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RESEARCH ARTICLE

Precursors to infant sensorimotor synchronization to speech and non-speech rhythms: A longitudinal study

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Abstract

Impaired sensorimotor synchronization (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 time points between 5- and 11 months of age. Infants were recorded drumming to acoustic stimuli of varying linguistic and temporal complexity: drumbeats, repeated syllables and nursery rhymes. Here we show, for the first time, developmental change in infants' movement timing in response to auditory stimuli over the first year of life. Longitudinal analyses revealed that whilst infants could not yet reliably synchronize their movement to auditory rhythms, infant spontaneous motor tempo became faster with age, and by 11 months, a subset of infants decelerate from their spontaneous motor tempo, which better accords 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 precursors of SMS in infancy to predict later language outcomes.

KEYWORDS
infancy, motion capture, rhythm, sensorimotor synchronization, speech

Research Highlight

- We present the first longitudinal investigation of infant rhythmic movement over the first year of life
- Whilst infants generally move more quickly and with higher regularity over their first year, by 11 months infants begin to counter this pattern when hearing slower infant-directed song

- Infant movement is more variable to speech than non-speech stimuli
- In the context of the larger Cambridge UK BabyRhythm Project, we lay the foundation for rhythmic movement in infancy to predict later language outcomes

1 INTRODUCTION

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 sensory discrimination of rhythm, atypical cortical tracking of slow speech rhythm patterns and impaired behavioural synchronization to a rhythmic beat. Behaviourally, poor rhythm tracking can be indexed by impaired sensorimotor synchronization (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 are linked to poor language outcomes. In typically-developing three- to four-year-olds, less accurate synchronization is associated with poor pre-reading skills (Carr et al., 2014; Politimou, et al., 2019; Rios-Lopez et al., 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 (Flaugnacco et al., 2014; Overy et al., 2003), 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 to 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 6- 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 et al., 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 & Trainor, 1998), 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 a nuanced understanding of the pathway(s) towards infant SMS, and potentially, language acquisition.

To date, developmental precursors 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 tempo-flexibility in relation to infants' own SMT. The Cambridge UK BabyRhythm project is a longitudinal study of 122 infants from two- to 30-months-of-age, investigating neural entrainment and behavioural responses 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. During the project, 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 naturalistic infant directed nursery rhymes sung at varying tempi from 1 – 2.33 Hz ('Nursery Rhymes'). In the current paper, we track infant precursors to SMS to speech and non-speech rhythmic sounds over the first year of life. We hypothesize 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 than the more complex naturalistic infant-directed song.

2 | METHODS

2.1 | 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 finalized before the wider BabyRhythm project commenced, the motion capture protocol took much longer to be finalized, and due to the longitudinal design of the project, this meant that some motion capture sessions are categorized 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 data points 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.

2.2 | Procedure

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

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

In the Drum condition the screen and speakers facing the infant presented 8 audio-visual trials of a hand hitting a drum at 2 Hz (500 ms IOI). During the first trial, and then alternating subsequent trials, the experimenter drummed along with the stimuli on their own small bongo drum, such that there were four 'social' trials, and four 'non-social' trials where the experimenter remained present and engaged with the infant but did not produce rhythmic actions in time with the stimuli. Each trial consisted of 16 seconds of stimuli appended by four seconds of silence. The Syllable condition was conducted in the same manner, except that the stimuli were eight trials of an audio-visual presentation of a female repeating the 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). Nursery Rhymes were selected from the larger project (see Attaheri et al., 2022a) as exemplars which were sung (i.e., not chanted), with a range of tempi. 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.

2.3 | 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, 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.

2.4 | 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 'mcfillgaps' 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 s window length and 1 s 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 or 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 vocalizations 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).

3 | RESULTS

3.1 | 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 is apparent in the 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.

To explore the conditions further, we fit a linear mixed-effects regression model in R (version 4.0.0, R Core Team, 2021) using the lmer() function of the lme4 package (Bates et al., 2015). Tempo mismatch was included as the dependent variable. Predictor variables comprised the within-participants factors condition (SMT, Drum, Syllable, Nursery Rhymes), timepoint (5, 6, 7, 8, 9 & 11 months) and the timepoint*condition interaction. Random intercepts were included for participants, 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 et al., 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 ($F(5,106) = 8.49$, $p < 0.001$), a significant main effect of condition ($F(3,1217) = 117.42$, $p < 0.001$), and an age*condition interaction ($F(15, 1209) = 4.48$, $p < 0.001$). The interaction arose largely because tempo mismatch increased with age in the Nursery Rhyme condition, see Table S4 for all coefficients.

