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RESEARCH ARTICLE

Beneficial effects of a music listening intervention on neural speech processing in 0–28-month-old children at risk for dyslexia

Virtala Paula[1] | Putkinen Vesa[1,2,3] | Gallen Anastasia[1] | Thiede Anja[1] | Trainor Laurel J[4,5,6] | Kujala Teija[1]

[1]Cognitive Brain Research Unit, Centre of Excellence in Music, Mind, Body and Brain, Department of Psychology and Logopedics, Faculty of Medicine, University of Helsinki, Helsinki, Finland

[2]Turku PET Centre, University of Turku, Turku, Finland

[3]Turku University Hospital, Turku, Finland

[4]Department of Psychology, Neuroscience & Behaviour, McMaster University, Hamilton, Ontario, Canada

[5]McMaster Institute for Music and the Mind, McMaster University, Hamilton, Ontario, Canada

[6]Rotman Research Institute, Baycrest Hospital, Toronto, Ontario, Canada

Correspondence
Teija Kujala, Cognitive Brain Research Unit, Centre of Excellence in Music, Mind, Body and Brain, P.O. Box 21, 00014, University of Helsinki, Helsinki, Finland.
Email: teija.m.kujala@helsinki.fi

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Abstract

Familial risk for developmental dyslexia can compromise auditory and speech processing and subsequent language and literacy development. According to the phonological deficit theory, supporting phonological development during the sensitive infancy period could prevent or ameliorate future dyslexic symptoms. Music is an established method for supporting auditory and speech processing and even language and literacy, but no previous studies have investigated its benefits for infants at risk for developmental language and reading disorders. We pseudo-randomized N~150 infants at risk for dyslexia to vocal or instrumental music listening interventions at 0–6 months, or to a no-intervention control group. Music listening was used as an easy-to-administer, cost-effective intervention in early infancy. Mismatch responses (MMRs) elicited by speech-sound changes were recorded with electroencephalogram (EEG) before (at birth) and after (at 6 months) the intervention and at a 28 months follow-up. We expected particularly the vocal intervention to promote phonological development, evidenced by enhanced speech-sound MMRs and their fast maturation. We found enhanced positive MMR amplitudes in the vocal music listening intervention group after but not prior to the intervention. Other music activities reported by parents did not differ between the three groups, indicating that the group effects were attributable to the intervention. The results speak for the use of vocal music in early infancy to support speech processing and subsequent language development in infants at developmental risk.

KEYWORDS
dyslexia, event-related potentials (ERPs), infants, mismatch response (MMR), music intervention, speech processing

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Research Highlights

- Dyslexia-risk infants were pseudo-randomly assigned to a vocal or instrumental music listening intervention at home from birth to 6 months of age.
- Neural mismatch responses (MMRs) to speech-sound changes were enhanced in the vocal music intervention group after but not prior to the intervention.
- Even passive vocal music listening in early infancy can support phonological development known to be deficient in dyslexia-risk.

1 | INTRODUCTION

The prevalent reading deficit developmental dyslexia can compromise language and literacy development from early on (Eden et al., 2016; Peterson & Pennington, 2015). Dyslexia is likely attributable to a phonological processing deficit, primarily associated with left-hemispheric structural and functional deficits (Kujala et al., 2021; Eden et al., 2016; Giraud & Ramus, 2013; Vellutino et al., 2004). Neural auditory and speech processing problems associated with dyslexia (Hämäläinen et al., 2013; Kujala, 2007) are present already in infants at familial risk (e.g., Thiede et al., 2019; Virtala et al., 2022), and can also predict future problems in language and literacy development (Kailaheimo-Lönnqvist et al., 2020; Leppänen et al., 2010; see also Cantiani et al., 2016; for a review, Volkmer & Schulte-Körne, 2018). Due to these associations, supporting speech processing, particularly phonological learning, early in development could diminish the risk of later difficulties. Optimally, interventions should be targeted in the first year after birth, when immense neural plasticity enables the acquisition of native language phoneme representations (Kuhl, 2004, 2010).

Music activities are associated with enhanced speech, language, and literacy skills, most likely due to their benefits for the auditory nervous system (for reviews: Kraus & Chandrasekaran, 2010; Virtala & Partanen, 2018). Intervention studies comparing music making to other meaningful group activities in school-aged children have shown benefits in reading and related skills (Chobert et al., 2014; Moreno et al., 2009), and also in dyslexics (Flaugnacco et al., 2015, see also Habib et al., 2016; Moreno et al., 2015; Overy, 2003). Social interactive musical settings seem to particularly enhance auditory and language skills in infants (Gerry et al., 2012; Trainor et al., 2012; see also Benasich et al., 2014; Musacchia et al., 2017; Zhao & Kuhl, 2016). Based on mostly correlational evidence, music activities can be beneficial at early ages even when they are rather informal, including also parent- or child-initiated activities at home without professional instruction (Linnavalli et al., 2018; Papadimitriou et al., 2021; Putkinen, Saarikivi & Tervaniemi, 2013; Putkinen, Tervaniemi & Huotilainen, 2013; Putkinen et al., 2015, 2019). However, also mere exposure to music can shape the auditory system early on (Partanen et al., 2013; Trainor et al., 2011). Music listening can take place very early in human development, well before more targeted, active, and structured interventions on language or reading can be administered. However, no previous study has assessed the potential beneficial effects of music listening on infants or young children at risk for language or reading disorders.

Auditory event-related potentials (ERPs) of the electroencephalogram (EEG) are an established method to study neural auditory and speech processing. ERPs have been found to reflect speech processing deficits in dyslexia and its risk in infancy (e.g., Thiede et al., 2019; Virtala et al., 2022; for a review, Volkmer & Schulte-Körne, 2018) and reflect intervention effects (e.g., Partanen et al., 2013; Trainor et al., 2012). In infants and young children, a repeating sound elicits a positive P1, followed by a negative N2 ERP (e.g., Choudhury & Benasich, 2011). Occasional changes in sound streams elicit a preattentive discrimination response, mismatch negativity (MMN), an orienting response, P3a, and a re-orienting negativity (RON; e.g., Horváth et al., 2008). In infants and small children, a corresponding pattern of an early negativity, a positivity, and a later negativity has been obtained (Choudhury & Benasich, 2011; Fellman et al., 2004; Kushnerenko et al., 2002; Virtala et al., 2022; for a review, see Kushnerenko et al., 2013), often referred to as mismatch responses (MMRs, e.g., He et al., 2009). While these peaks have several abbreviations in the literature, we will refer to them as MMN, positive MMR (P-MMR), and late discriminative negativity (LDN, e.g., Bishop et al., 2011; Kuuluvainen et al., 2016), respectively. In early childhood, MMN and LDN amplitudes tend to grow with increasing age, while latency (of at least MMN) decreases. The P-MMR decreases in both latency and amplitude after 6 months when it is at its largest (Choudhury & Benasich, 2011; Fellman et al., 2004; Kushnerenko et al., 2002; Virtala et al., 2022; for a review, Kushnerenko et al., 2013).

A large body of evidence suggests that these ERPs are associated with language and reading skills (see Volkmer and Schulte-Körne, 2018, for a review). For example, MMNs at the age of 5–6 years are stronger in children who are better in phoneme processing (Linnavalli et al., 2017). Furthermore, MMRs of 6- to 7-year-old (Maurer et al., 2009) and 2-year-old children (van Zuijen et al., 2013) have been found to be associated with later reading skills. Overall, a positive correlation between MMR amplitude and later spelling and reading abilities has consistently been found across studies (Volkmer and Schulte-Körne, 2018).

The present study investigated the effects of a music listening intervention on the development of neural speech processing as reflected by ERPs in infants and children at familial dyslexia risk. The intervention was administered to newborns, in order to tap the early sensitive period for phonetic learning (e.g., Kuhl, 2010). Passive music listening was chosen as a cost-effective and easy-to-administer intervention for infants. Newborns at risk for dyslexia were pseudo-randomized to three groups: a vocal music listening intervention, an instrumental music listening intervention, or no intervention. Before and after the 6-month intervention, and again at 28-month's follow-up, auditory P1 and N2 to repetitive speech sounds and MMRs to speech sound changes were recorded to assess the intervention effects.

We expected that particularly the vocal intervention would enhance ERPs and MMRs at 6 and 28 months. Vocal music should be beneficial for infant speech development (Kuhl, 2004), as it is appealing for infants (Nakata & Trehub, 2004) and consists of rhythmically, repetitively and slowly presented speech sounds, resembling parentese (or infant-directed speech; Ferdinand & Kuhl, 1987). We also hypothesized that the instrumental intervention would enhance MMRs to frequency changes given the central role of pitch in music. Due to prior evidence on the benefits of active, social music interventions, music playschool, and at-home music activities (Gerry et al., 2012; Linnavalli et al., 2018; Putkinen, Saarikivi & Tervaniemi, 2013; Putkinen, Tervaniemi & Huotilainen, 2013; Putkinen et al., 2015, 2019; Trainor et al., 2012), we ensured with questionnaires that the groups did not differ in these other music activities.

