Research Report

Infant Neural Tracking and Phonological Awareness at Pre-School Age

Major Research Project – Neuroscience and Cognition (MSc)

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Date: November 7, 2025

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Abstract

A growing body of research shows that neural tracking of language, especially infant-directed speech, is related to a child's subsequent language development. These studies equated language development with vocabulary size, but the relations with other linguistic abilities remain unknown. Phonological awareness (PA), or the ability to assess the sound structure of a language and to apply this understanding in expressive language, is a vital ability for formal reading and writing education. Therefore, the relationship between neural tracking and later phonological awareness was explored. A sample of 145 Dutch children watched a video of five naturalistically sung nursery rhymes during an EEG recording at 10 months old. From these EEG recordings and the speech envelope of the stimuli, speech-brain coherence (SBC) was calculated for stress rate (1-3 Hz), syllabic rate (3-5 Hz), and phonemic rate (5-15 Hz). During follow-up research at age 4:0-6:11, their PA was tested with the CELF Preschool-2^{NL}. Multiple linear regression models were fitted on these two measures to predict PA scores with SBC values. Age at both moments of testing and an age-normed general language ability score were included as covariates, based on two baseline models. While the testing model was significant ($F(6, 139) = 9.670$, $p < .001$, $R^2 = .295$), none of the SBC values significantly predicted PA (for all values: $p > .36$). These results indicate that SBC during the first year of life does not relate to phonological awareness at early school age. However, to convincingly draw conclusions on this relationship, examining this relationship at different time intervals and points, and using different language measures is necessary.

Plain language summary

Recent research has shown that humans neurally 'track' spoken speech: the waves in a speech (i.e. sound) signal and the listener's brain waves start to synchronise to a certain extent. This effect is even present in infants, as they can track the rhythm and syllables in spoken speech. This neural tracking is involved in language development, where better tracking of the speech signal leads to better language development. However, language development was tested as vocabulary size in these studies. Another important skill to learn is phonological awareness (or in short, PA), meaning that one can understand sentence structures and syllables within a word, form compound words, and rhyme. It is also a skill that is necessary to have when starting formal reading and writing education, which usually starts at 7 years old. Therefore, in this study, it was explored how neural tracking relates to PA. A sample of 145 Dutch children watched a video of sung nursery rhymes at 10 months old, while EEG was recorded. From this data of their brain waves in response to the speech in the video, a so-called speech-brain coherence (SBC) value was calculated, where a value of 0 meant no synchronisation and a value of 1 meant perfect synchronisation between both waves. The same children were tested for PA level about four years later, between ages 4 and 7. However, statistical analysis showed no relationship between SBC at 10 months old and later PA level at 4-7 years old, meaning that neural tracking does not seem to lead to better phonological awareness. This is not a definitive finding yet, because it is one of the first times that this relationship was examined; and therefore more specific research is necessary to confidently state that these two constructs are not related.

Introduction

Neural tracking of speech can be defined as temporal synchronisation of neural oscillations with an incoming speech signal (Gillis et al., 2022). Speech is composed of different sounds, loudness and rhythms. Therefore, a so-called speech envelope can be graphed, which visualises the speech signal's amplitudes, phases, and most importantly, frequencies. Different frequency bands in the speech signal relate to different linguistic units. Roughly, prosody (i.e. rhythm of a language) corresponds to ~2 Hz or delta band; syllables correspond to ~5 Hz or theta band; and phonemes (i.e. vowels and consonants) correspond to ~20 Hz or beta band (Leong & Goswami, 2015). This speech envelope is transmitted as is by the ears, but needs to be processed by the brain. During speech processing, most areas of the brain are involved, including parietal subcortical areas, temporal regions, and the frontal gyrus (Brodbeck et al., 2018; Çetinçelik et al., 2024; Koloszvári et al., 2021). Therefore, neural tracking is a measure of general neural synchronicity with the heard auditory signal. It is theorised to be a neural mechanism supporting language understanding (e.g. Giraud & Poeppel, 2012). A major argument is that neural tracking of speech seems to be enhanced in situations with background noise or interfering voices (e.g. An et al., 2023). Similarly, it is increasingly implicated in language development (e.g. Menn et al., 2022b).

