Dyadic Drumming Across the Lifespan

Reveals a Zone of Proximal Development in Children

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Abstract

Many social interactions require the synchronization – be it automatically or intentionally – of one's own behavior with that of others. Using a dyadic drumming paradigm, we delineate lifespan differences in interpersonal action synchronization (IAS). Younger children, older children, younger adults, and older adults in same- and mixed-age dyads were instructed to drum in synchrony with their interaction partner at a constant, self-chosen tempo. Adult-only dyads showed the highest and children-only the lowest levels of IAS accuracy. Importantly, children improved reliably in IAS accuracy when paired with older partners. The observed age-related differences in IAS accuracy remained reliable after statistically controlling for individual differences in the ability to synchronize to a metronome, and for between-dyad differences in tempo. We conclude that IAS improves from middle childhood to adulthood, and that adult interaction partners may facilitate its development.

Keywords: action synchronization, zone of proximal development, interpersonal coordination, lifespan, intergenerational interaction, interpersonal interaction

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The need to coordinate one's own behavior with that of others pervades social life. Salient examples include playing music, participating in team sports, or dancing. Collective play, everyday communication, and various bonding behaviors also rely on implicit or intentional forms of coordinated behavior. Even in antagonistic activities, such as boxing or soccer, individuals need to coordinate with each other to compete effectively (Marsh, Richardson, Baron, & Schmidt, 2006). A fundamental dimension of socially coordinated behavior is the ability to intentionally adapt the *timing* of one's own behavior to the timing of others' actions. In the following, we refer to this ability as interpersonal action synchronization (IAS).

The ontogeny of IAS is largely unknown. Certain forms of interpersonal synchronization are present at birth (for review, see Feldman, 2007; cf. Condon & Sander, 1974a, 1974b; Crown, Feldstein, Jasnow, Beebe, & Jaffe, 2002). Also, some psychological and developmental disorders, such as schizophrenia or autism, have been linked to difficulties in social interactions, including their dynamic aspects (e.g., Davalos, Kisley, & Freedman, 2005; Frith & Wolpert, 2003; Nadel, 2004). The aim of this study was to delineate lifespan differences in the ability to synchronize one's actions with another person of the same or of a different age. We were particularly interested in finding out whether IAS accuracy depends on the age composition of the dyad.

Individuals need to synchronize their actions in a wide range of situations and with different partners. Some researchers have proposed that individuals are endowed with an inherent rate of activity, or *preferred tempo*, which reflects biological and contextual factors (Boltz, 1994; Frischeisen-Köhler, 1933). According to this view, interaction partners need to adjust their internal states with each other to achieve synchronization (e.g., Nowak, Vallacher, & Zochowski, 2005). Thus, IAS can be understood as a reciprocal entrainment process (e.g., Haken, Kelso, &

Bunz, 1985; Schmidt, Richardson, Arsenault, & Galantucci, 2007). This process is facilitated by sensorimotor abilities, such as perceptual awareness and motor skills, as well as declarative and procedural knowledge about the social world.

Lifespan Differences in Correlates of Interpersonal Action Synchronization

Procedural and declarative social knowledge accumulate more or less steadily throughout the lifespan. Several theorists have claimed that inferring the intentions of interaction partners helps individuals to accurately anticipate that person's behavior (e.g., Blakemore & Decety, 2001). For instance, Schaffer (1977) argued that infants are not capable of dyadic actions before they have acquired the concept of intentionality (see also Tomasello, Carpenter, Call, Behne, & Moll, 2005; Tomasello & Racoczy, 2003). Presumably, intentions begin to generate conscious awareness of specific action components in the first years of life (e.g., Meltzoff, 1995). Knowledge about one's own and others' psychological processes (e.g., thoughts, intentions) continues to accumulate across the later parts of the lifespan (e.g., Happé, Winner, & Brownell, 1998; Schindler & Staudinger, 2005; Staudinger & Pasupathi, 2000).

In contrast, sensorimotor abilities, such as perceptual and motor skills, improve throughout childhood, peak in young adulthood, and decline thereafter (e.g., Bloch, 1998; Dempster, 1992; Hommel, Li, & Li, 2004; Kail, 1991; Li, Lindenberger, Hommel, Aschersleben, Prinz, & Baltes, 2004; Salthouse, 1984, 1996; Thelen, 1993). Age differences in individuals' synchronization abilities have been studied using mechanical time keepers (e.g., metronomes; Aschersleben, 2002; Aschersleben & Prinz, 1995; Drake, Jones, & Baruch, 2000; Drewing, Aschersleben, & Li, 2006; Fraisse, 1980; Repp, 2005; Wing & Kristofferson, 1973). According to this literature, the lifespan development of synchronization abilities follows an inverse U-shaped function (e.g., Drewing, et al., 2006). Tempo discrimination, tempo adaptation, and rhythmic performance have already been observed in neonates and 2- and 4-month-old infants

(e.g., Baruch & Drake, 1997; Condon & Sander, 1974a, 1974b; Demany, McKenzie, & Vurpillot, 1977; Pouthas, Provasi, & Droit, 1996). Furthermore, at the age of 4–5 years, children are able to synchronize their clapping to an externally timed tempo (e.g., Drake et al., 2000; Fitzpatrick, Schmidt, & Lockman, 1996). There is additional evidence suggesting that older children's tapping variability when synchronizing their finger tapping to an externally prescribed tempo is lower than that of younger children, and hence their synchronization accuracy, higher (e.g., Drake et al., 2000; Smoll, 1974a, 1974b; Volman & Geuze, 2000). Some empirical evidence suggests that the precision of internal time keepers shows little or no decline with advancing adult age (Drewing et al., 2006; Pouthas, Vanneste, Jacquet, & Gerard, 1998), but synchronization ability in more complex tasks declines from early to late adulthood (Jagacinski, Greenberg, Liao, & Wang, 1993; Krampe, Engbert, & Kliegl, 2001).

Since we aim at investigating interpersonal action synchronization on a basic level, we assume that the impact of declining sensorimotor abilities overrules the improving procedural skills across the lifespan. Hence, we predict that dyads composed of younger adults will show the highest levels of IAS accuracy of all possible dyadic combinations of younger children, older children, younger adults, and older adults.

Exploring the Zone of Proximal Development in Interpersonal Action Synchronization

Our second major hypothesis is based on the Vygotskian notion of the *zone of proximal development* (1933; cf. van der Veer & Valsiner, 1991). The zone of proximal development is generally defined as the distance between *actual* development, examined through independently solved tasks, and *potential* development, examined through tasks solved under the assistance of, or in cooperation with, older or more experienced partners (e.g., van der Veer & Valsiner, 1991). According to Vygotsky what children can do with the assistance of others is even more indicative

of their developmental status than what they can do alone (e.g., Brown, Metz, & Campione, 1996).