2 | METHODS

2.1 | Participants

Participants were recruited to this DyslexiaBaby study via advertisements during pregnancy or first days after birth (for details: Thiede et al., 2019). The sample consisted of infants at familial risk for dyslexia, pseudo-randomized to vocal music intervention (VOC), instrumental music intervention (INS), and no-intervention control groups (CON). At birth, $N = 131$ infants were included in the analyses (Table 1; samples included in the longitudinal analyses can be found in Table 2). This final sample was obtained after conducting exclusions from the original sample as follows: 29 infants were excluded due to unconfirmed parental diagnosis or child's severe health condition ($N = 16$), or failure to carry through the intervention ($N = 13$). Additional children were excluded from the analyses at 6 or 28 months due to failure to schedule the EEG recording ($N = 29$ at 6 months, $N = 15$ at 28 months), problems during the EEG recording (technical problems, very poor signal quality, child's loudness, restlessness, or refusal; $N = 7$), or insufficient ERP data quality (<30 accepted trials for several deviants; $N = 27$ at 6 months, $N = 6$ at 28 months).

Enrolment criteria were as follows: born healthy and at term, normal hearing, and at least one caretaker a native Finnish speaker. The infants had at least one biological parent with confirmed dyslexia, based on a recent diagnostic statement or by dyslexia assessment conducted in our study, which consisted of a clinical interview, a questionnaire (Adult Reading History Questionnaire [ARHQ], Lefly & Pennington, 2000), and a reading-test battery (text, word, and pseudoword reading, and writing speed; Nevala et al., 2006). The assessed parent had to (1) report no history of attention deficit disorder, individualized elementary school curriculum, or childhood brain trauma, (2) report reading and writing difficulties in elementary school, and (3a) have speed or accuracy at least 1 SD below norms in at least two reading tests, or (3b) have both a statement of dyslexia from elementary school and first- or second-degree biological relatives with diagnosed dyslexia. In the latter case (3b) the parental dyslexia was deemed compensated; otherwise (3a) active. One or both parents signed a written informed consent at the enrollment in the study.

2.2 | Music listening interventions

In the EEG recording at birth, the at-risk infants were assigned to the VOC, INS, and CON groups. Assignment was done pseudo-randomly (otherwise randomly, with the following exceptions: the first infants enrolled were directed to the CON group, as well as infants whose parental dyslexia status was not confirmed at the time of the EEG recording; toward the final participant enrolments, if the gender distribution of some groups was becoming clearly imbalanced, more boys/girls were assigned to groups so as to lessen this imbalance).

The families were instructed to play music (at least one playlist five times/week) to infants in peaceful surroundings and not to sing along, starting within the infant's first month of life and continuing until 6 months of age (Figure 1). The online song library provided to the families included a selection of nine 20-min-long playlists of Finnish children's and folk songs either with a vocalist singing (two female, three male singers; vocal intervention) or a musical instrument playing (banjo, mandolin, xylophone, or metallophone; instrumental intervention) the melody, both with the same soft acoustic guitar accompaniment.

The intervention was deemed successful when all three criteria were met: minimum duration of ~5 months (completed playlists in five 4-week periods), minimum intensity of ~1 h/week (~3 playlists/week) in at least four 4-week periods, and minimum listening amount of 24 h (72 playlists). These were both registered by the online song library and confirmed with phone interviews from families when necessary (details in Supplemental material). The intervention groups did not differ in drop-out rates (chi-square test for a comparison of the amounts of failed/completed interventions between VOC 8/42 vs. INS 5/46, $p = 0.392$) or listening amounts (group comparison of VOC 154 vs. INS 157 playlists with two-tailed independent sample's t test, $p = 0.838$; details in Supplemental material). Besides saving the dates and amounts of completed playlists, the online song library saved parent's responses to a short questionnaire on the infant's activities during listening (e.g., alertness state).

2.3 | Parent-reported music activities

Music activities of the families (Table 3: *shared music*, *music exposure*, and *musical play school attendance*; Table 4: samples included in the longitudinal analyses) were surveyed with questionnaires (identical at 6, 12, 18, and 24 months). For shared music items the parents rated

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TABLE 1 Background variables for children in each age group. Measurement age, gender, mother's education (in years), parental dyslexia status (comp = compensated vs. active dyslexia), home languages (one = mono-/, more = multilingual), and birth-related information in the three groups. *P*-values describe one-way analysis of variance (ANOVA) and chi-square statistics for group comparisons.

0 mo (*N* = 131)	VOC (*N* = 38)	INS (*N* = 40)	CON (*N* = 53)	Group comparison
Age, d (SD)	9.6 (3.9)	9.5 (3.5)	9.1 (3.9)	$p = 0.796$
Female/male	16/22	21/19	23/30	$p = 0.590$
Mother's education, y (SD)	16.7 (2.3)	16.9 (2.4)	17.1 (2.5)	$p = 0.727$
Comp/active dyslexia	8/30	7/33	14/38	$p = 0.547$
Mono-/multilingual	34/4	37/3	44/9	$p = 0.358$
Birth weight, g (SD)	3619.7 (418.3)	3587.2 (471.8)	3581.3 (397.3)	$p = 0.908$
Birth height, cm (SD)	50.9 (1.8)	50.5 (2.3)	50.6 (1.7)	$p = 0.651$
Gestational age, w (SD)	40.2 (0.9)	40.0 (1.2)	40.1 (0.9)	$p = 0.622$
Last Apgar (5/10 min)	9.5 (0.8)	9.4 (0.6)	9.5 (0.7)	$p = 0.785$
6 mo (*N* = 68)	VOC (*N* = 22)	INS (*N* = 24)	CON (*N* = 22)	
Age, mo (SD)	6.1 (0.3)	6.1 (0.4)	6.1 (0.3)	$p = 0.867$
Female/male	7/15	13/11	9/13	$p = 0.304$
28 mo (*N* = 103)	VOC (*N* = 30)	INS (*N* = 33)	CON (*N* = 40)	
Age, mo (SD)	28.0 (0.5)	28.1 (0.4)	28.1 (0.4)	$p = 0.731$
Female/male	10/20	17/16	19/21	$p = 0.314$

Note 1: There was one missing value in Apgar score in INS and CON groups; both infants had no indication of health issues at time of recording (7–8 days). Two other infants had an Apgar score of 6; they participated in the EEG recording at 13 days and were considered healthy at that time. Parental dyslexia status (compensated or active) was missing from one CON group infant in the 0 mo and 28 mo samples.
Note 2: Mother's education, proportions of compensated/active dyslexia, and proportions of mono-/multilingual home environment did not not differ statistically significantly between groups at any age.
Note 3: Associations of infant gender, mother's education, and parental dyslexia status with commitment to the intervention (drop-out vs. no drop-out) and to the follow-up (scheduling problem vs. no scheduling problem) were investigated with chi-square and independent sample's *t* tests. Infants of less educated mothers were more likely to not participate in the 28-month follow-up testing (15.5 vs. 17.1 years in the scheduling problem vs. not scheduling problem group, $p = 0.012$). Scheduling problems at 6 mo were more likely in the compensated (35.5%) than active dyslexia group (17.9%, $p = 0.035$). However, it should be noted that while at 0 and 28 months, all families were invited to the follow-up testing and scheduling problems were mostly family-related, at 6 months, the laboratory was over-booked and not all families could be invited to the testing (i.e., most scheduling problems were not family-related; 26% of the whole DyslexiaBaby sample had scheduling problems at this age and at least ~75% of them were not family-related, see Virtala et al., 2022).
Note 4: Differently analyzed 0-month EEG data of $N = 38/131$ participants reported here and additional participants have been reported by Thiede et al. (2019), and differently analyzed 6-month EEG data of $N = 64/68$ participants reported here and additional participants have been reported by Kailaheimo-Lönnqvist et al. (2020). Similarly analyzed EEG data of all participants and age groups reported here and additional participants were reported by Virtala et al. (2022). None of these publications have reported results of the music listening intervention (intervention group status used as a control variable by Kailaheimo-Lönnqvist et al., 2020).

how often someone sings, dances or moves to music, drums or claps rhythms, or plays instruments with the child. Music exposure items surveyed how often (disregarding the intervention and musical play school activities) the child has heard live music, live singing, or recorded music. Musical play school attendance was evaluated across the ages (when at least three questionnaires were returned; otherwise treated as missing values) based on three items on the (1) age, (2) duration, and (3) frequency of attendance. The groups did not differ statistically significantly in any of the variables (Tables 3 and 4), indicating that they did not influence the results obtained.

2.4 | EEG recordings

The stimuli were a pseudo-word /tata/ (70%), spoken by a native Finnish-speaking female with stress on the first syllable, and its variants (8.5% of each type) with a longer vowel duration /tata:/, higher second syllable frequency /tata/, and different vowel identity /tato/ (Figure 2). The variants were edited from the original /tata/ recording with Adobe Audition (CS6, 5.0, Build 708) and Praat (5.4.01) softwares (in /tato/, the second syllable was replaced with a naturally uttered /to/). Sequences also included rare novel stimuli (e.g., cry, cough, drill, telephone ring, see Sorokin et al., 2010; data for these stimuli will be reported elsewhere). Four standards started each of the four 472-stimulus-long blocks, of which at least four were presented per child, followed by the rest of the stimuli in pseudo-random order except that deviant and novel stimuli were always followed by a standard. For detailed descriptions of the stimuli, paradigm, and the EEG recordings, see Thiede et al. (2019), Kailaheimo-Lönnqvist et al. (2020), and Virtala et al. (2022).