3.2 | 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 probable that the age effects reported for tempo mismatch above reflect the general trend for infants to move more

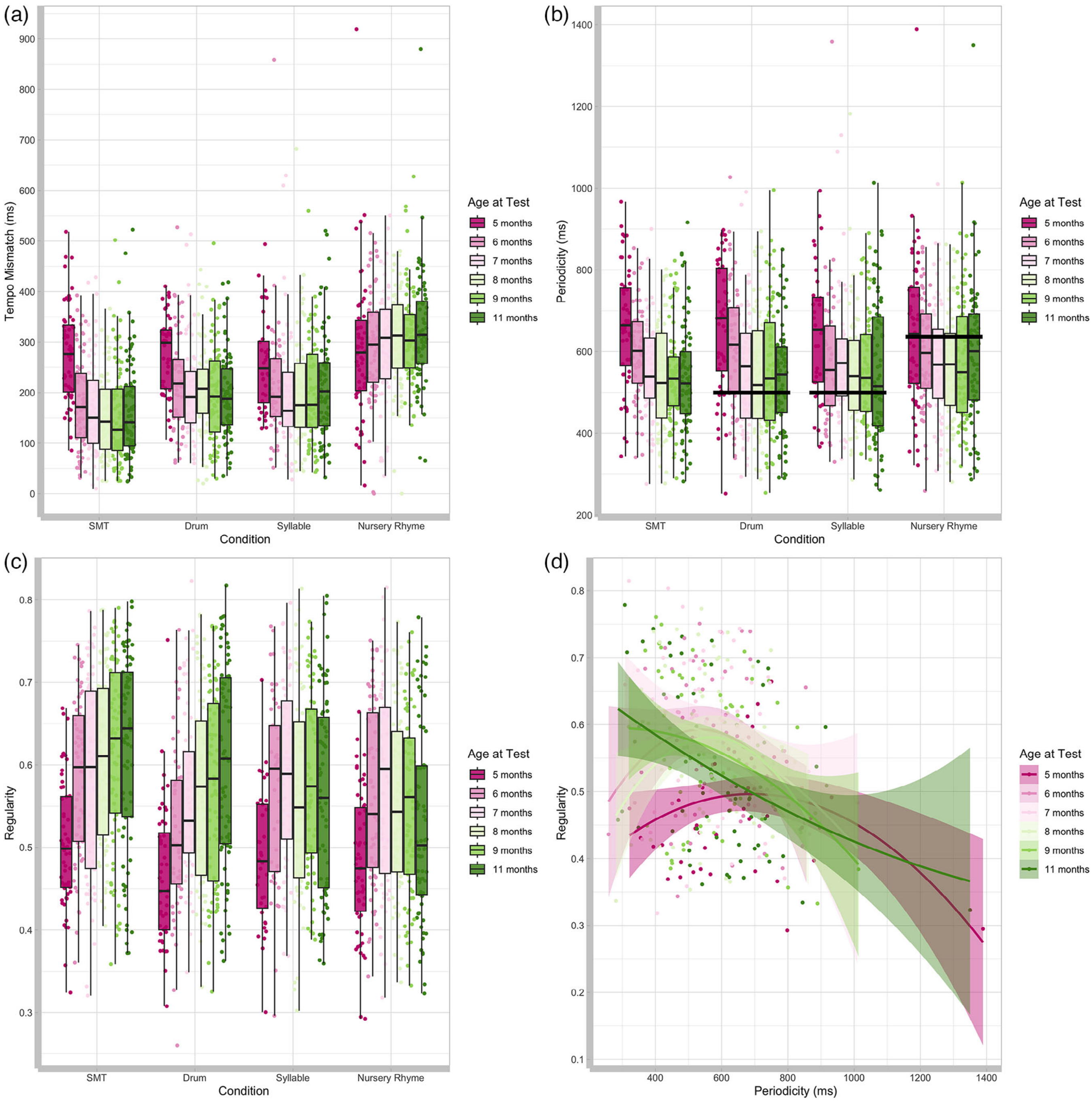

FIGURE 1 Box plots and jittered raw data, for each condition, and across age, for (a) infant tempo mismatch (difference in periodicity of drumming from the target rate of stimuli), (b) Periodicity of drumming in seconds, and (c) Regularity of infant drumming as indexed by their maximum enhanced autocorrelation 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). (d) 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.

