Infant sensorimotor synchronisation to speech and non-speech rhythms:

A longitudinal study

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Abstract

Impaired sensorimotor synchronisation (SMS) to acoustic rhythm may be a marker of atypical language development. Here, Motion Capture was used to assess gross motor rhythmic movement at six timepoints between five- and 11-months-of-age. Infants were recorded drumming to acoustic stimuli of varying linguistic and temporal complexity: drumbeats, repeated syllables and nursery rhymes. Longitudinal analyses revealed that whilst infants could not yet reliably synchronise their movement to auditory rhythms, infant spontaneous motor tempo became faster with age, and by 11-months, a subset of infants were able to decelerate from their spontaneous motor tempo, to better accord with the incoming tempo. Further, infants became more regular drummers with age, with marked decreases in the variability of spontaneous motor tempo and variability in response to drumbeats. This latter effect was subdued in response to linguistic stimuli. The current work lays the foundation for using individual differences in SMS in infancy to predict later language outcomes.

The ability to generate motor rhythms and couple them to external rhythms underlies many important features of our species, including social interaction, music, dance, and critically, language. The core role of rhythm in language development is captured by the Temporal Sampling framework (TSF, Goswami, 2011, 2018). The TSF proposes that accurate sensory/neural tracking of the slow rhythm patterns in the speech amplitude envelope is a key factor in language development, and that children with disorders of language development will show atypical cortical tracking. Behaviourally, rhythm tracking can be indexed by impaired sensorimotor synchronisation (SMS) to slower beat rates, particularly ~2 Hz, 120 beats per minute (Cumming et al., 2015).

Through childhood, reduced accuracy and greater variability in SMS is linked to poor language outcomes. In typically-developing three- to four-year-olds, less accurate synchronisation is associated with poor pre-reading skills (Woodruff Carr et al., 2014, Politimou, et al., 2019; Rios-Lopez, Molinaro, & Lallier, 2019). Children with dyslexia show less accurate SMS than typically developing peers, (Thomson & Goswami, 2008; Lee et al., 2015; Persici et al., 2019), and SMS is correlated with their language outcomes (Overy et al., 2003; Flaughnacco et al., 2014), over and above general motor dexterity (Thomson & Goswami, 2008). Similar patterns are evident in developmental language disorder (DLD; Corriveau & Goswami, 2009; Cumming et al., 2015), and in children who stutter (Falk et al., 2015; Olander et al., 2010). Recently, this converging evidence has led to an Atypical Rhythm Risk Hypothesis (ARRH; Ladanyi et al., 2020), which contends that impaired SMS, in addition to perceptual timing difficulties, can identify children at risk of speech and language disorders. SMS is a strong candidate for a simple behavioural risk marker of disordered language acquisition (Lundetrae & Thomson, 2018) and may also provide a route for remediation, helping mitigate the considerable life-long costs of language disorders. For example, preschool music interventions enhance phonological awareness (Dege & Schwarzer, 2011; Linnavalli et al., 2018), and children with more variable baseline SMS benefit most from rhythmic movement interventions (Bhide, et al., 2013).

The typical development of SMS is protracted, improving into adulthood (Drake et al., 2000; Thompson et al., 2015). SMS is not reliably seen in children until around 2.5 years (Kirschner & Tomasello, 2009), although case studies show the beginnings of SMS as young as three-four months-of-age (Fujii et al., 2014). SMS is preceded by tempo-flexibility, namely moving faster to faster auditory tempi and slower to slower tempi (Zentner & Eerola, 2010). Spontaneous rhythmic movements are elicited equally by simple isochronous drumbeats and naturalistic music, and generally more to musical stimuli than to naturalistic adult- and infant-directed speech (Zentner & Eerola, 2010). Critically, very young (three to four-month-old) infants tend to move more in silence than to music (Fujii et al., 2014), and six- to 10-month-olds move equally in silence as to music (de l'Etoile et al., 2020). Early repetitive motor movements, in which infants can spend 40% of their time, have been described as stereotypies, reflexive or rhythmic actions that precede deliberately-controlled movement (Thelen, 1981). Establishing infants' natural rate of rhythmic movement in the absence of stimulation (Spontaneous Motor Tempo; SMT) is therefore critical for understanding the development of SMS. Indeed, toddlers and children are only able to achieve SMS to tempi close to their SMT (Bobin-Begue & Provasi, 2008). Newborns (Bobin-Begue et al., 2006), toddlers (Bobin-Begue & Provasi, 2008) and children (McAuley et al., 2006) also demonstrate clear difficulties in deceleration compared to acceleration.

Infant SMT, as measured via a free drumming task, becomes faster and less variable with age, presumably in line with development of motor control (Rocha, Southgate & Mareschal, 2021). Rocha et al (2021) reported an SMT of drumming close to 2 Hz (542 ms Inter-Onset-Interval; IOI) for infants with a mean age of 11 months. This is notable, as during language acquisition the presence of stressed syllables in the speech signal at approximately 2 Hz intervals may provide a skeletal beat-based structure upon which human language processing builds (Cumming et al., 2015). Similar intonational patterns (stressed syllables approximately every 500 ms) are evident across languages (Dauer, 1983), and are carried by slow amplitude modulations in the speech envelope (Leong et al., 2017). The beat

rate of lullabies sung to infants across cultures is also 2 Hz (Trehub & Thorpe, 1989), and amplitude modulations focused around 2 Hz are heightened in infant-directed speech (IDS; Leong et al., 2017). By the TSF, individual differences in infant drumming at a 2 Hz rate could thus predict later language outcomes. Accordingly, repeated measurements of infant rhythm production can provide nuanced understanding of the pathway(s) towards infant SMS, and potentially, language acquisition.