EEG was recorded with an ActiCap (Brain Products GmbH, Gilching, Germany) with QuickAmp amplifier (v. 10.08.14; software: Brain

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TABLE 2 Background variables for children included in the longitudinal analyses. Measurement age, gender, mother's education (in years), parental dyslexia status (comp = compensated vs. active dyslexia), home languages (one = mono-/, more = multilingual), and birth-related information in the three groups. *P*-values describe one-way analysis of variance (ANOVA) and chi-square statistics for group comparisons.

0 mo–6 mo (*N* = 131)	VOC (*N* = 38)	INS (*N* = 40)	CON (*N* = 53)	Group comparison
N at 0 mo	38	40	53	
N at 6 mo	22	24	22	
Age 0 mo, d (SD)	9.6 (3.9)	9.5 (3.5)	9.1 (3.9)	$p = 0.796$
Age 6 mo, mo (SD)	6.1 (0.3)	6.1 (0.4)	6.1 (0.3)	$p = 0.867$
Female/male	16/22	21/19	23/30	$p = 0.590$
Mother's education, y (SD)	16.7 (2.3)	16.9 (2.4)	17.1 (2.5)	$p = 0.727$
Comp/active dyslexia	8/30	7/33	14/38	$p = 0.547$
Mono-/multilingual	34/4	37/3	44/9	$p = 0.358$
Birth weight, g (SD)	3619.7 (418.3)	3587.2 (471.8)	3581.3 (397.3)	$p = 0.908$
Birth height, cm (SD)	50.9 (1.8)	50.5 (2.3)	50.6 (1.7)	$p = 0.651$
Gestational age, w (SD)	40.2 (0.9)	40.0 (1.2)	40.1 (0.9)	$p = 0.622$
Last Apgar (5/10 min)	9.5 (0.8)	9.4 (0.6)	9.5 (0.7)	$p = 0.785$
6 mo–28 mo (*N* = 114)	**VOC (*N* = 32)**	**INS (*N* = 36)**	**CON (*N* = 46)**	
N at 6 mo	22	24	22	
N at 28 mo	30	33	40	
Age 6 mo, mo (SD)	6.1 (0.3)	6.1 (0.4)	6.1 (0.3)	$p = 0.867$
Age 28 mo, mo (SD)	28.0 (0.5)	28.1 (0.4)	28.1 (0.4)	$p = 0.731$
Female/male	11/21	18/18	21/25	$p = 0.411$
Mother's education, y (SD)	16.8 (2.4)	16.9 (2.5)	17.6 (2.3)	$p = 0.310$
Comp/active dyslexia	7/25	7/29	12/33	$p = 0.733$
Mono-/multilingual	30/2	33/3	38/8	$p = 0.245$
Birth weight, g (SD)	3627.2 (444.5)	3623.3 (459.5)	3546.7 (363.8)	$p = 0.619$
Birth height, cm (SD)	51.0 (1.9)	50.7 (2.2)	50.5 (1.6)	$p = 0.565$
Gestational age, w (SD)	40.1 (0.9)	40.0 (1.2)	40.1 (1.0)	$p = 0.782$
Last Apgar (5/10 min)	9.6 (0.6)	9.4 (0.6)	9.4 (0.7)	$p = 0.582$

Note: There was one missing value in Apgar score in INS and CON groups; both infants had no indication of health issues at time of recording (7–8 days). Two other infants had an Apgar score of 6; they participated in the EEG recording at 13 days and were considered healthy at that time. Parental dyslexia status (compensated or active) was missing from one CON group infant in the 0 mo and 28 mo samples.

Vision Recorder 1.20.0801, Brain Products GmbH, Gilching, Germany, Figure 2). The sampling rate was 500 Hz and the online filter 100 Hz low-pass, referenced to all-electrodes average. Stimuli were presented with Presentation 17.2 Software (Neurobehavioural Systems Ltd., Berkeley, CA, USA) and one (0 mo, 6 mo) or two (28 mo) Genelec speakers (intensity ~65 dB sound pressure level, SPL). Equipment, protocol, and measurement duration (1–2 h including preparations) were similar across ages. Measurements at 0 and 6 months took place in a quiet room at Helsinki University Jorvi Hospital (Espoo, Finland; 0 months $N = 120$; 6 months $N = 59$), or in a sound-proof laboratory at the University of Jyväskylä, Finland ($N = 11$; $N = 9$). Measurements at 28 months took place in a sound-proof, electrically-shielded laboratory at the University of Helsinki ($N = 97$) and in the same space at the University of Jyväskylä as at earlier ages ($N = 6$).

Newborns were lying on their back (speaker placed ~40 cm from infant's head, background noise ~40 dB SPL) and monitored by the researcher marking their alertness states with a response box (Cedrus RB844, Cedrus Corporation, California, USA: 'active'/'quiet' sleep, 'awake', or 'intermediate sleep stage', Grigg-Damberger et al., 2007). As no group differences were found in the proportion of infants in each of the states, the data of all states was pooled in the analyses (chi-square tests for group comparisons all yielded $p > 0.10$, see Supplemental material). The 6-month-olds were sitting on their caretaker's lap, awake and entertained silently with, for example, facial expressions and showing of objects.

The 28-month-olds were sitting in a chair (160 cm from the speakers) awake with the caretaker or researcher, and were entertained with silenced cartoons during the measurement and instructed to stay still and silent, ignoring the stimuli. Sounds and movements of the child were saved as time stamps in the continuous EEG and taken into account in the analyses (see 2.5). An illustrated "storybook" of the recording was presented to the family beforehand for ensuring the child's informed consent and diminishing any fears.

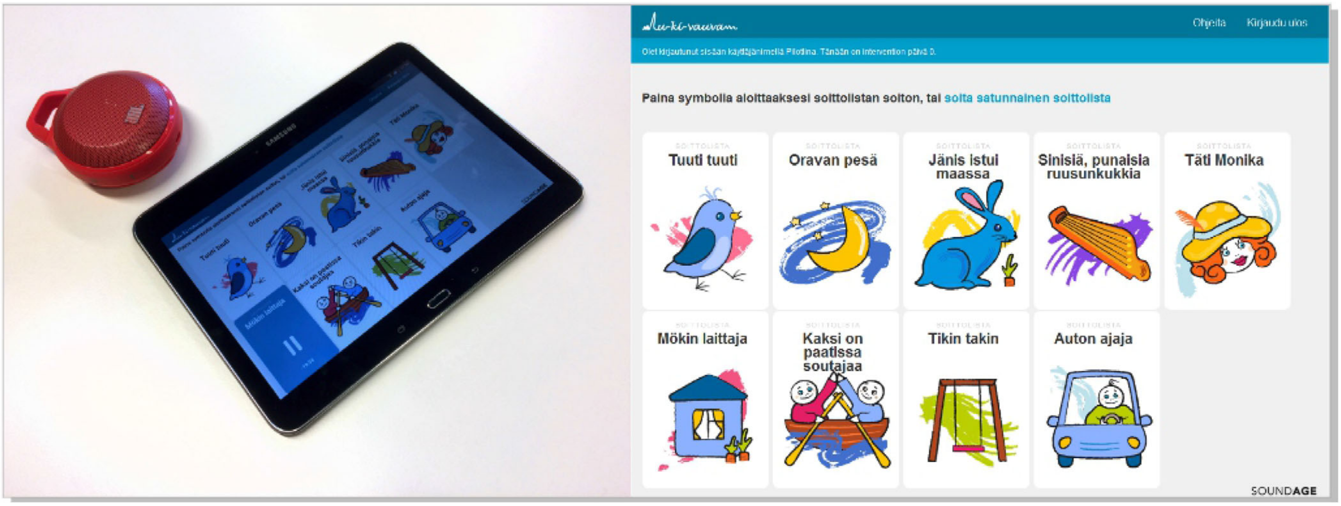

FIGURE 1 Music listening interventions. The music recorded for this study was provided to the families via a portable speaker and a tablet computer (left), and an online password-protected song library with individualized user-ID's (right: screen capture of the song library).

TABLE 3 Parent-reported music-related activities in the vocal (VOC) and instrumental (INS) intervention groups and in the no-intervention control group (CON). Shared music and music exposure were calculated from the mean value of several questionnaire items, averaged across the ages when at least two questionnaires were returned (otherwise treated as missing values). The percentage of missing values indicates the proportion of participants with too many missing questionnaires for each variable. Group comparisons were conducted with one-way analyses of variance (for shared music) and chi-square tests (for low/high music exposure and musical play school attendance never/seldom/often).

Activity	*N* (missing, %)	VOC	INS	CON	Group comparison
Shared music, 1–4	125 (5)	3.1	3.2	3.1	$p = 0.685$
Music exposure, h/week (% of high exposure)	124 (5)	8.4 (41)	9.8 (42)	8.6 (42)	$p = 0.994$
Musical play school attendance, never/seldom/often, %	120 (8)	35/35/29	38/43/19	33/31/37	$p = 0.493$

Note 1: Shared music is evaluated on a scale from 1 (never) to 4 (several times a week) and musical play school attendance as amounts of never (no attendance), seldom (maximum 1 year), and often (over 1 year).
Note 2: Due to a very skewed distribution of the answers, the amount of music exposure was transformed into a dummy variable in the analyses, where 0 = low, indicating average or below average amount (8.9 h/week) of music exposure and 1 = high, indicating above average amount of music exposure.