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'), showed a main effect of timepoint ($F(5,84) = 5.39$, $p < 0.001$), see Table S4 all coefficients), and condition ($F(3, 1134) = 3.20$, $p = 0.023$)), but no timepoint*condition interaction. Overall, infants were drumming at a faster tempo as they got 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 counter the clear pattern of

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	(096)	277	(077)	258	(093)	285	(145)
6	181	(093)	223	(099)	214	(126)	292	(110)
7	172	(096)	207	(096)	199	(121)	295	(112)
8	152	(08)	205	(089)	201	(114)	306	(096)
9	154	(101)	199	(098)	202	(103)	315	(093)
11	166	(097)	193	(083)	213	(107)	324	(115)

TABLE 2 Periodicity (milliseconds) by age and condition.

Age	SMT (M(SD))		Drum (M(SD))		Syllable (M(SD))		Nursery Rhyme (M(SD))	
5	663	(143)	660	(161)	646	(162)	648	(185)
6	597	(112)	619	(154)	582	(173)	599	(134)
7	553	(116)	554	(149)	584	(155)	578	(147)
8	530	(127)	548	(150)	553	(144)	564	(136)
9	541	(114)	559	(156)	562	(139)	580	(152)
11	535	(134)	533	(133)	554	(171)	596	(179)

drumming faster with age to drum more slowly in the Nursery Rhyme condition ($\beta = 85.51$, $t = 2.83$, $p < 0.005$; full means in Table 2, coefficients in Table S4). The Nursery Rhyme condition provides a range of tempi for infants to move with.

Accordingly, we next ran exploratory analyses to investigate whether the slower drumming at 11-months in the Nursery Rhyme condition reflected infant tempo modulation according to the rate of the song. Nursery Rhymes were classified post-hoc as Fast (~2 Hz) or Slow (1 Hz). Whilst infants drummed more quickly in the Fast condition than the Slow condition at 11-months (see Figure 2), this difference was not statistically significant (Fast M IOI = 588 ms, Slow M IOI = 614 ms, $p > 0.05$). However, a further question is whether infants were adapting away from their SMT when drumming to the Nursery Rhymes. If they were actively modulating their tempo, infants should show a slower periodicity during the Slow Nursery Rhymes than in silence, and faster periodicity during the Fast Nursery Rhymes than in silence. A Bayesian one-sided paired-sample t-test was applied to test the strength of evidence for the hypothesis of slower drumming to Slow Nursery Rhymes than in silence, over the null hypothesis of no difference. $BF_{10} > 10$ indicate strong evidence for a difference. There was very strong evidence for slower drumming in the Slow Nursery Rhymes than in silence (SMT M = 535 ms, Slow M = 614 ms; $t(58) = -3.363$, $p < 0.001$, $BF_{10} = 43.268$). In the equivalent analysis for Fast Nursery Rhymes, there was evidence for the null hypothesis ($BF_{10} < 0.3$ indicate moderate evidence for the null; SMT M = 535 ms, Fast M = 588; $t(65) = -2.520$, $p = 0.993$, $BF_{10} = 0.040$). These exploratory analyses suggest that at 11-months, infants are responding differently in the Nursery Rhyme condition dependent on the tempo of the rhyme they were hearing. Intriguingly, Figure 2 shows a bimodal distribution in the rate of drumming in the Slow Nursery Rhymes (Hartingtons' dip test for unimodal distribution D = 0.062, $p = 0.065$). This suggests that a subgroup of infants were driving the pattern of deceleration, a point we expand upon in the discussion.