To date, most of the available empirical studies investigating the zone of proximal development compared individual with collaborative planning strategies during problem-solving tasks (e.g., Brown, Ellery, & Campione, 1998; Rogoff, Malkin, & Gilbride, 1984). For example, with respect to planning imaginary errands, 9-year-old children showed more sophisticated planning strategies in post-tests after having collaborated with adults compared to after having collaborated with age-peers (Radziszewska & Rogoff, 1991). Also, 5-year-olds evinced more efficient imaginary route planning when working together with their mothers than when working with age peers (Gauvain & Rogoff, 1989). However, empirical evidence for a zone of proximal development in other domains of functioning and in more basic sensorimotor skills is lacking.

Here, we apply the concept of the zone of proximal development to the development of IAS to arrive at the second major hypothesis of this study. We expect that the presence of an adult interaction partner will improve IAS in children. In other words, if IAS increases during childhood and peaks in younger adulthood, and if interacting with a more competent partner facilitates IAS, then children should show higher levels of IAS when synchronizing with an older partner than when synchronizing with a younger or same-age partner.

The Dyadic Drumming Paradigm

To investigate the two major hypotheses of this study, we assessed *dyadic drumming* in same- and mixed-age dyads. The drumming paradigm used here was derived from the tapping paradigm, which has been widely used to study individual (i.e., non-dyadic) sensorimotor synchronization abilities (for review see Repp, 2005; see also Aschersleben & Prinz, 1995; Fraisse, 1980; Wing & Kristofferson, 1973). In the tapping paradigm, participants are typically instructed to tap with their index finger in synchrony with mechanic timekeepers (i.e., stable

metronome frequencies). Synchronization accuracy is measured as the temporal distance between the finger tap and the metronome click. In the dyadic drumming paradigm used here, pairs of individuals are asked to drum in synchrony with each other at a stable frequency that they feel comfortable with, only receiving auditory feedback from each other. The dyadic or shared goal is implemented by explicitly instructing individuals to synchronize with each other, and the discrepancy between the two individuals' drumming sequences is used to measure IAS accuracy.

IAS can be defined as bidirectional entrainment between two or more interaction partners (e.g., Kelso, 1984; Schmidt, Carello, & Turvey, 1990). The *Haken-Kelso-Bunz Dynamic Model* (Haken et al., 1985), which is often used to represent inter-limb coordination within individuals, posits two competing coordination attractors: one in-phase (symmetric movements) and the other anti-phase (alternate movements). In-phase coordination is generally more stable than anti-phase coordination, both in individual and dyadic contexts, and performance stability in both coordination modes has been found to decline as tapping frequency increases (e.g., Kelso, 1984; Schmidt, et al., 1990; Schmidt, Christianson, Carello, & Baron, 1994; Schmidt & Turvey, 1994). The purpose of the present study was to investigate natural adjustment processes that occur between individuals when synchronizing with each other to reach a shared goal, while at the same time reducing the complexity of synchronization processes as they naturally occur in everyday interactions (e.g., Boker, Cohn, Theobald, Matthews, Brick, & Spies, 2009; Boker & Rotondo, 2003). Therefore, in the present study, individuals were asked to synchronize symmetrically (i.e., in-phase) at a tempo they felt comfortable with.

Furthermore, some studies focused on the question whether individual synchronization differs with regard to the nature of the external stimuli used. Bartlett & Bartlett (1959) and Repp & Penel (2004) both show that synchronizing with auditory stimuli (e.g., a metronome) is more

accurate than synchronizing with visual stimuli. In addition to this advantage, the auditory paradigm used here allows complete control of the interaction: All information from one member of the dyad to the other can be fully recorded.

In the present study we used a drumming rather than a tapping task. There is empiric evidence for decline in fine motor skills in normal aging (Jagaczinsky et al., 1993; Salthouse, 1984). Drumming (i.e., forearm movements) requires less fine motor skills than tapping (i.e., finger movements). Hence, the dyadic drumming paradigm applies more readily to different age groups than a paradigm based on finger taps.

In sum, to explore the development of temporal aspects of intentionally coordinated behavior between two individuals, we used a drumming paradigm to assess IAS accuracy of children and adults in same- and mixed-age dyads. Based on the lifespan trajectories of relevant sensorimotor skills and social knowledge, we predicted that younger adults would show the highest levels of IAS accuracy, especially when paired with younger adults in same-age dyads. In line with the Vygotskian notion of the zone of proximal development (e.g., Vygotsky, 1933), we also predicted that children would increase their IAS accuracy when paired with older individuals.

Method

Participants

A total of 72 female individuals aged 5, 12, 20–30, and 70–80 years participated in the study ($n = 18$ per age group). Participants were recruited from the participant pool of the Max Planck Institute for Human Development, Berlin, newspaper advertisements, and through posters and flyers distributed in kindergartens and sports clubs. All participants were German-speaking inhabitants of Berlin, Germany, and from a middle-class background. Most of the younger

children (89%) had just entered elementary school and all older children were currently in sixth grade of lower (33%) or higher (67%) secondary school options in the early-tracking German school system. All younger adults were high-school or university graduates; among the older adults, 50% held a comparable degree, reflecting cohort differences in education.

We decided to include female participants only for two reasons. First, synchronization abilities develop at different rates in girls and boys, with girls being more accurate than boys in synchronizing with mechanical time keepers (e.g., Hiscock, Kinsbourne, Samuela, & Krause, 1985; Wolff & Hurwitz, 1976). Investigating these differences would have required including sex as a design factor, putting further requirements on sample size to maintain appropriate statistical power. Second, a design with individuals from both sexes also would have required the analysis of differences in the sex composition of the dyads (cf. Schmid Mast, 2004). Again, the inclusion of a second design factor at the dyad level would have necessitated a considerably larger number of participants and dyads.

All participants were right-handed, without active musical experience (i.e., children were not learning an instrument and adults had no practice for at least ten years), had normal hearing, and full functional mobility in both hands. The samples were age-typical in performance on measures of perceptual speed (Digit-Symbol-Test [Wechsler, 1981]; Items Correct: 12-year-olds: $M = 87.4$, $SD = 6.9$; younger adults: $M = 64.4$, $SD = 8.5$; older adults: $M = 43.6$, $SD = 8.6$) and verbal knowledge (Vocabulary Test – HAWIK [Wechsler, 1991]; 12-year-olds: $M = 30.9$, $SD = 9.0$; Spot-a-Word-Test [Lehrl, 1989]; younger adults: $M = 19.9$, $SD = 5.4$; older adults. $M = 27.1$, $SD = 3.4$). Younger children received 60 € for their participation in the study (six sessions) and older children and adults received 75 € (seven sessions). The institute's Ethics Committee approved the study.