TABLE 4 Parent-reported music-related activities in the vocal (VOC) and instrumental (INS) intervention groups and in the no-intervention control group (CON) of children included in the longitudinal analyses. The percentage of missing values indicates the proportion of participants with too many missing questionnaires for each variable. Group comparisons were conducted with one-way analyses of variance (for shared music) and chi-square tests (for low/high music exposure and musical play school attendance never/seldom/often).

Activity	*N* (missing, %)	VOC	INS	CON	Group comparison
0 mo–6 mo					
Shared music, 1–4	124 (5)	3.1	3.2	3.1	$p = 0.685$
Music exposure, h/week (% of high exposure)	124 (5)	8.4 (41)	9.8 (42)	8.6 (42)	$p = 0.994$
Musical play school attendance, never/seldom/often, %	120 (8)	35/35/29	38/43/19	33/31/37	$p = 0.493$
6 mo–28 mo					
Shared music, 1–4	107 (6)	3.1	3.2	3.1	$p = 0.544$
Music exposure, h/week (% of high exposure)	107 (6)	8.1 (36)	10.3 (47)	8.4 (42)	$p = 0.666$
Musical play school attendance, never/seldom/often, %	105 (8)	29/43/29	38/41/21	33/30/37	$p = 0.528$

Note 1: Shared music is evaluated on a scale from 1 (never) to 4 (several times a week) and musical play school attendance as amounts of never (no attendance), seldom (maximum 1 year), and often (over 1 year).
Note 2: Due to a very skewed distribution of the answers, the amount of music exposure was transformed into a dummy variable in the analyses, where 0 = low, indicating average or below average amount (8.9 h/week) of music exposure and 1 = high, indicating above average amount of music exposure.

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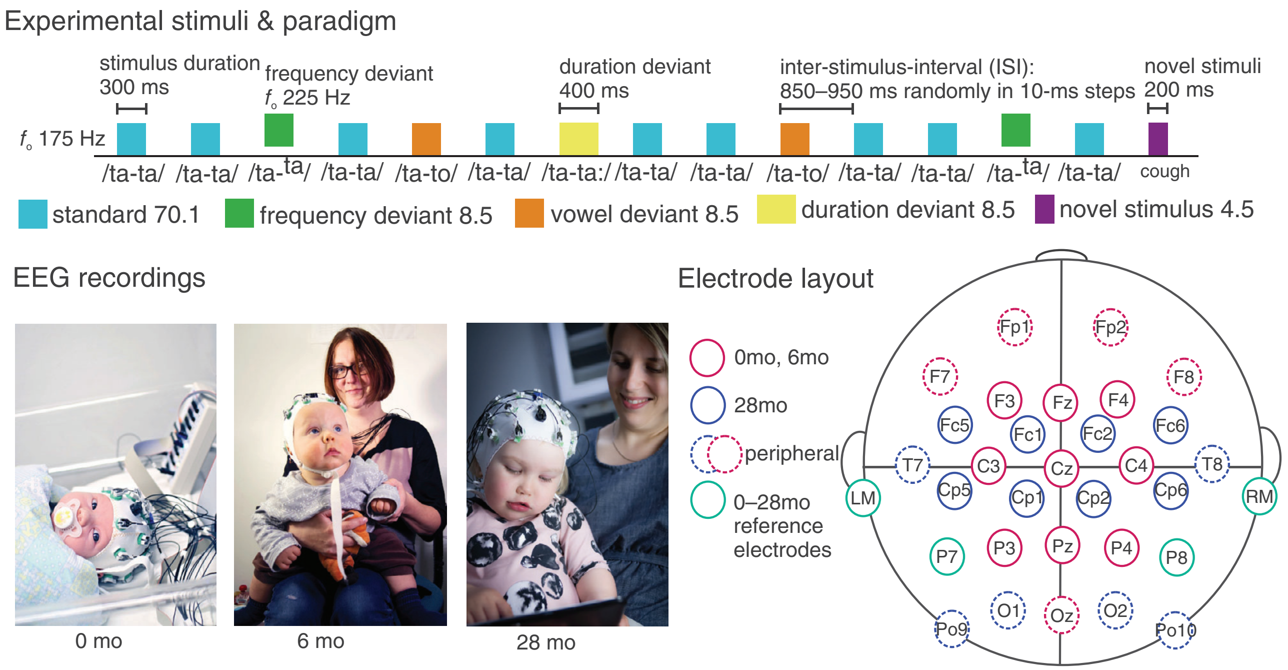

FIGURE 2 The experimental stimuli and paradigm (numbers following stimulus names indicate their average probabilities in %), and EEG recordings and electrode layout at 0, 6, and 28 months (mo). EEG recording photos have been taken by Peter Palo-oja (0 mo, 6 mo) and Anastasia Gallen (28 mo), with permission from one or both caretakers for University of Helsinki to use them without the child's name. Adapted with permission from Thiede et al. (2019) and Virtala et al. (2022).

2.5 | EEG data analysis

Stimulus blocks with continuous loud crying or voicing or with the 6- or 28-month-old accidentally falling asleep were first excluded (exclusions of whole datasets from a participant are listed in 2.1). Preprocessing with Matlab 2017a–2020a (The MathWorks, Inc., USA) Toolboxes EEGLAB 14.0.0b and 2019_0 (Delorme & Makeig, 2004) and ERPLAB 7.0.0 (Lopez-Calderon & Luck, 2014) started with preliminary filtering (0.025–40 Hz band pass) and visual inspection and marking of "bad" (flat/continuously noisy signal) electrodes (excluding peripheral and interpolating non-peripheral, see Supplemental material and Virtala et al., 2022). Time-stamped parts of the 28-month EEG with visually clear muscle-related noise in several electrodes were manually excluded, and visually clear eye-movement and heart-beat artifacts were noted for later removal. Preprocessing continued with filtering (0.5 high-pass; 25 Hz low-pass), re-referencing (average of LM, RM, P7, and P8; see Supplemental material), interpolation, and eye-movement and heart-beat artifact correction in the 28-month data (independent component analysis, ICA: fastica, Hyvärinen, 1999, or runica in EEGLAB) when appropriate based on visual inspection.

The EEG was epoched (−100 to 840 ms from stimulus onset, baseline correction from −100 to 0 ms). Epochs with standard stimuli following a deviant, with amplitude exceeding ±120 μV at Fp1 and Fp2 electrodes (indicating eye movements), with a drift of >100 μV, or with data points ±3 SD from the mean of all epochs (jointprob in EEGLAB, separately for each electrode and averaged across electrodes) were excluded. To form the ERPs, epochs were separately averaged for the standard and each deviant type. The final data had to have at least 30 epochs for two or three deviant types. Two children at the age of 6 months and three at 28 months did not meet this criterion. The VOC, INS, and CON groups had on average 115 (range: 63–184), 114 (48–168), and 111 (36–168) epochs per child for each deviant at 0 months, 51 (24–92), 51 (30–78), and 53 (30–87) at 6 months, and 77 (25–132), 81 (37–137), and 80 (24–120) at 28 months, respectively.

2.6 | ERP quantification and statistical analysis

For P1 and N2, the mean amplitudes and peak latencies were quantified from the standard ERPs (baseline correction at −100 to 0 ms from stimulus onset, Figure 3), and for MMRs (MMN, P-MMR, and LDN), they were quantified from the deviant-standard subtraction curves, separately for each deviant (baseline correction shifted to 125–225 ms for the duration deviant and to 80–180 ms for the frequency and vowel deviants (−100 to 0 ms from deviance onset, Figure 4)). As it was evident that not all MMRs were elicited at all ages, and in order to study the most prominent responses, only those MMRs deemed significant in the whole DyslexiaBaby sample were quantified (including a control group not at familial risk for dyslexia and not analyzed in the present study; reported in Virtala et al., 2022). Individual peak latencies were searched from the averaged standard ERPs and subtraction curves with an additional 10-Hz low-pass filter from broad latency windows (Figures 3 and 4) in a six-electrode region-of-interest (ROI; average of the electrodes in the ROI: fronto-central F3, Fz, F4, C3, Cz, C4; except for 6-month-LDNs due to their scalp distribution, centro-parietal C3, Cz, C4, P3, Pz, P4). The additional filtering was

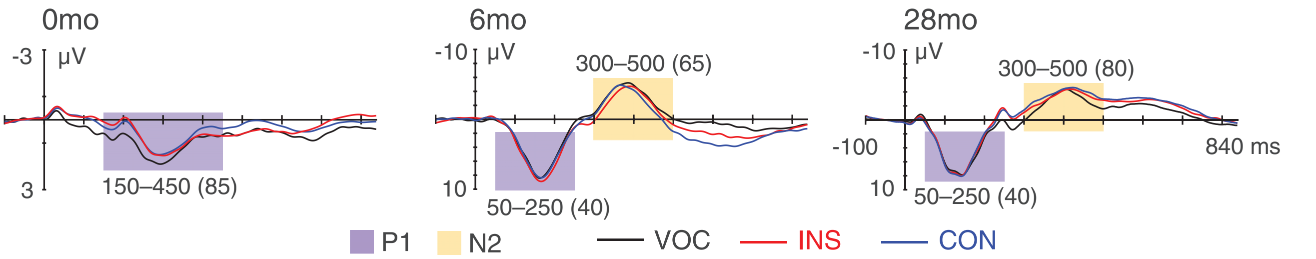

FIGURE 3 Event-related potential (ERP) responses to the standard stimulus illustrating the P1 and N2 in the vocal (VOC) and instrumental (INS) music listening intervention groups and the no-intervention control group (CON) at 0, 6, and 28 months (mo), with baseline at stimulus onset. The ERPs are depicted and quantified from a fronto-central region-of-interest (at 0 and 6 months: F3, Fz, F4, C3, Cz, C4; at 28 months: F3, Fz, F4, C3, Cz, C4, FC1, FC5, FC2, FC6). Colorful bars and the latency windows, in ms, next to them describe the latencies used for peak latency search (same windows for all groups). Mean amplitudes were quantified from latency windows (width in parentheses; same widths for all groups) centered around individual peak latencies.

done in order to eliminate high-frequency noise and components, to more accurately identify the individual peaks of the P1, N2, and MMR (frequency <5 Hz). Mean amplitudes were then calculated from the original-filtered data (with a band-pass of 0.5–25 Hz; see 2.5) from time windows around the individual peak latencies (listed in Figures 3 and 4), from the six-electrode ROI at 0 and 6 months and a 10-electrode ROI at 28 months (fronto-central F3, Fz, F4, C3, Cz, C4, FC1, FC5, FC2, FC6). In the case of missing peak latencies, group-average peak latency was used for mean amplitude calculation. If the individual peak latency was too close to the end of epoch (closer than window width for mean amplitude calculation divided by two), the latest possible latency window (ending at the end of epoch) was used for mean amplitude calculation.