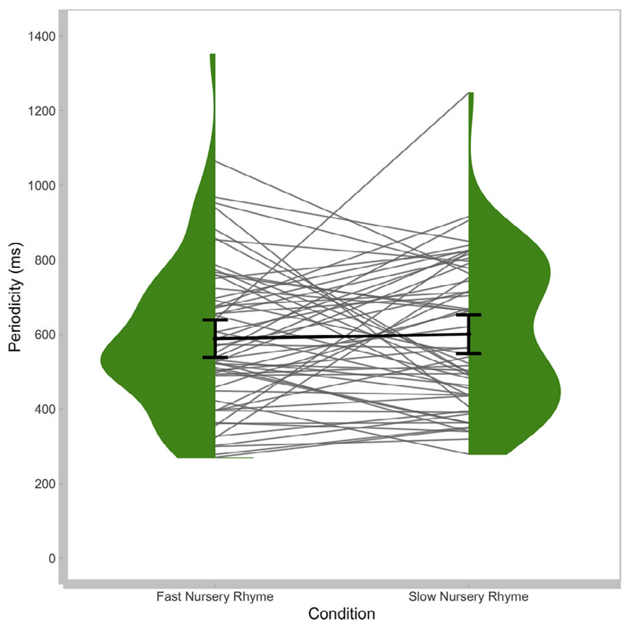

FIGURE 2 Periodicity of infant drumming at 11-months during Fast Nursery Rhymes and Slow Nursery Rhymes. Group level Means and CI are shown in bold, and individual data points are connected. Half violins show the distribution of results.

3.3 | Regularity

We predicted that infants would become more regular drummers with age. To test this hypothesis, we took the maximum enhanced autocorrelation value (reflecting infants' best performance in each condition; where 0 indicates no relationship, and 1 indicates a perfect relationship between the z-axis coordinates over a two second moving window), to index the dependent variable *Regularity*. Figure 1c shows a pattern of higher autocorrelation values at the later timepoints. This relationship was explored by a further linear mixed effect model with Regularity as the dependent variable, and the same structure as the models above (specification: 'regularity ~ condition *timepoint + (1+ timepoint|subject)'). The model revealed a significant main effect of timepoint ($F(5,74) = 21.86$, $p < 0.001$) and a significant main effect of condition ($F(3, 1100) = 23.86$, $p < 0.001$). The significant main effects show that infants indeed become more regular drummers with age, while regularity is greatest during spontaneous drumming. There was also a significant timepoint*condition interaction ($F(15, 1093) = 3.63$, $p < 0.001$). Inspection of the interaction revealed that whilst infants generally became more regular (less variable) with age, the increase in regularity was significantly smaller at 11-months in the Syllable ($\beta = -0.04$, $p = 0.037$), and Nursery Rhyme ($\beta = -0.07$, $p < 0.001$) conditions.

3.4 | Periodicity and regularity

Finally, we investigated whether periodicity and regularity of drumming were related within infants. The previous analyses suggest that the Nursery Rhyme condition induced different rhythmic behaviours compared to the 2 Hz experimental conditions: at the eldest timepoint infants seemed to be both decelerating their drumming from their SMT and producing more variable drumming. Figure 1e illustrates the relationship between regularity and periodicity in the Nursery Rhyme condition at each timepoint. Exploratory correlations showed that whilst there was no evidence of a linear relationship between rate of movement and the regularity of that movement at 5-months-of-age ($r = -0.106$, $t(52) = -0.765$, $p = 0.448$), at 11-months infants drumming at a slower tempo showed significantly less regularity ($r = -0.415$, $t(66) = -3.70$, $p < 0.001$). A regression utilizing data from all timepoints (specification: regularity ~ periodicity + periodicity^2) was suggestive of an overarching quadratic relationship, with a negative binomial coefficient ($\beta = -0.0000003$, $t(381) = -2.42$, $p = 0.016$; $F(2,381) = 17.79$, $p < 0.001$).

3.5 | Type and frequency of rhythmic movements

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

Infants engaged in more repetitive movements in the first SMT condition than in the subsequent experimental conditions (SMT $M = 0.377$, $SD = 0.163$, Drum $M = 0.225$, $SD = 0.140$, Syllable $M = 0.273$, $SD = 0.163$, Nursery Rhyme $M = 0.233$, $SD = 0.137$; see Figure 3b), suggesting that they attended to the acoustic stimuli. Frequentist and Bayesian repeated measure ANOVAs with post hoc tests revealed a strong effect of condition ($F(3, 41) = 13.106$, $p < 0.001$), which was driven by more rhythmic movement in silence than during stimulation (all $p < 0.001$; all $BF_{10} > 39$), and no difference between experimental conditions (all $p > 0.483$; all $BF < 1$; Drum and NR comparison $p = 1.00$, $BF_{10} = 0.181$). Importantly, this suggests that differences in tempo matching/regularity found in the Nursery Rhyme condition are not due to a different level of participation. Further, infants were also moving for an equal proportion of the fast and slow nursery rhymes, with a Bayesian paired t-test confirming good evidence for no difference in proportion of time spent moving between the fast NR ($M = 0.235$) and slow NR ($M = 0.213$) conditions, $BF_{10} = 0.235$; 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 ($M = 0.285$, $SD = 0.138$) than when they were ($M = 0.236$, $SD = 0.121$); ($t(2,47) = 4.40$, $p < 0.001$; $BF_{10} = 360.77$, Figure 3d).