To date, the development of SMS with different types of linguistic and musical stimuli in the same infants has not been studied. Further, existing studies do not consider the development of SMS in relation to infants' own SMT. The BabyRhythm project is a longitudinal study of 122 infants from two- to 30-months-of-age, investigating neural entrainment and SMS to acoustic rhythm in relation to typical language development. Gross motor rhythmic movement was measured using motion capture at six timepoints between five- and 11-months-of-age. Infants were recorded drumming to stimuli of increasing linguistic and temporal complexity: Silence ('Spontaneous Motor Tempo'; SMT), a 2 Hz (500 ms IOI) fixed rate drum beat ('Drum'), a 2 Hz repetition of the syllable 'ta' ('Syllable'), and infant directed songs of varying tempi from 1 – 2.33 Hz ('Nursery Rhymes'). In the current paper we track the typical development of infant SMS to speech and non-speech rhythmic sounds over the first year of life. We hypothesise that infant drumming will i) become faster and more regular with age, ii) will better match the tempo of rhythmic stimuli with age, and iii) will more accurately match the tempo of the simpler rhythmic stimuli.

Methods

Participants

Infants (N = 122, 57 female) were recruited for the longitudinal Cambridge UK BabyRhythm Project. Families were recruited from the local area via flyers and online advertisements, forming a sample of convenience. At laboratory visits at five, six, seven, eight, nine and

eleven months, infants first took part in an EEG testing session (see Attaheri et al., 2022), followed by the motion capture testing session detailed here. Table S1 provides details of infants contributing at each timepoint (5-month N = 65, 6-month N = 67, 7-month N = 68, 8-month N = 74, 9-month N = 82, 11-month N = 87); the full sample were not tested on this paradigm for reasons given below. First, unanticipated building work meant some sessions had to be conducted on a different site without motion capture technology, so infants only took part in the EEG paradigms (5-month N = 16, 6-month N = 21, 7-month N = 14, 8-month N = 9, 9-month N = 5). Second, whilst the EEG protocol was finalised before the wider BabyRhythm project commenced, the motion capture protocol took much longer to be finalised, and due to the longitudinal design of the project, this meant that some motion capture sessions are categorised as ‘pilots’, despite the infants’ membership in the final sample. The pilot phase did not produce comparable data – the baseline SMT condition did not always occur or occur first, the infant did not always have access to a drum, trial lengths were not set, the experimenter in the room did not follow a strict protocol of allowable prompts, and critically, recording thresholds were incorrectly applied, such that other objects in the recording space were detected by the system and many false datapoints were introduced. Data recorded under these conditions have not been processed or analysed, and whilst videos of these sessions are available, they are not presented here (5-month N = 27, 6-month N = 19, 7-month N = 18, 8-month N = 22, 9-month N = 20, 11-month N = 22). Finally, some sessions were not attempted on the day or were terminated without data due to infant fussiness or technical failure (5-month N = 14, 6-month N = 15, 7-month N = 17, 8-month N = 13, 9-month N = 11, 11-month N = 12). The study was approved by the University of Cambridge ethics committee. The caregiver gave written, informed consent concerning the experimental procedure. Infants received a certificate and small age appropriate gift as a thank you for participation (e.g. book, teething toy), and any travel expenses incurred were refunded to the caregiver.

131 Procedure

132 Rigid body arrays of three to four 10mm diameter spherical markers were attached via
133 elastic and Velcro straps onto the infant's wrists, ankles, and head. The infant was loosely
134 strapped into an adapted highchair, and a 12-inch tuneable wood shell and natural skin head
135 drum was secured to the arms of the highchair using clamps, such that the drum formed a
136 'table' in easy reach of the infant (see Figure S1). The infant was facing an LCD screen 2
137 meters away with speakers placed either side. The caregiver sat adjacent to and slightly
138 behind the infant, approximately one meter away. An experimenter sat adjacent to and
139 slightly in front of the infant, holding a separate drum. The infant took part in four conditions
140 (SMT, Drum, Syllable, and Nursery Rhymes). The baseline SMT condition was always
141 presented first, followed by counterbalanced presentation of the three experimental
142 conditions. Each condition block consisted of eight individual trials.

143 During the SMT trials the experimenter demonstrated that the infant's drum made a
144 sound by hitting the drum once, and talking to the infant to draw their attention to the drum.
145 Single drum hits by the experimenter were repeated as necessary during the trial, with a
146 minimum interval of 2 seconds between prompts to ensure no rhythmic example was
147 provided.