Group-wise MMR elicitation was investigated with one sample *t* tests (48 tests in total, 16 per group, Bonferroni-corrected criterion $p = 0.05/16 = 0.003$). For the P1, N2, and the statistically significant MMRs, group differences in peak latencies and mean amplitudes and their maturation were analyzed with linear mixed models (LMMs) in R (lme4 package, Bates, et al., 2007) with group and age as fixed factors and subject as a random factor. For all MMRs elicited by two or more deviants at the same age, deviant was also included as a fixed factor. Only statistically significant effects including group are reported for the LMMs. Bonferroni-corrected post hoc pairwise comparisons were conducted in case interaction effects or visual observation of the responses indicated that the group effect was dependent on age or deviant type. The P-MMR maturation was only analyzed across two ages at a time (0 vs. 6 mo and 6 vs. 28 mo) mainly due to its nonlinear amplitude maturation (Virtala et al., 2022). In case a response was elicited at one age only, group differences were analyzed with analyses of variance (ANOVAs) or, in case of several deviants eliciting the same response at a given age, with repeated-measures (RM-)ANOVAs with deviant as a within-subject and group as a between-subject's factor.

3 | RESULTS

Mean amplitudes, peak latencies, and one sample *t* test results of the MMRs are reported in Table 5. Figure 3 illustrates the P1 and N2 to the standard stimulus, and Figures 4 and 5 illustrate the MMRs and their maturation. Section 3.1 lists the statistically significant MMRs, and Section 3.2 lists the statistically significant effects in the LMMs including group (for complete statistics, see Table S1).

3.1 | MMR elicitation

3.1.1 | Birth

All deviants elicited a P-MMR in all groups.

3.1.2 | 6 months

All deviants elicited a P-MMR in all groups. Duration and frequency deviants elicited an LDN in all groups (however, duration-LDN in the VOC and frequency-LDN in the CON group were not significant after correcting for multiple comparisons).

3.1.3 | 28 months

Frequency deviants elicited an MMN in all groups (duration-MMN was not significant in all groups after correcting for multiple comparisons). Duration and vowel deviants elicited a P-MMR in all groups (however, duration-P-MMR was not significant in the VOC group after correcting for multiple comparisons). All deviants elicited an LDN in all groups.

Based on the one sample *t* test results, all quantified MMRs except for the duration-MMN at 28 months were included in the LMMs.

3.2 | Group differences in ERPs and MMRs

3.2.1 | P-MMR amplitudes from 0 to 6 months

The LMM for duration-, frequency-, and vowel-P-MMRs between 0 and 6 months demonstrated a statistically significant Age X Group

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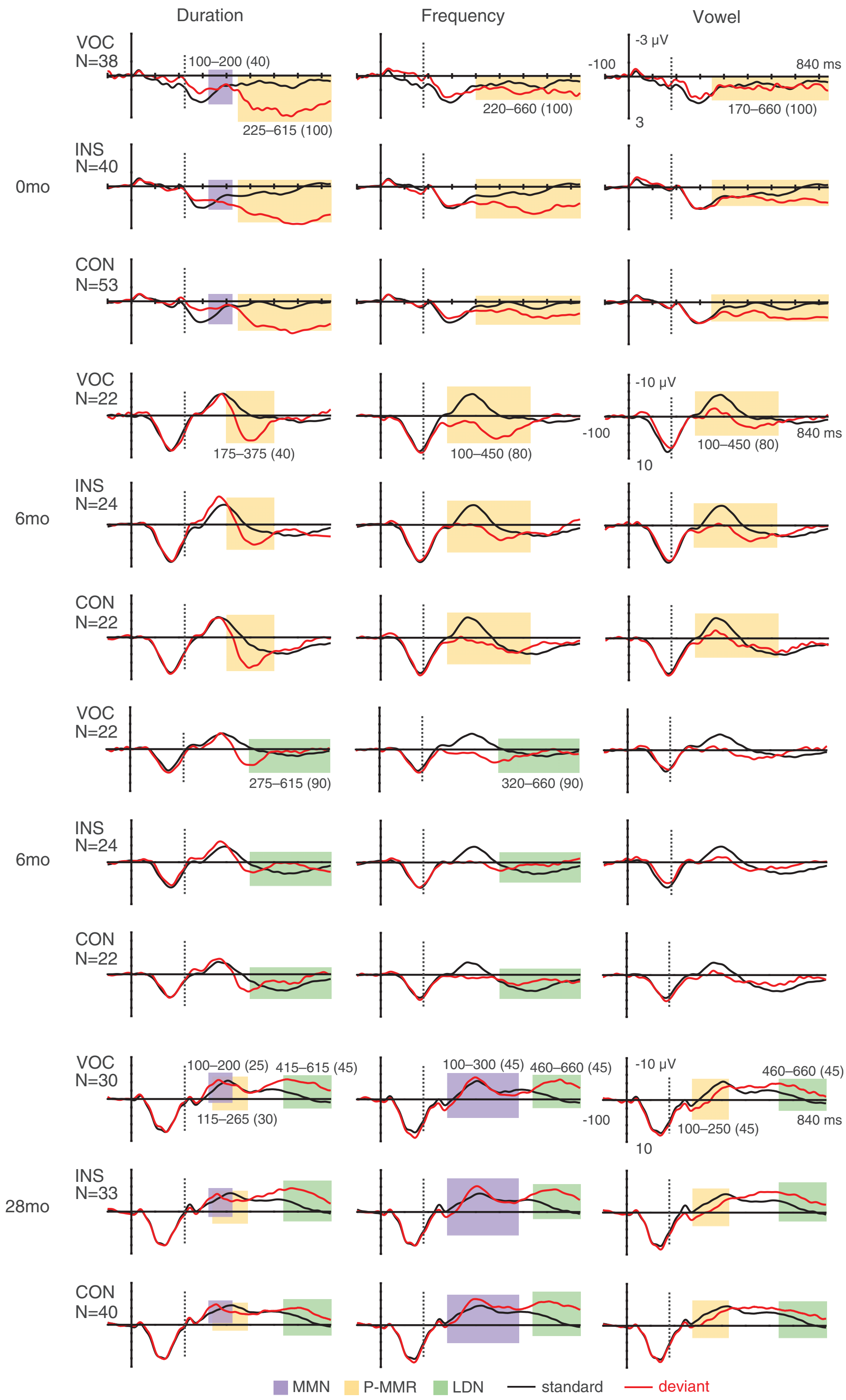

FIGURE 4 Standard and deviant event-related potential (ERP) waveforms in the vocal (VOC) and instrumental (INS) music listening intervention groups and the no-intervention control group (CON), at 0, 6, and 28 months (mo) in response to the three speech-sound deviants, with baseline at stimulus onset (−100 to 0 ms). Deviance onset is marked with a dashed line. Colorful bars and the latency windows, in ms, next to them describe the latencies used for peak latency search (same windows for all groups). Mean amplitudes were quantified from latency windows (width in parentheses; same widths for all groups) centered around individual peak latencies. At 0 and 6 months (mo), the MMRs are depicted and quantified from a fronto-central region-of-interest (ROI: F3, Fz, F4, C3, Cz, C4), except for the LDNs at 6 months from a centro-parietal ROI (C3, Cz, C4, P3, Pz, P4). At 28 months, the MMRs are depicted and quantified from a fronto-central ROI (F3, Fz, F4, C3, Cz, C4, FC1, FC5, FC2, FC6).

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TABLE 5 Mean amplitudes (ampl, in μV, standard deviation in brackets) and peak latencies (lat, in ms from stimulus onset, standard deviation in brackets, in case of missing values: Sample size in square brackets) of the event-related potentials (ERPs) P1 and N2, mismatch negativities (MMN), positive mismatch responses (P-MMRs), and late discriminative negativities (LDNs) in the vocal (VOC), instrumental (INS), and dyslexia-risk control (CON) groups.