4 | DISCUSSION

The TSF (Goswami, 2011) proposes that accurate sensory/neural tracking of rhythm is a key factor in language development, and that children with disorders of language development will show impaired behavioural synchronization to a rhythmic beat (SMS, see data in Cumming et al., 2015; Thomson & Goswami, 2008). The related ARR hypothesis (Ladanyi et al., 2020) predicts that impaired SMS, in addition to perceptual timing difficulties, can identify children at risk of speech and language disorders. Here we explored individual differences in neurotypical infants' ability to generate motor rhythms and the tempo matching of these actions 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 contextualize the development of precursors to infant SMS. Through novel longitudinal measurements, we show

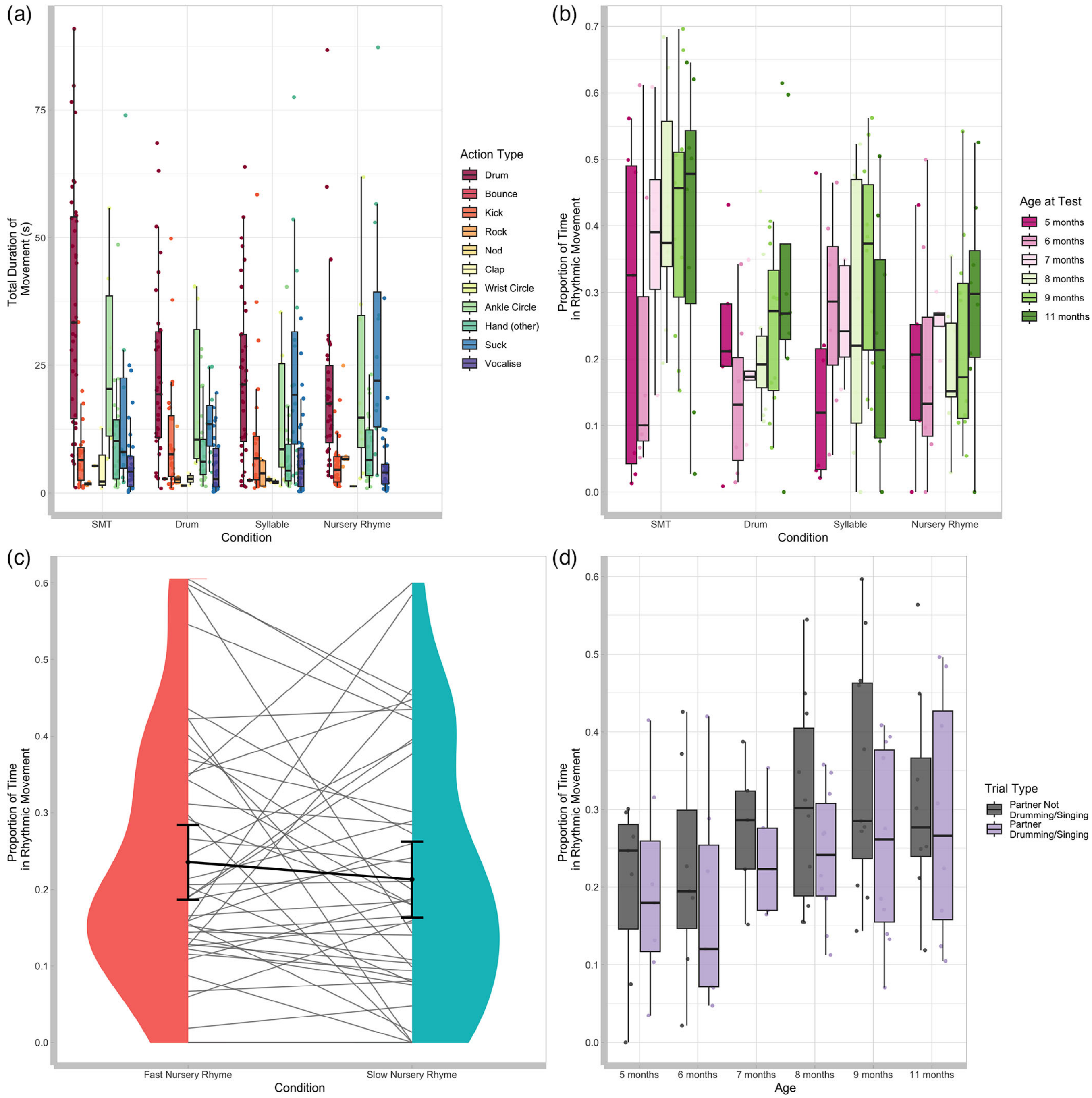

FIGURE 3 (a) Total duration of rhythmic movements by movement type, by condition. Note: Movements could be performed concurrently (e.g., drumming and kicking). (b) Proportion of time spent in rhythmic movement by age and condition. (c) Proportion of time spent in rhythmic movement in Slow (1 Hz) and Fast (~2 Hz) Nursery Rhymes. Group level Means and CI are shown in bold, and individual data points are connected. Half violins show the distribution of results. (d) Proportion of time spent in rhythmic movement by whether the experimenter was drumming or singing along with the pre-recorded video stimuli.

here that infants' rhythmic movement becomes faster and more regular with development. We also show, for the first time, developmental change in infants' movement timing in response to auditory stimuli over the first year of life. Particularly, by 11-months infants were decelerating from their SMT, showing closer tempo-matching 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 who is 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, some of the 11-month infants decelerated during the slower sung tempi. Speculatively, these infants may later go on to show better language outcomes. 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 individual differences in precursors of SMS. Further, 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 amplitude rise time than the drumbeat. This increased linguistic complexity did not affect infant matching of their rate of movement.

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

Qualitative analyses indicated that the differences found across conditions were unlikely to be due to a differential level of engagement. Infants exhibited an equal level of rhythmic movements in the most complex Nursery Rhyme condition and the simplest Drum condition. However, the generalizability of our findings may depend on the different kinds of stimulation compared. While similar infant data could be expected across languages for drumbeats and syllables, the Nursery Rhyme condition may prove an exception. The qualitative analyses also showed