Overview of Study Design

The experiment consisted of one initial session for the assessment of covariates, in which younger (preschool) children did not participate (as they were not yet able to fill out questionnaires), followed by six experimental sessions. Covariates were assessed in small groups of two or three individuals, and included socio-demographic information, self and personality questionnaires, and cognitive tasks. In the first experimental session, individual synchronization performance was measured in nine different metronome conditions. This was followed by four dyadic sessions in which participants drummed together with a different partner in each session, one per age group. Thus, each individual's synchronization performance was assessed in one same-age and three mixed-age dyads, amounting to 144 dyadic sessions. The order of same- and mixed-age dyads was counter-balanced across participants. Each session consisted of two blocks of eight trials (45 s and 60 drumbeats recorded from at least one individual). The mean time between sessions was about eight days ($M = 8.4$; $SD = 5.1$). The time range between sessions did not differ significantly by age composition of dyad, $F(9, 288) = .39$, *n.s.* Drumming partners had not met each other before participating together in a dyadic session and two partners of a given dyad did not share any other dyadic drumming partner in the study. The final experimental session was identical to the first and again served to assess individual synchronization to a metronome.

Paradigm and Measures

Covariate session. Besides socio-demographic characteristics and well-established cognitive tasks on perceptual speed and verbal knowledge (e.g., Digit-Symbol Test; Wechsler, 1981), the covariate session also comprised a set of questionnaires assessed for other purposes, such as the NEO (Costa & McCrae, 1992), which was administered to adults only and will not reported here.

Individual drumming with a timekeeper (Experimental Sessions 1 and 6). At the beginning of the individual experimental sessions, participants' *preferred tempo* was assessed by asking participants to drum at the stable frequency they felt most comfortable with. Four trials of at least 60 drumbeats and 45s were recorded. In the individual synchronization conditions, participants had to synchronize to computer-generated drumbeats of three different tempi presented through soundproof headphones: (1) 419 ms inter-stimulus interval, (2) 757 ms inter-stimulus interval and (3) the mean value of each participants own preferred tempo. Each tempo was presented first in stable, metronome-like conditions and afterwards in two different degrees of variability (low, high) meant to represent "human-like" variability in drumming performance in counter-balanced order across participants.[1] In the resulting nine conditions with four trials each, trial length was at least 60 stimuli and 45 s. Synchronization accuracies with the metronome were highly correlated between the stable and variable conditions ($r = .93$, $p < .01$). For the purpose of the control-analysis reported below, we used the mean aggregate of individuals' synchronization performance in the first experimental session as an indicator of individuals' ability to synchronize with a mechanical timekeeper.

Dyadic drumming (Experimental Sessions 2–4). In the dyadic drumming paradigm, pairs of individuals were asked to drum with as accurate synchronization to each other as possible, at a constant frequency they felt comfortable with. Participants were separated from each other by a partition screen to exclude the influence of non-verbal interactional cues and drummed with drumsticks on digital drums. They received digitalized auditory feedback of their own and their partner's drum sounds through soundproof earphones. To increase the similarity of synchronization stimuli between the metronome and dyadic conditions, participants heard their own drum sounds as digital drum-beats in either one of two frequencies (high; low). The low drum sound had already been used as the drumming-feedback sound in the individual sessions,

and the high drum sound had formerly been used as the metronome signal. Each participant was assigned to the low and high drum sound twice respectively in the four dyadic sessions. The order of the sound assignment was randomized across participants. Acceleration sensors (BIOVISION; single axis, sensitivity: 50 g), attached to the top end of the drumsticks were used to measure their movements. Data were recorded with a data logging card (National Instruments®️ M 16 E; Range: -10/+10 V) in a personal computer with an Intel Pentium®️ 4 processor (2.8 GHz; 1 GB RAM, Windows XP Service Pack 2).

Measure of asynchrony. The lack of synchronization accuracy when drumming with a metronome or another person, respectively, was operationalized by a newly developed measure of asynchrony. This measure compares two time series of drumbeats, one from a target person A and the other from the metronome or interacting person B, by calculating the distance between the two series as costs of transforming one series into the other to reach perfect synchrony. This is done by either shifting drumbeats to later or earlier points in time, or by inserting or deleting drumbeats (see Appendix A for a formal description). The algorithm automatically pairs drumbeats such that an optimal trade-off between shifting and inserting missing drumbeats is assumed, that is, the algorithm minimizes the cost function. This optimization is achieved by dynamic programming (e.g., Corman, Leiserson, & Rivest, 1994). Kreuz, Haas, Morelli, Abarbanel, and Politi (2007) compared various measures of synchronization in the context of neural spike train synchrony. The six different synchrony measures were all highly correlated. Furthermore, they found that the edit distance as applied in this study was the best spike-based measure of synchrony in a clustering simulation. The scale of this measure is symmetrical (i.e., it is unimportant which time series functions as Series 1 or Series 2). Transfer costs are expressed in milliseconds, and indicate the duration of the needed time-shifts and the additional costs for insertion or deletion of drumbeats, which corresponded to half the mean drumbeat interval of the

series of question.[2] The asynchrony measure has a minimum of 0, indicating perfect synchrony, and no fixed maximum. Panel A in Figure 1 displays the degree of instantaneous asynchrony, pooled within 200 ms intervals, for a younger child drumming with another younger child. In contrast, Panel B in Figure 1 displays the degree of asynchrony when the same child is drumming with a younger adult. Asynchrony sum scores were calculated for each trial, and reflect cumulative asynchrony in the course of the trial. These sum scores were averaged across trials, and log-transformed to better approximate a normal distribution. The log-transformed score of average asynchrony served as the dependent variable in this study. Panels C and D of Figure 1 show how asynchrony accumulates over time. The mean dyadic asynchrony of the present sample was $M = 8.65$ ($SD = 0.63$). The same algorithm was applied to calculate a measure of individualized synchronization performance in the first individual experimental condition used as control variable ($M = 8.81$, $SD = 0.55$).

Statistical Procedures

We applied multilevel modeling techniques to accommodate for the hierarchical structure of the data (Hox, 2002; Snijders & Bosker, 1999). These models allow the separate consideration of two levels of variance: the dyadic level (i.e., differences in dyadic performance related to differences between dyads) and the individual level (i.e., differences in dyadic performance related to differences between individuals within dyads). Importantly, these models also allow the representation of dependencies between dyads. Such dependencies are present in this data set, as each participant was paired with four different partners.

The models were estimated using WinBUGS 1.4.1 (Windows Bayesian Inference Using Gibbs Sampling; Lunn, Thomas, Best, & Spiegelhalter, 2000). We used Markov Chain Monte Carlo (MCMC) modeling (e.g., Gelman & Hill, 2007). MCMC fit multilevel models that are too complex to be estimable with a Maximum Likelihood (ML) approach using currently available

software packages. The MCMC method generates a large number of simulated random draws

from conditional distributions of all the parameters, for example, by means of a *Gibbs Sampling*

algorithm (e.g., Gelman & Hill, 2007; Gill, 2002; Spiegelhalter, Thomas, Best, & Lunn, 2003).