		VOC	INS	CON
0 mo		N = 38	N = 40	N = 53
P1	ampl	1.93 (1.63)	1.56 (1.59)	1.51 (1.61)
	lat	289.7 (47.2) [37]	305.0 (50.9)	285.6 (60.6)
DUR-MMN	ampl	0.18 (2.18)	0.01 (1.79)	−0.12 (1.57)
	lat	381.6 (32.8) [22]	375.9 (30.9) [20]	369.6 (31.2) [19]
DUR-P-MMR	ampl	**3.52 (3.04)*****	**3.14 (2.72)*****	**3.01 (2.46)*****
	lat	638.3 (109.1)	661.8 (110.0)	654.9 (110.5)
FRE-P-MMR	ampl	**2.28 (2.62)*****	**2.30 (2.43)*****	**1.85 (2.01)*****
	lat	633.6 (134.3)	637.4 (132.5)	620.6 (132.2)
VOW-P-MMR	ampl	**1.79 (2.31)*****	**1.83 (2.62)*****	**1.87 (1.65)*****
	lat	598.2 (144.0)	616.3 (144.8) [39]	604.2 (147.8) [52]
6 mo		N = 22	N = 24	N = 22
P1	ampl	8.32 (3.64)	9.14 (2.83)	8.72 (3.19)
	lat	167.1 (17.1)	168.8 (16.5)	168.4 (17.2)
N2	ampl	−5.78 (3.45)	−4.76 (3.80)	−4.85 (3.09)
	lat	388.6 (36.0)	389.1 (26.0)	374.6 (25.2)
DUR-P-MMR	ampl	**6.51 (7.41)*****	**6.01 (3.90)*****	**6.81 (3.60)*****
	lat	488.6 (22.3)	488.4 (50.5)	482.7 (45.0)
FRE-P-MMR	ampl	**8.51 (5.12)*****	**6.33 (5.35)*****	**6.12 (3.35)*****
	lat	426.5 (66.9)	431.6 (73.8)	404.4 (65.8)
VOW-P-MMR	ampl	**7.56 (4.48)*****	**5.96 (3.57)*****	**3.98 (4.31)*****
	lat	446.3 (86.9)	421.2 (66.4)	407.6 (66.5)
DUR-LDN	ampl	−3.06 (5.45)* $p = 0.016$	**−2.90 (4.13)**** $p = 0.002$**	**−3.44 (3.73)*****
	lat	687.0 (74.6) [21]	660.1 (76.6)	671.1 (98.4)
FRE-LDN	ampl	**−2.75 (3.63)**** $p = 0.002$**	**−4.16 (4.32)*****	−2.97 (4.64)** $p = 0.007$
	lat	703.5 (72.2)	683.2 (88.2)	654.9 (60.3)
28 mo		N = 30	N = 33	N = 40
P1	ampl	8.18 (2.75)	8.22 (3.04)	8.31 (2.73)
	lat	138.8 (24.7)	133.2 (16.9)	131.7 (14.6)
N2	ampl	−4.22 (2.63)	−4.52 (2.91)	−4.91 (3.79)
	lat	399.9 (35.1)	405.3 (36.8) [32]	406.2 (41.2) [39]
DUR-MMN	ampl	−1.67 (3.26)** $p = 0.009$	−1.64 (3.14)** $p = 0.005$	−1.48 (3.28)** $p = 0.007$
	lat	352.8 (22.0) [20]	354.4 (21.0) [27]	351.2 (21.4) [34]
DUR-P-MMR	ampl	1.50 (4.45) $p = 0.075$	**2.38 (3.06)*****	**2.82 (3.58)*****
	lat	423.1 (31.3) [26]	423.3 (28.9) [32]	429.6 (28.5) [38]
DUR-LDN	ampl	**−4.78 (3.67)*****	**−5.40 (2.91)*****	**−2.91 (4.30)*****
	lat	733.0 (51.0) [29]	737.3 (46.3)	735.5 (42.1) [38]
FRE-MMN	ampl	**−3.25 (4.85)**** $p = 0.001$**	**−2.72 (2.96)*****	**−3.33 (3.90)*****
	lat	380.4 (51.8) [29]	392.6 (36.2) [32]	390.4 (44.4)
FRE-LDN	ampl	**−6.24 (4.37)*****	**−5.43 (3.02)*****	**−5.73 (3.59)*****
	lat	746.3 (42.9)	739.9 (40.8) [32]	752.7 (50.0) [37]

(Continues)

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TABLE 5 (Continued)

28 mo		N = 30	N = 33	N = 40
VOW-P-MMR	ampl	**3.01 (3.18)*****	**2.69 (3.05)*****	**2.36 (3.09)*****
	lat	380.9 (42.0) [28]	354.2 (36.9)	349.8 (35.5) [36]
VOW-LDN	ampl	**−3.96 (3.90)*****	**−4.25 (3.48)*****	**−3.34 (4.25)*****
	lat	737.0 (54.4) [27]	735.1 (44.7) [30]	744.0 (56.5) [38]

Note: Uncorrected statistical significance of the one sample *t* tests for the MMNs, P-MMRs, and LDNs is marked with asterisks (****p* < 0.001, ***p* < 0.01, **p* < 0.05—Bonferroni-corrected criterion *p* = 0.003).

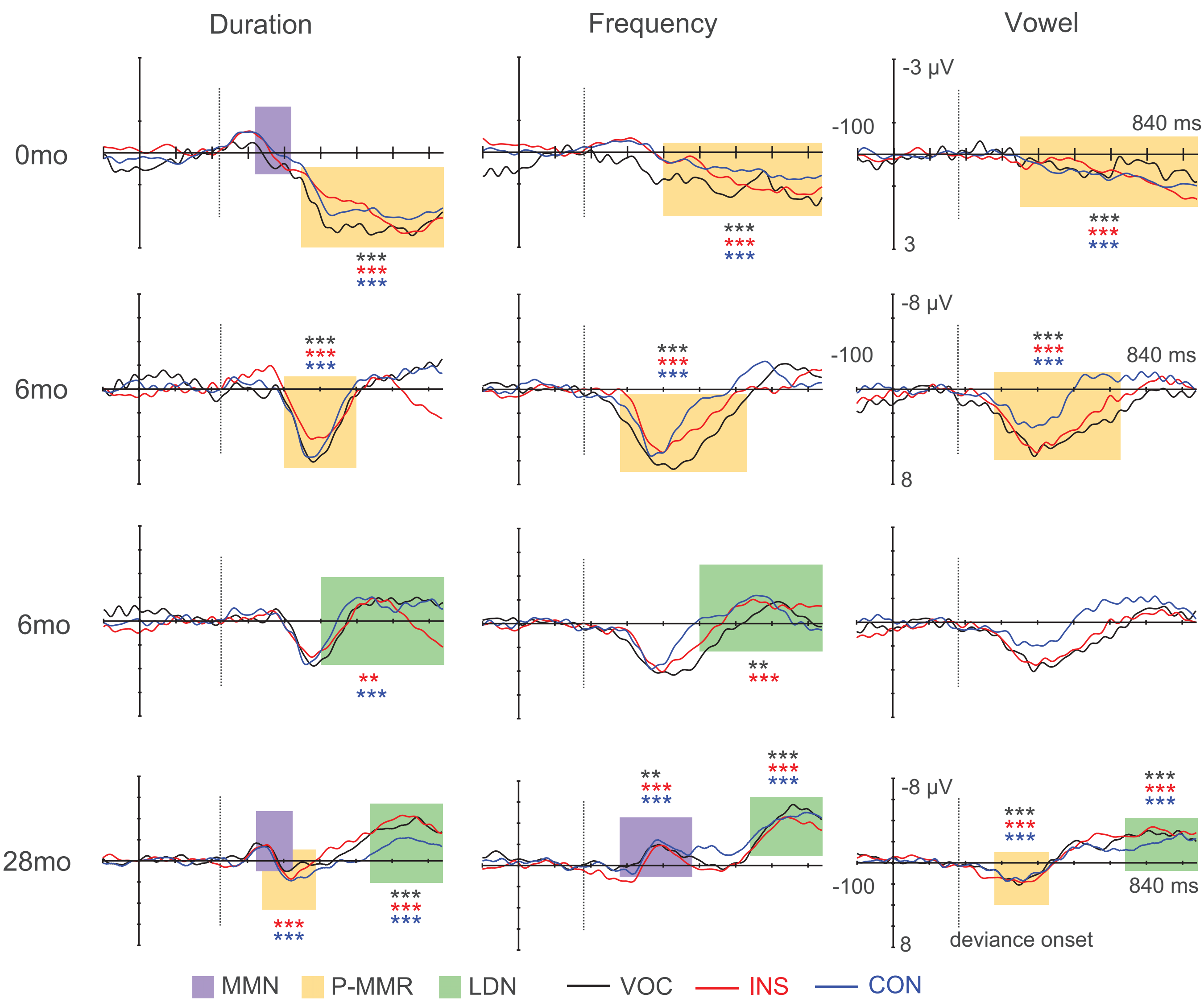

FIGURE 5 Subtraction waveforms illustrating the mismatch negativities (MMNs), positive mismatch responses (P-MMRs), and late discriminative negativities (LDNs) in the vocal (VOC) and instrumental (INS) music listening intervention groups and the no-intervention control group (CON), at 0, 6, and 28 months (mo) in response to the three speech-sound deviants, with baseline at deviance onset (−100 to 0 ms from the dashed line). Statistically significant responses after correcting for multiple comparisons (criterion *p* = 0.003) are marked with asterisks (****p* < 0.001, ***p* < 0.003). Colorful bars illustrate the latency windows used for peak latency search. At 0 and 6 months (mo), the MMRs are depicted and quantified from a fronto-central region-of-interest (ROI: F3, Fz, F4, C3, Cz, C4), except for the LDNs at 6 months from a centro-parietal ROI (C3, Cz, C4, P3, Pz, P4). At 28 months, the MMRs are depicted and quantified from a fronto-central ROI (F3, Fz, F4, C3, Cz, C4, FC1, FC5, FC2, FC6).