148 In the Drum condition the screen and speakers facing the infant presented 8 audio-
149 visual trials of a hand hitting a drum at 2 Hz (500 ms IOI). During the first trial, and then
150 alternating subsequent trials, the experimenter drummed along with the stimuli on their own
151 small bongo drum, such that there were four 'social' trials, and four 'non-social' trials where
152 the experimenter remained present and engaged with the infant but did not produce rhythmic
153 actions in time with the stimuli. Each trial consisted of 16 seconds of stimuli appended by
154 four seconds of silence. The Syllable condition was conducted in the same manner, except
155 that the stimuli were eight trials of an audio-visual presentation of a female repeating the
156 syllable 'ta' at 2 Hz, and the experimenter spoke along with the video during the social trials.

The Nursery Rhyme condition was similar, except that each trial presented a different Nursery Rhyme verse (see Table S2), which varied in tempo (range = 430 ms IOI – 1000 ms IOI, M = 636 ms IOI). The experimenter sang along with the rhymes during the social trials. During all trials, if the infant was not engaged the experimenter would repeat a single hit of the infant's drum to encourage a response. If infants became fussy, the experimenter moved to the next block, or terminated the experiment.

Apparatus

Kinematic data were recorded using a Vicon system. Six to eight Vicon Vero version 1.3 cameras (two cameras were unreliable and offline for some periods of data collection) provided 360-degree coverage of the testing space, and data were captured at a frame rate of 200 Hz using Vicon Tracker (Versions 3.4-3.7). Video stimuli were presented using a custom script in PsychoPy (Peirce et al., 2019), at a comfortable volume, ~65 dB. Responses were time locked to the stimuli using audio triggers recorded via the Vicon Lockbox. Simultaneous video recording of the testing session was conducted using a Logitech C525 webcam positioned on top of the presentation screen, with a 27.75 Hz frame rate, and audio was recorded at a sampling rate of 48000 kHz using a RS Pro Lavalier Wired Microphone lapel microphone clipped to the infant highchair.

Data Processing

Coordinates of infant movement across all recorded markers were processed using the Motion Capture Toolbox (MCT; Burger & Toiviainen, 2013), in Matlab (MATLAB R2017b; The MathWorks Inc.). Missing frames were filled using the 'mcfllgaps' function, which uses linear interpolation. For each trial, markers corresponding to the infants' right and left wrists were selected and a windowed enhanced autocorrelation was performed using the

‘mcwindow’ and ‘mcperiod’ functions, with a 2 second window length and 1 second window hop. The maximum enhanced autocorrelation value for z-axis (vertical plane) was taken as the dependent variable *Regularity*. The periodicity (tempo) of z-axis movement corresponding to this maximal autocorrelation value was extracted, and the mean periodicity across trials used as the dependent variable *Periodicity*. A custom MATLAB script filtered out trials where the maximum enhanced autocorrelation value was less than .01 (to remove noise), and/or gave corresponding periodicities of less than 100 ms (to remove noise and rapid periods) or more than 1500 ms (to remove slow oscillations), then selected the infants’ highest autocorrelation value on each trial from left and right wrists. Mismatch scores were calculated as the difference between the periodicity produced and the target periodicity of each trial. For the SMT trials where no target periodicity was expected, 500 ms (equating to a 2 Hz rhythm) was used as the ‘target’ in order to later test whether infant tempo matching to 2 Hz targets in test trials differed from their baseline performance. Data were exported to R (version 4.0.0, R Core Team, 2021) for analysis.

Video coding was also conducted for a subsample of infants (N = 13, 5-month N = 7 , 6-month N = 7 , 7-month N = 5, 8-month N = 10, 9-month N = 11, 11-month N = 8). Type and frequency of repetitive movements (two or more movements occurring on the same plane, with less than 2 seconds between movements) were annotated by a naïve coder using ELAN (Version 6.0; Sloetjes & Wittenburg, 2008). Table S3 describes the video coding scheme. Annotations started one frame before movements started and ended in the first frame of resting state following the movement. The number of actions performed, as well as the duration of the movement series, were recorded. Infants could perform multiple repetitive actions at the same time (e.g. drumming and nodding head). The duration of vocalisations were also annotated. Data were excluded when the infant became very fussy, was out of view of the camera, or where the parent/experimenter made contact with the infant (e.g. to adjust posture, reposition markers), and could therefore influence their movement. Data were managed using REDCap electronic data capture tools (Harris et al., 2009).

Results

Tempo Mismatch

Figure 1A shows the tempo mismatch of infant drumming (difference from periodicity of infant drumming to target periodicity) at each timepoint (age), in each condition. Tempo mismatch in the silent SMT condition refers to mismatch from a non-existent 500 ms / 2 Hz tempo for comparison with experimental conditions. A mismatch closer to zero in the experimental conditions indicates more accurate performance. Table 1 displays the means and standard deviations for each timepoint by condition. It appears that performance becomes more accurate with age in the Drum and Syllable conditions, but a relatively stable pattern/ less accurate drumming with age appears to characterise Nursery Rhyme condition. Tempo mismatch closer to zero with age in the SMT condition reflects infant drumming becoming closer to a 2 Hz tempo in the absence of any stimuli.