Parameter estimations are continuously updated by drawing values from the respective

distributions assuming that the current estimated values for the other parameters are true. The

basic principle is that once these repeated updates have run long enough, they will approach the

desired posterior distribution (Gill, 2002). It is then possible to calculate the posterior mean of

this distribution as the best point estimate for each parameter.

There are mainly two estimation criteria that we will refer to in the result section to

identify meaningful results of the estimation procedure: the Bayesian Credible Interval (BCI) and

the Deviance Information Criterion (DIC). As a parameter estimation criterion, the BCI is the

posterior probability interval in which an estimated parameter t lies with a specified probability.

In analogy to confidence intervals in ML statistics, the BCI is based on the 2.5th and 97.5th

percentile points of the posterior distribution. That is, the true value of the estimated parameter

lies within this interval with a probability of .95 (Gelman & Hill, 2007; Spiegelhalter, Best,

Carlin, & van der Linde, 2002). BCIs not including zero as possible values can be interpreted as

estimated parameter values that are reliably different from zero (i.e., in short: *reliable* effects).

The DIC, as an indicator of model fit, is a generalization of the Akaike Information Criterion

(AIC; Akaike, 1973) and the Bayesian Information Criterion (BIC; Schwarz, 1978) for complex

hierarchical models (Congdon, 2006; Gelman & Hill, 2007; Spiegelhalter et al., 2002).[3] The DIC

consists of two additive components. The first is a goodness-of-fit measure of the estimated

model, that is, the mean deviance over all n simulated parameter vectors. The better the model

fits the data, the smaller the value of this measure is. Second, it includes an additional penalty

term for increasing model complexity (i.e., it specifies the effective number of parameters).

Generally speaking, when comparing two or more models, a lower absolute value of the DIC can be interpreted as a model with a higher model fit. To evaluate differences in model fit, a preliminary rule of thumb has been proposed: $\text{Diff}_{DIC1-DIC2} \geq 10$: important difference; $\text{Diff}_{DIC1-DIC2} = 5-10$: substantial difference; $\text{Diff}_{DIC1-DIC2} < 5$: non-interpretable difference (Spiegelhalter et al., 2003).

Model Notation

The simplest multilevel model separates the variance components at the individual and the dyadic level (i.e., differentiates between variance in dyadic asynchrony explained by differences between individuals and between dyads) and can be formulated as follows:

$$Y_i = \beta_0 + u_j\,[p1_i] + u_j\,[p2_i] + \varepsilon_i \tag{1}$$

with $u_j \sim N(0, \sigma^2_u)$ and $\varepsilon_i \sim N(0, \sigma^2_\varepsilon)$.

This model is a varying-intercept model with normally distributed dyadic and individual-level errors, where Y_i represents the dyadic asynchrony for the dyad i and β_0 represents the average dyadic asynchrony across all dyads in the whole sample. The model postulates the asynchrony within a dyad to be an additive effect of each individual's influence on the dyadic outcome; $p1_i$ refers to the first person in the dyad i and $p2_i$ refers to the respective second person. That is, the variability in the dyadic outcome, which is related to the differences between individuals, is divided equally between the two individuals (i.e., $u_j\,[p1_i]$ and $u_j\,[p2_i]$). The average individual performance across its four dyads was extracted from the respective dyadic outcomes by estimating u_j for each individual. The prior distribution of the u_j was set to a normal distribution with zero mean. The value of the respective estimated variance parameter σ^2_u refers to the variance component between individuals. The variance component that was related to differences between dyads was indicated by the estimated value of the parameter σ^2_ε. [4] This first

model assumes that variance in dyadic asynchrony is explained solely by differences between individuals and between dyads. It is therefore possible to discriminate proportions of the total variance that are related to differences between and within dyads (i.e., between individuals). Thus, this model was used as a baseline model (i.e., an *unconditional model*) for further model comparison. Appendix B documents the WinBUGS program code used to implement the model.

Specifying differences between age-group compositions. It was further possible to include additional predictors at the dyadic level. Dummy-coded variables that referred to each of the ten possible dyadic age-group compositions were included as predictors (fixed effects) to further explain variance in dyadic asynchrony across dyads. In the respective model, it was postulated that the intercepts varied across dyads due to the age-group composition of the respective dyad:

$$Y_i = \beta_0 + u_j\,[\,p1_i\,] + u_j\,[\,p2_i\,] + \beta_1 \cdot YCYC + \beta_2 \cdot YCOC \qquad (2)$$

$$+ \beta_3 \cdot YCYA + \beta_4 \cdot YCOA + \beta_5 \cdot OCOC + \beta_6 \cdot OCYA$$

$$+ \beta_7 \cdot OCYA + \beta_8 \cdot OCOA + \beta_9 \cdot OAOA + \varepsilon_i$$

with $u_j \sim N(0,\ \sigma^2_u)$ and $\varepsilon_i \sim N(0,\ \sigma^2_\varepsilon)$.[4]

Follow-up analyses: Controlling for individual synchronization abilities. To control for differences in individual synchronization abilities (i.e., with a mechanical time keeper), a final model (Model 3) included both the dyadic age-group compositions (at the dyadic level) and the predictor individual asynchrony (at the individual level). The model was equivalent to Model 2, except that each individual's sensorimotor synchronization performance was introduced as a fixed effect at the individual level, that is, u_j was further specified as $u_j \sim N(a \cdot$ individual asynchrony, $\sigma^2_u)$.

Results

By using multilevel modeling techniques, we aimed to investigate differences in IAS accuracy of same-age and mixed-age dyads of different ages. To establish a baseline model against which to evaluate differences between dyadic age-group compositions, a varying intercept model (Model 1) was fitted to discriminate proportions of total variance as related to differences (a) between dyads and (b) between individuals within dyads. The dependent variable was dyadic asynchrony, the inverse of IAS. Table 1 shows the estimates for the variance components (i.e., posterior means) of dyadic asynchrony along with the BCIs of the corresponding models.[6] The mean of the posterior distribution of the intercept, $M = 8.65$, represents the grand-mean of dyadic asynchrony across all dyads (β_0). The value refers to the mean value of asynchrony between two individuals within one session. Comparing the means of the posterior distributions of the variance components at each level indicates that 24% of the total explained variance in dyadic asynchrony could be attributed to differences between dyads ($\sigma^2_\varepsilon = 0.06$), whereas 76% could be related to differences between individuals within dyads ($\sigma^2_u = 0.19$). Therefore, it can be concluded that more than three times as much of the total variance in dyadic synchronization accuracy was explained by differences between individuals than by differences between dyads.

