One explanation for this shift from positive to negative mean asynchrony could be that the participants needed to constantly push their “system of internal oscillations” (Large & Jones, 1999) toward the external driving rhythm at 600 ms ISI; this is also reflected by the median interresponse interval that rarely reached the ideal value of 600 ms. The combination of an imperfectly entrained oscillation system and a continuous error correction activity (Repp, 2005) that tries to compensate for the former would theoretically result in the observed tendency to precede the stimulus beat at 600 ms ISI but not at 400 ms ISI.

Regarding methodology, our findings qualify the joint drumming setup as an appropriate paradigm to study the early ontogeny of rhythmic entrainment in more detail in the future because it accesses

sensorimotor synchronization at earlier ages than did previous methodical approaches. Using circular statistics to calculate mean and variance of asynchronies proved to be the convenient method when handling the much more variable drumming behavior of young children (Brakke, Fragaszy, Simpson, Hoy, & Cummins-Sebree, 2007), especially because we avoided any subjective exclusion criteria of response taps. Some open questions for further studies are, for example, how preschool children react to isochronous beats faster than their spontaneous motor tempo, sudden phase and period shifts in the stimulus beat, and more complex drum rhythms. The joint drumming paradigm is also particularly suitable to study spontaneous rhythmic entrainment among peers under 4 years of age.

Finally, we emphasize the important role of culture (Hannon & Trainor, 2007), in particular the effect of early exposure to musical–rhythmic stimuli on the ontogeny of beat perception (e.g., Hannon & Trehub, 2005) and synchronization (e.g., Drake & Ben El Heni, 2003). We predict that children who grow up in cultures with a more active and social musical practice develop synchronization skills earlier and differently from their contemporaries in societies where musical stimuli nowadays come largely from electronic devices outside of meaningful social contexts.

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