Table 1: *Tempo mismatch scores (milliseconds) by age and condition*

Age	SMT (M(SD))	Drum (M(SD))	Syllable (M(SD))	Nursery Rhyme (M(SD))
5	277(95)	278(76)	264(98)	297(160)
6	181(93)	226(100)	214(126)	292(110)
7	172(96)	209(96)	206(120)	296 (111)
8	155(82)	206(89)	202(114)	309(99)
9	155(100)	202(97)	205(103)	326(109)
11	169(98)	196(83)	213(106)	332(132)

To test this pattern we fit a linear mixed-effects regression model in R (version 4.0.0, R Core Team, 2013) using the lmer() function of the lme4 package (Bates, Maechler, & Bolker,

2013). Tempo mismatch was included as the dependent variable. Predictor variables included the within-participants factors condition (SMT, Drum, Syllable, Nursery Rhymes), and timepoint (5, 6, 7, 8, 9 & 11 months) and the timepoint*condition interaction. Random intercepts were included for subjects, and correlated random slopes for timepoint. The model specification was as follows: 'tempo mismatch ~ condition * timepoint + (1+ timepoint|subject)'. SMT was used as the base case. Significance was calculated using the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017), which applies Satterthwaite's method to estimate degrees of freedom and generate p-values for mixed models.

This analysis indicated a significant main effect of timepoint, such that infants reduce their tempo mismatch with age ($F(5,107) = 7.62, p < .001$), a significant main effect of condition ($F(3,1235) = 119.69, p < .001$), and an age*condition interaction ($F(15, 1227) = 4.13, p < .001$), largely reflecting that tempo mismatch increased with age in the Nursery Rhyme condition, see Table S4 for all coefficients.

Periodicity

Given that in the absence of stimulation (SMT condition), infants seem to show a similar pattern of 'mismatch' as during the Drum and Syllable conditions, it is possible that the age effects reported for tempo mismatch above reflect the general trend for infants to move more quickly as they get older. In Figure 1B, the mean periodicity of infant movement is plotted in seconds for each condition at each timepoint. A linear mixed-effects model with the same structure as above (specification: 'periodicity ~ condition * timepoint + (1+ timepoint|subject)'), shows a main effect of timepoint ($F(5,87) = 5.39, p < .001$), see table S4 all coefficients). There is also a marginal main effect of condition ($F(3, 1170) = 2.61, p = .05$), but no timepoint*condition interaction. Overall, infants are drumming at a faster tempo as they get older (5-month SMT = 655 ms, 11-month SMT = 530 ms). Though the full interaction term is

not significant, it appears that by 11-months, infants are drumming more slowly in the Nursery Rhyme condition ($\beta = 87.56$, $t = 2.80$, $p = .005$; full means in Table 2, coefficients in Table S4). Whilst at 5-months infants show roughly the same periodicity in the Nursery Rhyme condition as in silence, by 11-months infants are *decelerating* the tempo of their drumming (demonstrating a longer IOI) in response to the Nursery Rhyme stimuli, as depicted in Figure 2, and Table S3. To directly test this pattern, we classified Nursery Rhymes as Fast (~2 Hz) or Slow (1 Hz). We ran Bayesian one-sided paired-sample t-tests to demonstrate the strength of evidence for the hypothesis of slower drumming to Slow Nursery Rhymes than in silence, over the null hypothesis of no difference. $BF_{10} > 3$ indicate moderate evidence for a difference between conditions, and $BF_{10} > 10$ indicate strong evidence for a difference. At 11-months, there is indeed strong evidence for slower drumming to the Slow Nursery Rhymes (Slow M = 604 ms, SMT M = 530 ms; $t(61) = -2.93$, $p = .002$, $BF_{10} = 13.24$). This can be contrasted with the infants' performance at 5-months (Slow M = 682 ms, SMT = 655 ms, $t(45) = -.934$, $p = .178$, $BF_{10} = .393$, a non-significant difference with anecdotal evidence for the null hypothesis. Intriguingly, Figure 2 shows a bimodal distribution, suggesting that a sub-group of infants are driving the pattern of deceleration, a point we expand upon in the discussion.

Table 2: *Periodicity (milliseconds) by age and condition*

Age	SMT (M(SD))	Drum (M(SD))	Syllable (M(SD))	Nursery Rhyme (M(SD))
5	655 (152)	648(174)	655(168)	633(199)
6	597 (112)	610(167)	582(173)	599(134)
7	553(116)	552(148)	565(174)	578(146)
8	526(133)	544(154)	548(148)	560(141)
9	534(119)	549(164)	556(146)	576(170)
11	530(137)	533(137)	551(171)	587(187)

272

273 Regularity

274 We predicted that infants would become more regular drummers with age. To test this
 275 hypothesis, we took the maximum enhanced autocorrelation value (reflecting infants' best
 276 performance in each condition; where 0 indicates no relationship, and 1 indicates a perfect
 277 relationship between the z-axis coordinates over a two second moving window), to index the
 278 dependent variable *Regularity*. Figure 1D shows a pattern of higher autocorrelation values at
 279 the later timepoints. This relationship was supported by a further linear mixed effect model
 280 with Regularity as the dependent variable, and the same structure as the models above
 281 (specification: 'regularity ~ condition *timepoint + (1+ timepoint|subject)'), which reveals a
 282 significant main effect of timepoint ($F(5,74) = 20.92$, $p < .001$). We also find a significant
 283 effect of condition ($F(3,1136) = 24.92$, $p < .001$), where regularity is greatest during
 284 spontaneous drumming, and a significant timepoint*condition interaction ($F(15,1128) = 3.63$,
 285 $p < .001$). Inspection of the interaction revealed that whilst infants generally became more
 286 regular (less variable) with age, the increase in regularity was significantly smaller in the
 287 Nursery Rhyme condition at 9-months ($\beta = -0.04$, $p = .046$), and 11-months ($\beta = -0.07$, $p <$
 288 $.001$), a trend also seen in the Syllable condition at 11-months ($\beta = -0.04$, $p = .050$).