Figure 2 reports the degree of dyadic asynchrony for each of the ten possible dyadic age-group combinations across the 16 trials of the dyadic sessions. Dyads including children showed higher dyadic asynchrony and higher variance between trials than dyads not including children. At the same time, younger adults drumming with younger adults showed the lowest dyadic asynchrony. To statistically analyze differences between dyadic age-group compositions, a second model (Model 2) was fitted with dyadic age-group compositions as dummy-coded predictor variables at the dyadic level and the dyadic combination of younger adults with younger

adults as reference group (also see Table 2, left column). The mean of the posterior distribution

for the intercept (β_0), $M = 7.93$, indicates the mean dyadic asynchrony for the reference group of

younger adults drumming with younger adults. Estimated means of the posterior distributions of

all other age-group compositions showed positive deviations from the intercept, indicating higher

values of dyadic asynchrony relative to the reference dyads consisting of younger adults only.

Younger children drumming with younger children showed the highest degree of dyadic

asynchrony relative to the reference group, $\beta_{0\,(YCYC)} = 7.93 + 1.71 = 9.64$. All discrepancies in

dyadic asynchrony between a given dyadic age-group combination and the reference group of

younger adults drumming with younger adults differed reliably from zero, with two exceptions.

The two exceptions involved the age-group combinations "younger adult – older adult" and

"older adult – older adult." Taken together, these results indicate that younger and older adults

did not differ from each other in IAS accuracy. Direct comparison between the two models

suggested a better fit for Model 2 ($\Delta_{DIC} = 65.91$), indicating that the age composition of the dyads

was reliably related to differences in IAS accuracy. Specifically, including age composition as a

predictor accounted for 33% of the explained variance at the dyadic level and for 84% of the

explained variance at the individual level.

       Our second major hypothesis was that children would benefit from synchronizing with

older persons. Thus we predicted that children would show lower asynchrony when paired with

older interaction partners than when paired with a same-age peer. Therefore, Model 2 was set up

again, with same-age dyads of either younger or older children as the reference groups (Model 2a

and Model 2b, see Table 2, right columns). As reported above, younger children drumming with

younger children showed the highest dyadic asynchrony ($M = 9.64$). Moreover, in line with the

second hypothesis, the three types of dyads pairing a younger child with an older partner attained

higher IAS than dyads consisting of younger children only. At the same time, the dyadic

combinations including one younger child did not differ reliably among each other. For example, differences in dyadic asynchrony were not reliable when younger children were paired with either younger or older adults.

When analyzing the data with the "older child – older child" dyad as reference group, we found that older children reliably decreased in IAS accuracy when paired with a younger child, $\beta_{0\,(YCOC)} = 8.53 + 0.70 = 9.23$. At the same time, their IAS accuracy increased reliably relative to the "older child – older child" dyad when drumming either with younger adults ($\beta_{0\,(OCYA)} = 8.53 - 0.25 = 8.28$) or older adults ($\beta_{0\,(OCOA)} = 8.53 - 0.20 = 8.33$); differences between older children drumming with younger adults and older children drumming with older adults were not reliable. In sum, both younger and older children's dyadic drumming performance benefited from the presence of younger or older adults in the dyad.

We also observed reliable age-group differences in non-dyadic, individualized synchronization performance as assessed with a mechanical timekeeper, $F(3, 68) = 44.91$, $p < .01$, $\eta^2 = .67$. Relative to the other three age groups, younger children showed the lowest individualized synchronization performance ($M = 9.55$, $SD = 0.17$). Older children showed lower individualized synchronization performance ($M = 8.74$, $SD = 0.29$) than younger adults ($M = 8.37$, $SD = 0.41$), and both younger adults and older children did not differ significantly from older adults ($M = 8.60$, $SD = 0.37$).

In follow-up analyses, we added individualized synchronization performance (i.e. the individual's ability to synchronize with stable and variable frequencies provided by a metronome) as a covariate in the dyadic analyses to statistically control for individual differences in sensorimotor aspects of synchronization performance. Relative to the results reported before, differences in dyadic asynchrony between the dyadic combinations were slightly reduced in magnitude but remained reliable. Specifically, though individualized synchronization

performance accounted for 20–31% of the differences between dyadic age-group compositions, its inclusion did not lead to a substantial improvement in model fit ($\Delta_{DIC} = 0.78$). The rank-order of age-combination differences in dyadic asynchrony also remained stable after including each dyad's mean drumming tempo as a fixed effect at the dyadic level. Here, the mean dyadic tempo did not show a reliable effect on dyadic asynchrony and including it as covariate in the model did not substantially improve the model fit ($\Delta_{DIC} = 2.20$). Absolute differences between the partners' preferred tempi did not account for a reliable proportion of variance in dyadic asynchrony in further follow-up analyses. In other words, the observed effect of age composition of dyads on IAS could neither be statistically accounted for by differences in sensorimotor aspects of synchronization abilities nor by differences in mean dyadic or individual drumming tempi.

Discussion

The aim of the present study was to investigate age-related differences in IAS from middle childhood to early old age using a dyadic drumming paradigm. Previous research had shown that non-intentional forms of interpersonal synchronization appear early in development (e.g., Condon & Sander, 1974a, 1974b; Feldman, 2007) and accompany social interactions throughout the lifespan (e.g., Sebanz, Bekkering, & Knoblich, 2006; van Baaren, Holland, Kawakami, & van Knippenberg, 2004). Intentional interpersonal synchronization, or IAS, is assumed to play an important role in social development and social interactions, but its lifespan trajectory is largely unknown. Here, we explored IAS by assessing same-age and mixed-age dyads with a newly developed dyadic drumming paradigm.

The main results of the present study can be summarized as follows. In line with the first hypothesis, same-age dyads with two younger adults showed higher IAS accuracy than dyads that included one or two children. For dyads that only included adults, IAS accuracy was not reliably related to age group. In line with the second hypothesis, both younger and older children showed

higher synchronization accuracy with an older partner. This effect remained reliable after controlling for individual synchronization performance.

Empirical findings from previous research suggest that task-relevant sensorimotor abilities and experience-based social skills improve throughout childhood and peak in younger adulthood, followed by a aging-related decline (e.g., Drewing et al., 2006; Happé et al., 1998; Krampe, Engbert, & Kliegel, 2002; Pouthas et al., 1998). Hence, we hypothesized that younger adults would show the highest levels of IAS accuracy, especially when synchronizing with a partner of their own age group. Our results confirm the hypothesized advantage of younger adults over children, but do not support the predicted age-associated decline in IAS accuracy in adulthood.

Several factors may have hampered the detection of adult age differences in IAS accuracy in this study. In natural interactions, individuals need to detect and implicitly or explicitly commit themselves to shared goals (e.g., Bratman, 1992; Searle, 1990), and they need to implement synchronized behavior as a means for reaching the shared goal. In the present experimental paradigm, the shared goal was specified beforehand. This may have facilitated the synchronization process, as it reduced the number of action alternatives. Also, in contrast to previous studies (e.g., Drewing et al., 2006; Krampe et al., 2002), older adults did not differ reliably from younger adults in individual synchronization performance. In addition, participants only received *auditory* feedback of the other person's actions. This also differentiates from naturally occurring interactions in which it is necessary to combine feedback from different channels. Thus the simplicity of the drumming task may have contributed to the lack of adult age differences in IAS accuracy.