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interaction, $F(2,571) = 3.301$, $p = 0.038$, resulting from a larger P-MMR in the VOC than in the INS ($p = 0.027$) or CON ($p = 0.007$) groups at age 6 months across all deviants.

3.2.2 | P-MMR amplitudes from 6 to 28 months

The LMM for the duration- and vowel-P-MMRs between 6 and 28 months demonstrated a statistically significant Deviant X Group interaction, $F(2,229) = 3.632$, $p = 0.028$, resulting from a larger vowel-P-MMR in the VOC than in the CON group ($p = 0.025$, Figure 6). (Group-wise age effect Beta estimates for analyses which revealed significant group differences reported in Table S2).

The P-MMRs revealed no statistically significant main or interaction effects of group on peak latency. The P1 and N2, the duration- and frequency-MMN at 28 months, or the duration- and frequency-LDN between 6 and 28 months revealed no statistically significant main or interaction effects of group on amplitude or peak latency.

4 | DISCUSSION

We investigated the effects of vocal and instrumental music listening interventions in infancy on neural speech processing. As an early index of phonological and language development, speech-elicited ERPs were recorded before (at birth) and after the intervention (at 6 months), and at the 28 months follow-up. Consistent with our hypotheses, speech-sound discrimination was enhanced, as reflected by larger P-MMRs, in the vocal music intervention group compared to the other groups after the intervention. The instrumental intervention group did not significantly differ from the no-intervention control group in any response at any age. No group differences were found for the other MMRs, (MMN and LDN), or the P1 and N2 elicited by the repeating pseudoword. Our study thus showed intervention effects on speech sound discrimination abilities, reflected by the P-MMRs, rather than on basic feature extraction of the stimuli, reflected by the P1 and N2 responses.

The results show, for the first time and with a large sample size, beneficial effects of vocal music exposure on speech-sound discrimination in infants at risk for dyslexia. The enhancement of MMRs after intervention suggests plastic changes in the auditory system reflecting improved phoneme discrimination. These results suggest that the musically-induced exposure to native speech sounds improved the tuning, or neural commitment, to these sounds. The intervention enhanced those auditory neural abilities that were shown to be deficient in dyslexia and its familial risk (Hämäläinen et al., 2013; Volkmer & Schulte-Körne, 2018), and tapped phoneme processing, which is the core problem in dyslexia according to the phonological deficit theory (Eden et al., 2016; Giraud & Ramus, 2013; Peterson & Pennington, 2015; Vellutino et al., 2004). Importantly, the groups did not differ at baseline, nor in the amounts of other music-related activities or music exposure. This indicates that the group effect is attributable to the intervention itself. The results support the use of native language vocal music in facilitating auditory and speech processing development in at-risk groups during the first months after birth.

4.1 | Speech processing deficits in dyslexia and the promises of music

The enlarged P-MMR amplitudes after the vocal intervention indicate beneficial effects of vocal music exposure in early infancy on neural speech processing. Pre-existing group differences are unlikely, as the pseudo-randomized groups neither differed in MMRs at birth, nor in any relevant background factors. The effects also seem to be attributable to the vocal intervention specifically, as the instrumental intervention served as a meaningful and equally stimulating control intervention: music materials of the two interventions were otherwise identical, and the (low) drop-out rates and the estimated listening amounts did not differ in the two interventions. Furthermore, the results are not explained by differences in interactive music activities or other music exposure in the intervention groups, as the groups did not differ in the amount of these parent-reported activities; in fact, they were rather high in all groups (for example, 9 h/week of music exposure on average, more than the instructed or estimated intervention listening amounts).

Most importantly, our results on the beneficial effects of vocal music exposure concerned infants who were at dyslexia risk. To our knowledge, this study is the first to demonstrate the benefits of music on dyslexia-risk infants or young children, previously demonstrated in older healthy (e.g., Chobert et a., 2014; Moreno et al., 2009; Putkinen, Saarikivi & Tervaniemi, 2013; Putkinen, Tervaniemi & Huotilainen, 2013), and dyslexic children (Flaugnacco et al., 2015; Habib et al., 2016; Overy, 2003; for a review, Kraus & Chandrasekaran, 2010). Crucially, these effects were found in infants at a highly sensitive age for phonetic learning (Kuhl, 2004, 2010) and auditory maturation (Virtala et al., 2022), but unable to participate in active interventions.

MMNs/MMRs have been shown to reflect deficient auditory and speech-sound discrimination in dyslexia and its familial risk (Hämäläinen et al., 2013; Volkmer & Schulte-Körne, 2018), compatibly with the phonological deficit theory (Eden et al., 2016; Giraud & Ramus, 2013; Peterson & Pennington, 2015; Vellutino et al., 2004). The enhanced vowel-P-MMRs we found after vocal intervention indicate improved phoneme processing. Consistent with this, we previously found a diminished vowel-P-MMR in the no-intervention group of the present study compared to a control group without dyslexia risk (Virtala et al., 2022; see also van Leeuwen et al., 2006; van Leeuwen et al., 2008).

The group effect at 6 months was evident in the frequency- and vowel-P-MMRs, but not in the duration-P-MMRs. While deficiencies in discriminating all these contrasts have been reported in dyslexia and its risk (Hämäläinen et al., 2013; Volkmer & Schulte-Körne, 2018), the results on duration-MMRs in infants have been rather inconclusive and even enlarged amplitudes in dyslexia risk have been reported (Leppänen et al., 2002). It is also possible that the high acoustical salience of the duration change compared to the two more subtle deviants resulted in a ceiling effect, contributing to the absent

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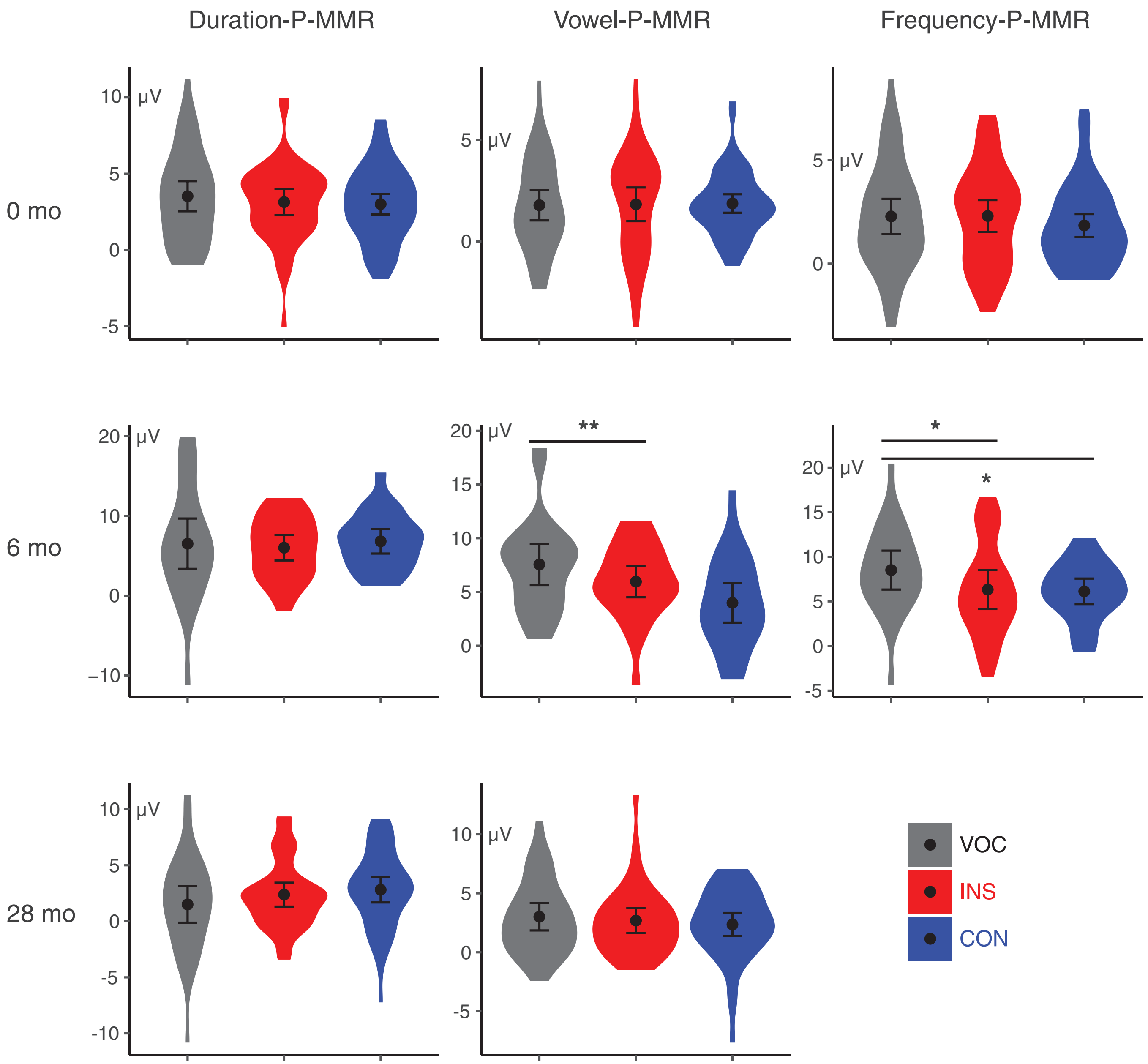