289

290 Periodicity and Regularity

291 These analyses suggest that the Nursery Rhyme condition induces different rhythmic
 292 behaviours than the 2 Hz experimental conditions: at later timepoints infants seem to be both
 293 decelerating their drumming from their SMT and producing more variable drumming.
 294 Accordingly, we investigated whether periodicity and regularity of drumming was related
 295 within infants attempting to tempo-match. Figure 1E illustrates the relationship between
 296 regularity and periodicity in the Nursery Rhyme condition at each timepoint. Exploratory

297 correlations show that whilst we do not find evidence of a linear relationship between rate of
 298 movement and the regularity of that movement at 5-months-of-age ($r = -.029$, $t(54) = -.22$, p
 299 $= .829$), at 11-months infants drumming at a slower tempo show significantly less regularity
 300 ($r = -.317$, $t(68) = -2.75$, $p = .008$). However, a regression utilising data from all timepoints
 301 (specification: $\text{regularity} \sim \text{periodicity} + \text{periodicity}^2$) suggests an overarching quadratic
 302 relationship. We see a positive relationship between regularity and periodicity, suggesting
 303 that infants who were drumming more slowly to the nursery rhymes were also drumming
 304 more regularly ($\beta = 0.0004$, $t(391) = 3.021$, $p = .003$), but a negative binomial coefficient ($\beta =$
 305 -0.0000004 , $t(391) = -4.208$, $p < .001$; $F(2,391) = 18.85$, $p < .001$), suggesting that infants
 306 who were drumming very slowly were also drumming irregularly.

Figure 1. Box plots and jittered raw data, for each condition, and across age, for A) infant tempo mismatch (difference in periodicity of drumming from the target rate of stimuli), B) Periodicity of drumming in seconds, and C) Regularity of infant drumming as indexed by their maximum enhanced autocorrelation score (0-1). Note that in A, there was not a target rate for infant drumming in the SMT condition, and an artificial 2 Hz (500 ms IOI) target rate has been imposed for comparability across conditions. Horizontal lines in B show the mean target IOI for each experimental condition (no target IOI for baseline SMT condition). **Figure 1D.** Scatterplot shows the raw data, and polynomial (second order) regression lines with 95% CI, of the relationship between regularity and periodicity of infant drumming in the Nursery Rhyme condition at each timepoint.

Figure 2. Periodicity of infant drumming during silence (SMT) and Slow (1 Hz) Nursery Rhymes, at 5-months (left, pink) and 11-months (right, green). Group level Means and CI are shown in bold, and individual data points are connected. Half violins show the distribution of results.

308 Type and frequency of rhythmic movements

309 Finally, whilst the focus of our analyses thus far has been on infant drumming as a potential
 310 future marker of language acquisition, here we present a general description of infant
 311 rhythmic behaviour, across effectors, that were exhibited in response to our stimuli. Video,
 312 rather than motion capture data, are used for this purpose, to code a wide range of motions
 313 (see Table S3 for coding scheme). A pseudo-randomly selected subsample of infants'
 314 videos (infants chosen who had multiple recordings; N = 13, 5-month N = 7, 6-month N = 7,
 315 7-month N = 5, 8-month N = 10, 9-month N = 11, 11-month N = 8) were manually coded for
 316 the type, number and duration of repetitive movements according to the coding scheme
 317 (Table S3), and duration of vocalisations. On average, infants spent 26 % of the trial duration
 318 performing repetitive movements. Drumming was prominent, but a variety of movements
 319 were seen at all ages, with rhythmic sucking and circling of the ankles particularly notable
 320 (see Figure 3A). Note that movements could take place concurrently across the body.

321 Infants engaged in more repetitive movements in the first SMT condition than in the
 322 subsequent experimental conditions (SMT M = .377, SD = .163, Drum M = .225, SD = .140,
 323 Syllable M = .273, SD = .163, Nursery Rhyme M = .233, SD = .137; see Figure 3B),
 324 suggesting that they attended to the acoustic stimuli. Frequentist and Bayesian repeated
 325 measure ANOVAs with post hoc tests revealed a strong effect of condition ($F = 13.106$, $p <$
 326 $.001$), which was driven by more rhythmic movement in silence than during stimulation (all p
 327 $< .001$; all $BF_{10} > 39$), and no difference between experimental conditions (all $p > .483$; all BF
 328 < 1 ; Drum and NR comparison $p = 1.00$, $BF_{10} = .181$). Importantly, this suggests that
 329 differences in tempo matching/regularity found in the Nursery Rhyme condition are not due
 330 to a different level of participation. Further, infants were also moving for an equal proportion
 331 of the fast and slow nursery rhymes, with a Bayesian paired t-test confirming good evidence
 332 for no difference in proportion of time spent moving between the fast NR (M = .235) and slow
 333 NR (M = .213) conditions, $BF_{10} = .235$; see Figure 3C.