In line with our second hypothesis, both younger and older children showed higher IAS accuracy when drumming with adults than when drumming with their age-matched peers. This finding is consistent with the notion that older individuals activate children's zone of proximal

development (e.g., Vygotsky, 1933), allowing them to reach levels of performance that they would not reach without a facilitating social context. It is also in line with the idea that intergenerational interactions, such as (grand)parents–child, teacher–pupil, or expert–novice dialogues may provide a major impetus in development across the lifespan (e.g., Kessler & Staudinger, 2007).

We acknowledge that the mechanisms mediating the performance-enhancing influence of adults on children's IAS accuracy remain to be identified. Some of these mechanisms may reflect explicit or implicit role assignments in interpersonal processes (e.g., Schmid Mast & Hall, 2003; Smelser, 1961). As Brown and Reeve noted in 1987, children and adults may differ in goal structure when working together on a problem. For instance, it seems likely that adults in the present study sought to display a type of synchronization behavior that enabled children to improve their synchronization performance. For example, given that stable rhythmic patterns in interaction processes facilitate the partner's anticipation of future actions (Tickle-Degnen & Rosenthal, 1987; Warner, 2002), adults may have stabilized their performance to restrict children's variability in performance and allowing them to adjust more easily to their frequency of performance. Hence, future work should be directed at discovering the dynamic properties of the interaction between the two partners that allow the zone of proximal development to evolve (Boker, 2002; Boker & Rotondo, 2003).

The present results also suggest that age differences in IAS accuracy are not entirely determined by individual differences in individualized synchronization performance as assessed by synchronization to a metronome. This result supports the claim that a reliable amount of variance in IAS accuracy is an emergent property of the interaction dynamics, which are influenced by the age composition of the dyads in ways yet unknown. In interpersonal interactions, individuals need to continuously adjust their own actions to the actions of others,

which in turn are also influenced by the interaction partner (e.g., Boker et al., 2009; Nowak et al., 2005; Tognoli, Lagarde, de Guzman, & Kelso, 2007). In the context of the present task, coupled oscillators may provide a viable model for delineating age-based differences in interaction dynamics (e.g., Ashenfelter, Boker, Waddell, & Vitanov, in press; Boker & Laurenceau, 2007).

Outlook

Given the central importance of IAS for the capability of humans to perform joint actions and cooperate socially, it is surprising how little is known about its ontogeny. In this study, we sought to break new ground in the developmental study of IAS by instructing same-age and mixed-age dyads to synchronize their drumbeats as accurately as possible. This study provides an initial sketch of IAS development across the lifespan and poses a number of further questions for future research. First, the sample was restricted to girls and women. Hence, the degree to which the present results generalize to boys and men is not known. Second, the results presented in this article focus on synchronization using auditory feedback. Synchronization, especially for children, may be different if visual feedback would be available. Third, the results of our study document children's short-term gains in IAS accuracy when interacting with an adult partner. Future research needs to address whether these benefits persist longitudinally and generalize to other social tasks requiring a high degree of IAS accuracy. Fourth, empirical work on intergenerational contexts that are supposed to provide zones of proximal development (e.g., child–parent, child–grandparent, or pupil–teacher) may benefit from paying greater attention to developmental changes in IAS. And finally, the neuronal correlates of IAS (Lindenberger, Li, Gruber, & Müller, 2009) need to be investigated from a developmental perspective.

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Footnotes

[1] In accordance with the finding that older adults show higher variability than younger adults when continuously tapping a specific frequency (Krampe, Mayr, & Kliegl, 2005), the inter-stimulus intervals (ISI) presented were randomly and independently drawn from normal distributions with M = ISI and variances ISIyounger= 0.00163 · ISI – 243 and ISIolder= 0.00134 · ISI – 99 by. Each ISI was only based on the previous stimulus, that is, the correlation between the lags was zero.

[2] To verify our metric to simpler metrics like the relative phase, we also performed all analyses in this article with the average relative phase in each dyad. Overall, the results were the same. However, all results were more pronounced with our metric. For example, in the baseline group the distance of the confidence interval from zero was 18.8 times the breadth of the confidence interval with our metric, while it was only 0.8 using the relative phase ankle. For one of the age-group combinations, the phase ankle metric was not even able to exclude zero from the confidence interval, albeit a clear trend remained.

[3] In models with negligible prior information, the estimation of the DIC is equivalent to the AIC.

[4] Non-informative prior distributions were specified for all fixed and random effects in the model: $\beta_0 \sim N(0, 1{,}000{,}000)$, $\sigma^2_\varepsilon \sim \Gamma(0.001, 100)$, and $\sigma^2_u \sim \Gamma(0.001, 100)$, assuming that variances were gamma-distributed to avoid negative values.

[5] YC: younger child, OC: older child, YA: younger adult, OA: older adult; reference category: YAYA combination. Non-informative prior distributions were specified for all fixed, $\beta_0 - \beta_9 \sim N(0, 1{,}000{,}000)$, and random effects, $\sigma^2_\varepsilon \sim \Gamma(0.001, 100)$; $\sigma^2_u \sim \Gamma(0.001, 100)$, in the model.

[6] BCIs not including "0" as possible values can be interpreted as reliable effects.

Table 1

Model 1: Characteristics of Between-Person and Between-Dyad Variance in Dyadic Asynchrony

(N = 144)

	Mean	95% BCI
Fixed Effects		
Intercept	**8.65**	(8.45, 8.86)
Random Effects (Variance Components)		
Between dyads	**0.06**	(0.04, 0.08)
Between individuals	**0.19**	(0.13, 0.27)
DIC	**59.75**	

Note. BCI = Bayesian Credible Interval; DIC = Deviance Information Criterion; bold = estimated value reliably different from zero.

Table 2

Model 2, 3, & 4: Variance in Dyadic Asynchrony Explained by Dyadic Age-Group Compositions with Different Reference Groups (N = 144)

	Model 2 Reference: Younger Adult – Younger Adult		Model 2a Reference: Younger Child – Younger Child		Model 2b Reference: Older Child – Older Child	
	Mean	**95% BCI**	**Mean**	**95% BCI**	**Mean**	**95% BCI**
Fixed Effects						
Intercept	**7.93**	(7.72, 8.13)	**9.64**	(9.43, 9.85)	**8.53**	(8.32, 8.73)
Dyadic Age-Group Compositions						
Younger child – younger child	**1.71**	(1.41, 2.00)	–	–	**1.11**	(0.82, 1.21)
Younger child – older child	**1.30**	(1.04, 1.55)	**-0.42**	(-0.61, -0.22)	**0.70**	(0.50, 0.89)
Younger child – younger adult	**1.20**	(1.00, 1.39)	**-0.51**	(-0.71, -0.32)	**0.60**	(0.34, 0.85)
Younger child – older adult	**1.24**	(0.99, 1.50)	**-0.47**	(-0.66, -0.27)	**0.65**	(0.39, 0.90)