FIGURE 6 Mean amplitudes of the positive mismatch responses (P-MMRs) to all three speech-sound deviants in the vocal (VOC) and instrumental (INS) music listening intervention groups and the no-intervention control group (CON) at ages 0, 6, and (to duration and vowel deviants; frequency-P-MMR not statistically significantly elicited) 28 months (mo). In the LMMs, the VOC group had statistically significantly larger P-MMRs across deviants at 6 months and statistically significantly larger vowel-P-MMRs across 6 and 28 months, but the two group effects were driven by the frequency- and vowel-P-MMRs and by the vowel-P-MMRs at 6 months, respectively. The error bars represent 95% confidence intervals. Statistically significant post hoc comparisons are marked with asterisks: * $p < 0.05$, ** $p < 0.01$.

intervention effect for this deviant. Furthermore, against our hypotheses, frequency discrimination was not enhanced in the instrumental intervention group. Possibly, the speech stimuli used in the ERP recording were not optimal for tapping these effects, which might have emerged if musical stimuli had been used (see, e.g., Trainor et al., 2011).

The increase in P-MMR amplitude in the vocal intervention group was no longer visible at 28-months' follow-up (Figure 6). While this absent group effect may be attributable to many factors (see 4.3), the duration of the intervention effects and their transfer to language and literacy development will be determined more carefully in our continuing DyslexiaBaby follow-up study. If the benefits of vocal music exposure in infancy on neural speech-sound processing transfer into benefits on literacy, it would suggest the importance of early phonetic learning on the development of dyslexia and, hence, support the phonological deficit theory (Eden et al., 2016; Giraud & Ramus, 2013; Peterson & Pennington, 2015; Vellutino et al., 2004).

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4.2 | The efficacy of music interventions to promote speech and language in infancy

Previous intervention studies with older infants and in more interactive and structured settings have shown similar benefits of music for auditory and speech processing as the present study (Trainor et al., 2012; Zhao & Kuhl, 2016; Benasich et al., 2014; Musacchia et al., 2017). For example, an active music making intervention from 6 to 12 months, compared to a play group with background music, enhanced P1-like ERPs to musical stimuli (Trainor et al., 2012). Furthermore, a social intervention to 9-month-olds including music enhanced MMRs to speech sound changes compared to an intervention without music (no baseline measurement; Zhao & Kuhl, 2016).

Our results add to the earlier findings by suggesting that even a passive music intervention in younger infants can facilitate speech processing. Due to their requirements for active participation and (financial and other) resources, the interventions used in the aforementioned studies are not well-suited for young infants or easily available to all families. In contrast, music listening requires notably less effort and resources from the families and can begin already at birth (or even earlier). Its benefits on auditory ERPs have also been reported previously in infants without known developmental risks (Partanen et al., 2013; Trainor et al., 2011) and in adults (Särkämö & Soto, 2012). However, instead of investigating transfer effects on speech and language processing, these infant studies determined the effects of auditory learning of the presented stimuli or their features (melody, timbre).

Our findings are consistent with the hypothesis that vocal intervention is the most beneficial for neural speech processing. Compared to instrumental music, singing provides native-language speech sounds in an appealing, repetitive, and rhythmic format resembling infant-directed speech (Fernald & Kuhl, 1987; Nakata & Trehub, 2004). Our vocal materials were specifically designed to mimic parental singing, being simple with soft accompaniment only, and sung with clear pronunciation as to an infant (see Supplemental material). These features may be necessary to obtain benefits for speech development. Similar benefits of nursery rhymes (also rhythmic, repetitive, and resembling infant-directed speech) were recently shown on speech learning in infants (Suppanen et al., 2019). Interestingly, our results are in line with a study in another neurodevelopmental risk population, premature infants, which focused on promoting parental singing or humming with the help of music therapy during skin-to-skin contact (The Singing Kangaroo study; Kostilainen et al., 2021; Partanen et al., 2022). Auditory MMRs recorded with EEG (Kostilainen et al., 2021) and magnetoencephalography (Partanen et al., 2022) were enhanced by the singing intervention, compared to kangaroo care without it, at term age (no baseline measurement was conducted).

Although the beneficial mechanisms of vocal music exposure as sung by the parents in the Singing Kangaroo study may differ from those of the present study with recorded music, both studies support the use of vocal music in infants at risk for neurodevelopmental deficits. The intervention in the present study also offers some practical advantages compared to the Singing Kangaroo intervention: while singing may not come naturally to everyone, with mobile devices and Internet access, playing recorded vocal music is highly effortless. Future studies should investigate whether music sung live by the parent in interaction with their infant is superior at facilitating, for example, social-emotional development, compared to when it is played from recordings (as suggested by the results of, e.g., Gerry et al., 2012, and Kostilainen et al., 2021).

4.3 | Considerations for the future and limitations

The seemingly absent group difference in the MMRs at 28 months may stem from many sources. Firstly, it may indicate that while the vocal intervention provided a boost for speech learning in infancy, the other groups caught up with the vocal intervention group in these rather basic speech-sound discrimination abilities by 28 months. The follow-up period of nearly 2 years crosses the border from preverbal to verbal period in language development, and numerous factors contribute to the maturation of speech processing by this age. Therefore, the effects of the intervention on the studied processes might have diminished. Yet, the “boost” obtained from the intervention may still have cumulative benefits for many aspects of speech and language development during the early years that were not caught by the particular ERP measurements at 28 months.

Alternatively, or additionally, the less evident group difference at 28 months might stem from the marked maturation of the auditory MMRs during early childhood (e.g., Choudhury & Benasich, 2011; Virtala et al., 2022). For example, while the P-MMR seems to be the most prominent MMR in infancy, its amplitude decreases with age (Choudhury & Benasich, 2011; Slugocki & Trainor, 2014; Virtala et al., 2022). By 2–3 years, the MMR complex reaches a much more fine-grained morphology of 2–3 distinct peaks (Putkinen et al., 2012; Virtala et al., 2022), making it difficult to hypothesize which of the peaks reflect the same functions of auditory neurocognition as the infant P-MMR, and how. Thus, possible intervention effects on the MMRs may have become “lost in maturation.”

Some factors in the DyslexiaBaby sample and setting should be taken into account when interpreting the present results and planning future studies. Unfortunately, the sample size—although still reasonable ($N > 20$/group)—was smallest at 6 months mainly due to scheduling problems unrelated to the families and poorest quality of the EEG data. While newborn infants are mostly silent and still, and 28-month-olds can follow verbal instructions to stay still and focus on the muted cartoons relatively well, 6-month-olds can be quite restless and loud during the recordings, which influences data quality. This led to a notable variation in the number of usable epochs across age. This unfortunate challenge in investigating ERPs across different ages during early development means that the results have to be interpreted cautiously.

Also, as is a general practice in the field, we compared ERPs of mostly asleep newborns with ERPs of awake older infants and children. Thus, differences in the MMRs between ages may partly reflect these differences in alertness, complicating the comparison of the MMRs at intervention baseline with the MMRs recorded at later ages.

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Importantly, however, there were no statistically significant differences between the groups in the proportions of the alertness states in the newborn recordings.

Our study included two control groups, one being exposed to placebo treatment and one getting no treatment, which is a strength as compared to many other intervention studies usually having only one of these control groups. However, intervention studies on developmental language deficits ideally should also include a comparison group without a family history of language deficit and even another such group getting intervention. A control group without a family history enables assessment of the extent to which speech processing becomes normal-like in the familial-risk intervention group. A group without a family history and with the intervention would be valuable in determining whether the intervention would indeed benefit all children. This is especially useful since not all children who develop a language or reading deficit have a familial background for the disorder. Whereas these issues remain to be addressed by future studies, the results of our three participant groups (song intervention, instrumental intervention, and no intervention groups) lead to the conclusion that interventions including songs specifically improve neural speech processing in children at risk for dyslexia.

5 | CONCLUSIONS

We found benefits of vocal music exposure during the first 6 months after birth on neural speech-sound discrimination as reflected by MMRs in infants at risk for dyslexia. Promoting speech processing in this population has high relevance for dyslexia amelioration, as deficient speech processing is associated with dyslexia and its familial risk, and as phonological deficits are proposed to underlie dyslexia. Effective, evidence-based interventions for young infants can result in cumulative positive effects, changing the developmental course from the very beginning. Based on our results, regular listening to simple and repetitive vocal music like lullabies and folk songs is an extremely easy-to-administer and cost-effective intervention that can be recommended to all families with a newborn baby.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

The DyslexiaBaby longitudinal study is approved by the Ethics Committee for Gynaecology and Obstetrics, Pediatrics and Psychiatry of the Hospital District of Helsinki and Uusimaa and the study has been conducted in compliance with the Declaration of Helsinki.

DATA AVAILABILITY STATEMENT

The final subject-wise data (response amplitudes and peak latencies) and the R code for running the main statistical analyses as well as the intervention materials (playlists) are available at https://osf.io/jf7bz/?view_only=5caab5746b7d43caa7e1aa8815a7bb52.

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