In pilot testing, we observed that some infants moved more when they had an interactive partner drumming or singing with them, but that some infants were more inhibited when the partner joined in. We therefore alternated trials where the partner was drumming/singing and not drumming/singing, throughout all experimental conditions (i.e. not including SMT). In this sub-sample qualitative analysis, we find very clear evidence that infants spent a higher proportion of time in rhythmic movement when the partner was not drumming/singing ($M = .285$, $SD = .138$) than when they were ($M = .236$, $SD = .121$); ($t(2,47) = 4.40$, $p < .001$; $BF_{10} = 360.77$, Figure 3D).

344 **Figure 3A.** Total duration of rhythmic movements by movement type, by condition. Note:
345 Movements could be performed concurrently (e.g. drumming and kicking). **Figure 3B.**
346 Proportion of time spent in rhythmic movement by age and condition. **Figure 3C.** Proportion
347 of time spent in rhythmic movement in Slow (1 Hz) and Fast (~2 Hz) Nursery Rhymes.
348 Group level Means and CI are shown in bold, and individual data points are connected. Half
349 violins show the distribution of results. **Figure 3D.** Proportion of time spent in rhythmic
350 movement by whether the experimenter was drumming or singing along with the pre-
351 recorded video stimuli.

Discussion

Here we explored infants' ability to generate motor rhythms and couple them to external acoustic speech (syllable, nursery rhyme) and non-speech (drumbeat) rhythms. Importantly, we also measured infants' natural rate of rhythmic movement in the absence of stimuli (SMT) to contextualise the development of sensorimotor synchronisation (SMS). Through novel longitudinal measurements, we show that infants' rhythmic movement becomes faster and more regular with development. We also show, for the first time, developmental change in the ability of infants to adapt their movements in response to auditory stimuli over the first year of life. Particularly, by 11-months infants were decelerating from their SMT to better match the rate of slow nursery rhymes. Accordingly, behavioural markers of rhythm development can be identified within the first year of life. Individual differences in these measures can potentially be used in future work to identify those at risk of poorer language outcomes.

The updated TSF (Goswami, 2018) predicts that SMS around a beat rate of 2 Hz could be developmentally important. Infant SMT indeed increased towards a ~2 Hz tempo over time, a pattern mirrored when infants were exposed to a 2 Hz drum beat or repeated syllable. Critically, in the Nursery Rhyme condition, older infants adapted to the slower sung tempi. Given established difficulties in deceleration through childhood (Bobin-Begue & Provasi, 2008; McAuley et al., 2006), it is particularly noteworthy that at 11-months approximately half our sample showed deceleration from SMT when drumming with slow nursery rhymes. Change from SMT to slow rhythms may provide a critical index of early sensorimotor synchronisation ability. We did not find differences in periodicity or tempo matching between the repeated drum beat and repeated syllable conditions. The presence of a strong beat in both conditions apparently ameliorated potential effects of increased complexity regarding the repeated 'ta' sound, which had a longer and more variable

377 amplitude rise time than the drumbeat. This increased linguistic complexity did not affect
378 infant matching of their rate of movement.

379 Overall, infant drumming showed a significant increase in regularity with
380 development. Infant actions were more variable when the infant was attempting
381 sensorimotor synchronisation than when producing an internally generated rhythm, as
382 regularity was greater in silence than during auditory stimulation. However, gains in
383 regularity were not as pronounced in the linguistic conditions. A similar rate of drumming but
384 diverging variability across the Drum and Syllable conditions may indicate that rather than
385 temporal matching per se, infants struggle with consistency of responding. Consistency is an
386 important indicator for children with dyslexia, who are significantly more variable than
387 typically-developing controls in tapping to a 2 Hz metronome beat (Thomson & Goswami,
388 2008). Regularity of drumming did not increase in the Nursery Rhyme condition, despite
389 infants being better able to decelerate from their SMT with age. Indeed, at 11-months,
390 infants who were drumming more slowly also showed greater variability. As we follow up
391 these infants' language development, the possible importance of consistency, deceleration
392 and regularity regarding individual differences may be revealed.

393 Qualitative analyses indicated that the differences found across conditions were
394 unlikely to be due to a differential level of engagement. Infants exhibited an equal level of
395 rhythmic movements in the most complex Nursery Rhyme condition and the simplest Drum
396 condition. However, the generalizability of our findings may depend on the different kinds of
397 stimulation compared. While similar infant data could be expected across languages for
398 drumbeats and syllables, the Nursery Rhyme condition may prove an exception. The
399 qualitative analyses also showed that infants moved more when the adult experimenter was
400 not drumming/singing along with the stimuli. Whilst a social partner is beneficial for achieving
401 synchrony in toddlerhood (Kirschner & Tomasello, 2009), infants inhibit dance behaviours in
402 the presence of a partner (Rocha & Mareschal, 2017). Hence there may be different

403 motivations for interpersonal versus sensorimotor synchronisation and this may also affect
404 generalizability.