Older child – older child	**0.60**	(0.31, 0.89)	**-1.11**	(-1.41, -0.82)	–	–
Older child – younger adult	**0.35**	(0.16, 0.55)	**-1.36**	(-1.62, -1.10)	**-0.25**	(-0.44, -0.05)
Older child – older adult	**0.40**	(0.15, 0.66)	**-1.31**	(-1.57, -1.05)	**-0.20**	(-0.40, -0.00)
Younger adult – younger adult	–	–	**-1.71**	(-2.01, -1.41)	**-0.60**	(-0.90, -0.30)
Younger adult – older adult	0.12	(-0.08, 0.31)	**-1.59**	(-1.85, -1.33)	**-0.48**	(-0.74, -0.22)
Older adult – older adult	0.08	(-0.22, 0.38)	**-1.63**	(-1.93, -1.33)	**-0.52**	(-0.81, -0.22)
Variance Components						
Between dyads	**0.04**	(0.03, 0.05)	**0.04**	(0.03, 0.05)	**0.04**	(0.03, 0.05)
Between individuals	**0.03**	(0.02, 0.05)	**0.03**	(0.02, 0.05)	**0.03**	(0.02, 0.05)
DIC	**-6.16**		**-6.23**		**-6.20**	

Note. BCI = Bayesian Credible Interval; DIC = Deviance Information Criterion; bold = estimated value reliably different from zero.

Figure Captions

Figure 1. Asynchrony in dyadic drumming: Illustrative example. Panel A in Figure 1 displays the degree of instantaneous asynchrony in milliseconds, pooled within 200 ms intervals, for a younger child drumming with another younger child. Panel B in Figure 1 displays the degree of asynchrony when the same child is drumming with a younger adult. For each trial, asynchrony is summed over time to obtain a measure of overall asynchrony. These sum scores were averaged across trials within conditions, and log-transformed to better approximate a normal distribution. The log-transformed score of average asynchrony served as the dependent variable in this study. Panels C and D of Figure 1 show how asynchrony accumulates over time.

Figure 2. Dyadic asynchrony as a function of age-group composition of dyad. Higher values correspond to less synchronous dyadic drumming. Error bars refer to the Bayesian Credible Interval (BCI) of the mean, which ranges from the 2.5th to the 97.5th percentile points of the posterior distribution. YC = Younger Child; OC = Older Child; YA = Younger Adult; OA = Older Adult.
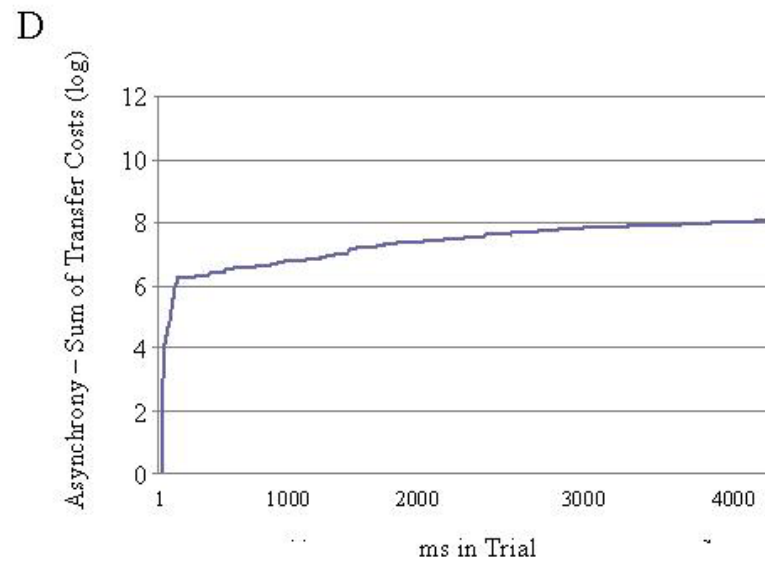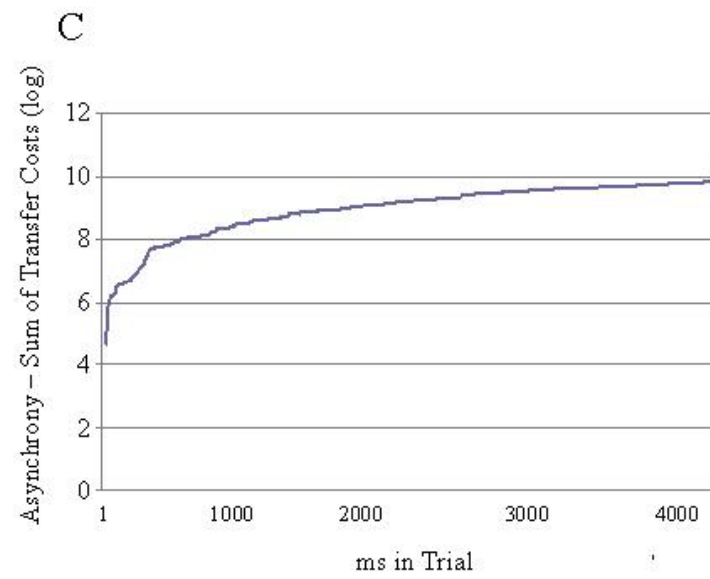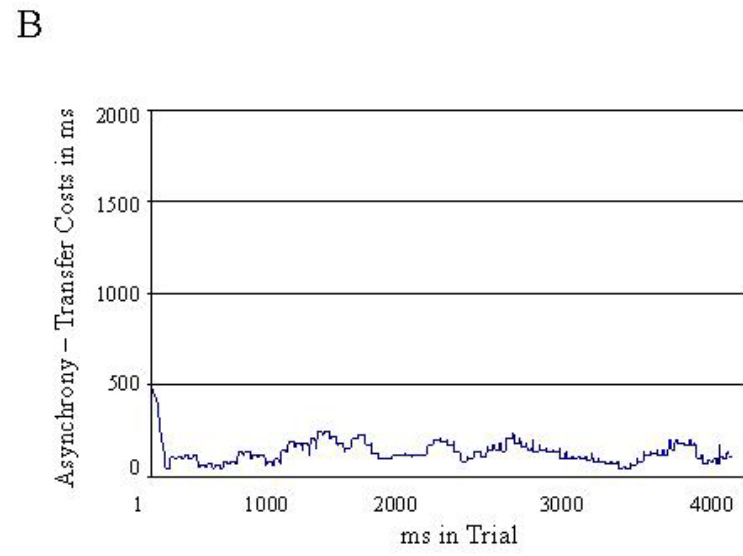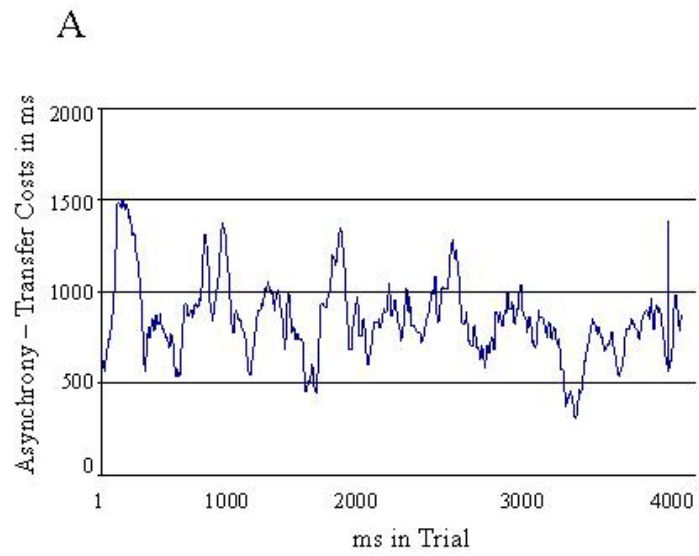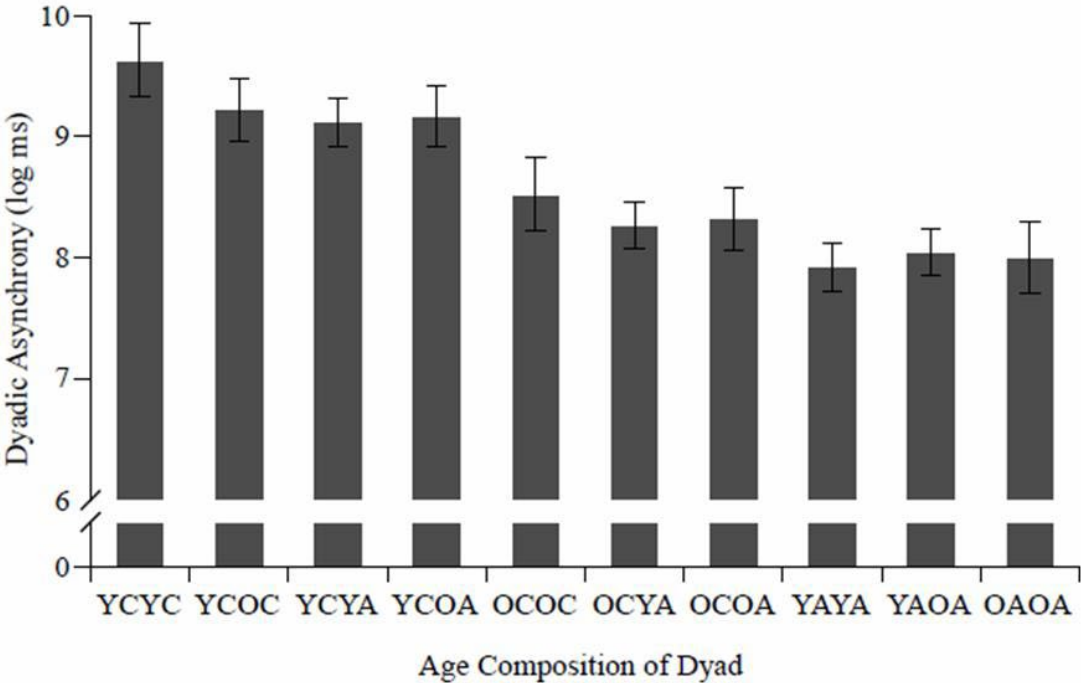
Figure 2