that infants moved more when the adult experimenter was *not* drumming/singing along with the stimuli. Whilst a social partner is beneficial for achieving synchrony in toddlerhood (Kirschner & Tomasello, 2009), infants inhibit dance behaviours in the presence of a partner (Rocha & Mareschal, 2017). Hence there may be different motivations for interpersonal versus sensorimotor synchronization, and this may also affect generalizability. Importantly, the current study alternated the actions of the live partner between synchronizing with the stimuli or simply encouraging the infant, in an attempt to motivate infants to produce drumming. The extent to which the actions versus presence of the partner guides the attentional spotlight of the infant could be further investigated.

As our infants age, our individual differences approach will allow one of the core tenets of the TSF to be tested. The infants enrolled in the current study are being followed to 42 months-of-age, participating in a battery of language tasks measuring phonological awareness, grammar, speech timing, and vocabulary. Our ongoing work will use the data in the current report to feed into models of language outcome, which may contribute vital knowledge regarding developmental pathways towards successful language acquisition. Whilst in this case measurements were derived using Motion Capture, which requires specialist equipment, the same analyses can be applied to 2D video data using AI technology (e.g., Rocha & Addyman, 2022), or even by measuring the sound signal produced by the drumming infant (e.g., Rocha et al., 2021). The current data can therefore provide distinct added value to neural measures in finding behavioural markers that are suitable for large scale, low cost, screening for intervention.

In conclusion, our current findings characterize the typical development of spontaneous motor tempo and tempo-flexibility over the first year of life. We find that prior to their first birthday, infants' rhythm production becomes faster and more regular. We further show that by the end of the first year, more complex linguistic stimuli are met with more variable infant behaviour, and that at least a subset of infants seem to adapt their tempo towards the rate of external auditory stimulation. This is potentially developmentally important, given that rhythmic linguistic routines characterize nursery settings in many cultures and are thought to benefit language development. In future analyses with our sample, we can extend our behavioural findings to identify which are early markers of successful and less successful language acquisition. Behavioural, in contrast to neural measures of rhythm, are a cheap, accessible, and 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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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available at https://osf.io/6rb4u/.

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