405 As our infants age, our individual differences approach will allow one of the core
406 tenets of the TSF to be tested. The infants enrolled in the current study are being followed to
407 2.5 years-of-age, participating in a battery of language tasks measuring phonological
408 awareness, grammar, speech timing, and vocabulary. Our ongoing work will use the data in
409 the current report to feed into models of language outcome, which may contribute vital
410 knowledge regarding developmental pathways towards successful language acquisition.
411 Whilst in this case SMS was measured using Motion Capture, which requires specialist
412 equipment, the same analyses can be applied to 2D video data using AI technology, or even
413 by measuring the sound signal produced by the drumming infant (e.g. Rocha et al., 2021).
414 The current data can therefore provide distinct added value to neural measures in finding
415 behavioural markers that are suitable for large scale, low cost, screening for intervention.

416 In conclusion, our current findings characterise the typical development of
417 spontaneous motor tempo and infant sensorimotor synchronisation over the first year of life.
418 We find that prior to their first birthday, infants' rhythm production becomes faster and more
419 regular, and that infants become better able to adapt their tempo towards the rate of external
420 auditory stimulation. We further show that by the end of the first year, more complex
421 linguistic stimuli are met with more variable infant behaviour. This is potentially
422 developmentally important, given that rhythmic linguistic routines characterise nursery
423 settings in many cultures and are thought to benefit language development. In future
424 analyses with our sample, we can extend our SMS findings to identify which are early
425 markers of successful and less successful language acquisition. Measurement of
426 sensorimotor synchronisation, in contrast to neural measures, is a cheap, accessible, and
427 sustainable platform that may identify those at risk of disordered language development.

Accordingly, the current study has potentially far-reaching implications for both theory and practise.

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Supplementary Materials

Table S1 *Number and age in days of infants who provided data at each time point*

Time Point	N	Mean Age Days (Min – Max)
5 months	65	144 (134 – 155)
6 months	67	186 (165 – 201)
7 months	68	214 (209 – 229)
8 months	74	242 (232 – 256)
9 months	82	270 (265 – 283)
11 months	87	333 (325 – 350)

608

609 Figure S1. Photograph of infant seated in adapted highchair with drum attachment, with

610 head and wrist reflective markers visible.

611 Table S2 *Details of Nursery Rhyme stimuli (NB. IOI calculated as the average distance in*
 612 *milliseconds between p-centres of each stress syllable)*

Rhyme	Rate (Hz)	IOI (ms)	Presentation Order	Slow/Fast
Mary Had a Little Lamb (verse 1)	1	1000	3	Slow
Mary Had a Little Lamb (verse 2)	1	1000	4	Slow
Mary Had a Little Lamb (verse 3)	1	1000	5	Slow
Incy Wincy Spider	1.82	550	2	Fast
Sing a Song of Sixpence	1.89	530	7	Fast
Twinkle Twinkle Little Star	2	500	8	Fast
Frere Jacques	2.13	470	1	Fast
Simple Simon	2.33	430	6	Fast

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615

616 Table S3 *Behavioural coding scheme*

Behaviour	Criteria
Drumming	Vertical arm movements, does not need to make contact with the drum
Bouncing	Lengthens and contracts torso in vertical motion
Kicking	Swings leg(s) in any direction
Rocking/Swaying	Moves torso left to right or forward and backward, does not include up and down motion
Nodding	Moves head on a single plane in any direction
Clapping	Claps palms of hands together
Wrist circle	Circles hand in any direction from wrist
Ankle circle	Circles foot in any direction from ankle
Hand other	Other repetitive movements of the hand e.g. scratching the
Sucking	drum Sucking on thumb/hand/dummy

617

618

619 Table S4 *Table of coefficients for linear mixed effect models*

<i>Predictors</i>	Tempo Mismatch			Periodicity			Regularity		
	<i>Estimates</i>	<i>CI</i>	<i>p</i>	<i>Estimates</i>	<i>CI</i>	<i>p</i>	<i>Estimates</i>	<i>CI</i>	<i>p</i>
(Intercept)	279.1 2	251.26 – 306.9 7	<0.001	645.6 5	603.16 – 688.1 4	<0.001	0.50	0.48 – 0.53	<0.001
condition [drum]	-0.33	- 36.67 – 36.01	0.986	-1.81	- 49.38 – 45.75	0.941	-0.04	- 0.07 – 0.00	0.024
condition [ta]	-12.05	- 52.22 – 28.12	0.557	5.99	- 46.86 – 58.84	0.824	-0.02	- 0.05 – 0.01	0.226
condition [nr]	16.73	- 18.56 – 52.01	0.353	-21.94	- 67.93 – 24.06	0.350	-0.02	- 0.05 – 0.01	0.111
timepoint [6]	-97.59	- 135.35 – 59.83	<0.001	-48.26	- 103.94 – 7.42	0.089	0.08	0.04 – 0.11	<0.001
timepoint [7]	- 105.7 1	- 143.20 – 68.21	<0.001	-90.60	- 145.14 – 36.06	0.001	0.08	0.05 – 0.11	<0.001
timepoint [8]	- 125.0 0	- 160.59 – 89.41	<0.001	- 125.1 0	- 181.73 – 68.47	<0.001	0.11	0.07 – 0.14	<0.001
timepoint [9]	- 125.2 0	- 160.04 – 90.35	<0.001	- 106.5 5	- 160.46 – 52.64	<0.001	0.11	0.08 – 0.14	<0.001
timepoint [11]	- 110.8 0	- 147.04 – 74.56	<0.001	- 111.1 0	- 168.90 – 53.30	<0.001	0.12	0.08 – 0.15	<0.001
condition [drum] * timepoint [6]	40.91	- 9.78 – 91.61	0.114	11.13	- 55.17 – 77.44	0.742	-0.03	- 0.07 – 0.01	0.162