Appendix A

The asynchrony measure between two drumming series *A* and *B* applied in this article is based on the minimal cost to transfer *A* into *B* or vice versa. The cost is the sum of all milliseconds that drum beats from series *A* need to be shifted to match beats from series *B*. If the distances are too large, beats may be removed or inserted for a fixed cost penalty defined as half the mean drumbeat interval of the series in question. The actual asynchrony value is the cost for the most efficient transformation.

In the following, a Java source code is given that computes this transformation. For efficiency, dynamical programming is applied to this problem. A table *T* of length *a* of *A* times the length *b* of *B* is initialized; after the algorithm has stopped, the entry (i,j) in the table will give the minimal cost to transform the suffix of *A* beginning at *i* to the suffix of *B* beginning at *j*. The entry $(a+1,b+1)$ is initialized at zero. Then, a loop counts down *i* from *l1+1* to *0* and *j* from *l2+1* to *0*. In each loop, the table entry at (i,j) is computed dependent on the entries in $(i+1,j+1)$, $(i,j+1)$ and $(i+1,j)$, which have been computed before. The new entry at (i,j) is the minimum of three possibilities: the entry $(i+1,j+1)$ plus the distance of the *i*th beat in *A* to the *j*th beat in *B*, the entry of $(i+1,j)$ plus the deletion penalty, or the entry of the $(i,j+1)$ plus the deletion penalty. After the loop has ended, the entry at $(0,0)$ is the minimal cost to transfer *A* to *B*.

The following Java program computes the entries of *T* and returns the total cost as well as the optimal series of shifts and insertions/deletions:

```
public double[] asynchronity(int[] series1, int[] series2, int penalty) {

  int s1len = series1.length, s2len = series2.length;
  int[][] bestKnownDistance = new int[s1len+1][s2len+1];

  // Computation of Table T
```

```
 bestKnownDistance[s1len][s2len] = 0;
 for (int i = s2len-1; i>=0; i--) bestKnownDistance[s1len][i] =
bestKnownDistance[s1len][i+1] + penalty;
 for (int i = s1len-1; i>=0; i--) bestKnownDistance[i][s2len] =
bestKnownDistance[i+1][s2len] + penalty;
 for (int i=s1len-1; i>=0; i--)
   for (int j=s2len-1; j>=0; j--)  bestKnownDistance[i][j] = Math.min(
       Math.min(bestKnownDistance[i+1][j],bestKnownDistance[i][j+1]) + penalty,
       bestKnownDistance[i+1][j+1] + Math.abs(series1[i]-series2[j]) );


 int gesValue = bestKnownDistance[0][0];


}
```

Appendix B

Implementation of the Statistical Model (WinBugs-Code)

```
asynchrony <- function(){
for(i in 1:C) {
logmean[i] ~ dnorm( mu[i] ,tau) ;
mu[i] <- beta + u2[ vp1[i] ] +  u2[ vp2[i] ] ;}
for (j in 1:N){
u2[j] ~ dnorm( 0 , tau2 ) ;}
beta ~ dflat() ;
tau ~ dgamma(0.001000,0.001000) ;
sigma <- 1/tau;
tau2 ~ dgamma(0.001000,0.001000) ;
sigma2 <- 1/tau2;}
inits <- function(){
    list( beta = runif( 1 , -50 , 50 ) ,
        tau = runif( 1 , 0 , 100000 ) ,
        tau2 = runif( 1 , 0 , 100000 ) ,
        u2 = rnorm( N , 0 , 10 ))
}
```