condition [ta] *	43.15	-	0.121	-22.19	-	0.544	0.01	-	0.812
timepoint [6]		11.41 – 97.71			93.83 – 49.45			0.04 – 0.05	
condition [nr] *	93.57	44.51 – 142.62	<0.00 1	23.78	-	0.466	0.00	-	0.817
timepoint [6]					40.16 – 87.71			0.04 – 0.05	
condition [drum] *	36.23	-	0.150	3.47	-	0.916	0.01	-	0.675
timepoint [7]		13.07 – 85.52			60.91 – 67.85			0.03 – 0.05	
condition [ta] *	45.74	-	0.088	8.57	-	0.807	0.01	-	0.688
timepoint [7]		6.76 – 98.23			60.20 – 77.34			0.04 – 0.05	
condition [nr] *	105.2 5	56.62 – 153.89	<0.00 1	48.80	-	0.131	0.01	-	0.564
timepoint [7]					14.57 – 112.16			0.03 – 0.05	
condition [drum] *	51.72	3.68 – 99.77	0.035	19.89	-	0.535	-0.00	-	0.812
timepoint [8]					42.87 – 82.65			0.05 – 0.04	
condition [ta] *	59.46	8.06 – 110.87	0.023	20.41	-	0.553	-0.03	-	0.167
timepoint [8]					47.02 – 87.83			0.07 – 0.01	
condition [nr] *	137.4 3	90.26 – 184.60	<0.00 1	55.76	-	0.075	-0.03	-	0.153
timepoint [8]					5.71 – 117.23			0.07 – 0.01	
condition [drum] *	46.84	-	0.053	11.50	-	0.716	-0.00	-	0.875
timepoint [9]		0.61 – 94.28			50.51 – 73.52			0.04 – 0.04	
condition [ta] *	64.77	13.87 – 115.67	0.013	16.32	-	0.632	-0.02	-	0.347
timepoint [9]					50.46 – 83.11			0.06 – 0.02	
condition [nr] *	154.0 4	107.60 – 200.4 7	<0.00 1	59.52	-	0.054	-0.04	-	0.044
timepoint [9]					0.99 – 120.03			0.08 – 0.00	
condition [drum] *	28.37	-	0.239	7.51	-	0.812	0.01	-	0.668
timepoint [11]		18.84 – 75.59			54.22 – 69.24			0.03 – 0.05	
condition [ta] *	59.10	8.61 – 109.60	0.022	20.30	-	0.548	-0.04	-	0.051
timepoint [11]					45.94 – 86.54			0.09 – 0.00	

condition [nr]	149.2	102.38	<0.00	87.56	26.41 –	0.005	-0.07	-	<0.001
*	4	– 196.1	1		148.72			0.11 – -	
timepoint [11]		0						0.03	

Random Effects

σ^2	9119.13		15455.45		0.01
T ₀₀	2556.54	filename	12157.84	filename	0.00 filename
T ₁₁	3915.65	filename.timepoint6	17759.63	filename.tim epoint6	0.00 filename.timepoint6
	4017.61	filename.timepoint7	16813.11	filename.tim epoint7	0.01 filename.timepoint7
	2515.78	filename.timepoint8	24053.45	filename.tim epoint8	0.01 filename.timepoint8
	1938.65	filename.timepoint9	18939.20	filename.tim epoint9	0.01 filename.timepoint9
	4481.56	filename.timepoint11	29139.85	filename.tim epoint11	0.01 filename.timepoint11
ρ_{01}	-0.75		-0.79		0.13
	-0.66		-0.82		-0.11
	-0.77		-0.89		-0.15
	-0.56		-0.74		-0.16
	-0.78		-0.82		-0.08
ICC	0.17				0.47
N	100	filename	100	filename	100 filename
Observations	1537		1537		1537
Marginal R ² / Conditional R ²	0.221 / 0.356		0.073 / NA		0.110 / 0.525

621

622 Table S5 *Tempo Mismatch and Periodicity in milliseconds, for Slow and Fast Nursery*
 623 *Rhymes*

Age	Tempo Mismatch		Periodicity	
	Slow NR (M(SD))	Fast NR (M(SD))	Slow NR (M(SD))	Fast NR (M(SD))
5	370 (221)	252(146)	682(238)	618(208)
6	438 (183)	206(126)	576(194)	620(147)
7	466(178)	210(134)	557(201)	600(182)
8	471(158)	219(97)	575(204)	555(167)
9	468(188)	220(112)	572(238)	573(181)
11	454(160)	239(139)	604(231)	580(208)

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