This neural tracking of speech can be measured in various ways. Common tactics are de- or encoding models, utilizing different algorithms (Gillis et al., 2022). Most prominent in neurolinguistic research into language development is speech-brain coherence (Snijders & Menn, 2023). Note that speech-brain coherence (SBC) is dissimilar to common coherence measures for brain measures: rather than measuring only coherence within the brain, it measures correlational coherence between the internal EEG signal and the external speech envelope. SBC allows for naturalistic speech as a stimulus, making it an ecologically valid measure of spoken and sung language understanding. It is therefore especially valuable in analysing linguistic development.

Neural Tracking of Language in Infants

Although infants' neural tracking of speech is less robust and slightly different to adults' neural tracking (Vander Ghinst et al., 2019), it occurs already in newborns. Newborns (≤ 5 days old) show differing delta and theta oscillations for rhythmically different languages, which implicates that newborns can neurophysiologically discriminate languages based on prosody (Ortiz-Barajas et al., 2023). Indeed, ongoing research even attempts to show that neural tracking starts prenatally, as familiarity with the rhythm of the first language seems to

be acquired during pregnancy (Florea et al., 2024). At 4 months old, infants can significantly track prosody (delta band) and syllables (theta band) when hearing sung nursery rhymes (Attaheri et al., 2022). The tracking of prosody is enhanced in 6-months-olds when hearing their native language, instead of an artificial language (Choi et al., 2020). The authors argue that this suggests statistical learning, underlining the involvement of neural tracking in language development. This is corroborated by the findings that significant neural tracking of low-frequency information, such as stressed syllables (1-3 Hz) and regular syllable rates (2.5-3.5 Hz), in continuous naturalistic speech, significantly predicts later vocabulary at 18 and 24 months old (Çetinçelik et al., 2024; Menn et al., 2022b).

Interestingly, this neural tracking relies solely on the auditory signal, as Çetinçelik and colleagues (2024) found that audiovisual speech cues do not affect neural tracking of speech at 10 months old. This was assessed by presenting the same stimulus, in an audiovisual and audiovisual-blocked condition. In the audiovisual-blocked condition, the mouth and jaw of the woman speaking was covered by a simple grey block. Similarly, directed or averted eye-gaze did not significantly modulate neural tracking of stress and syllable rates at the same age (Çetinçelik et al., 2023). Related to this attention issue, the aforementioned audiovisual speech cues did cause better attention in infants, evaluated by looking times at the stimulus screen – but no significant modulatory effect was found either of attention on neural tracking of speech (Çetinçelik et al., 2024).

An important note to these results is the difference between adult-directed speech (ADS) and infant-directed speech (IDS) presented as stimuli. Typically, adults adjust their speech when it is directed to an infant (Kalashnikova et al., 2018). It encompasses slower speech than usual ADS and more regularly stressed syllables, thereby supplying more prosodic information to the listener. As it was established that prosody is one of the first linguistic aspects to be significantly neurally tracked by infants (Ortiz-Barajas et al., 2023; Attaheri et al., 2022), IDS might be acoustically structured to facilitate language understanding. Supporting this, Leong and colleagues (2017) found that infants exhibit greater modulation energy (i.e. amplitude or power changes that modulate an effect) in delta band frequencies – corresponding to prosody – when hearing IDS, than when hearing ADS. ADS, on the other hand, causes greater modulation energy in theta band – corresponding to syllables – as less emphasis is spoken, compared to IDS. Kalashnikova and colleagues (2018) also found that 7-month-olds exhibit stronger low-frequency neural tracking when hearing IDS, compared to hearing ADS. More specifically, Menn and colleagues (2022a) found that SBC is significantly higher for IDS compared to ADS at prosodic rates (1-2.5 Hz) in 9-months-olds.

It is therefore important to keep in mind that results on infant neural tracking are based on stimuli with IDS, such as mothers enunciating extensively, or word play such as nursery rhymes. In relation to neurolinguistic research, it means generally lower frequency bands are examined than in adult research. This, however, is still an ecologically valid stimulus, as IDS is commonly used to address infants, and infants preferably listen to IDS compared to ADS (Fernald, 1985).

Subsequent Language Development: Phonological Awareness

A few of these results show that neural tracking of language, especially IDS, can be related to a child's subsequent language development (e.g. Attaheri et al., 2024). However, these studies have examined the relations between neural tracking and vocabulary development. The relations with other linguistic abilities remain unknown. A child has to develop an understanding of several linguistic aspects, namely: semantics (i.e. vocabulary), syntax (i.e. grammar), pragmatics (i.e. language use in context), morphology (i.e. word structure), and phonology (i.e. speech structure and sound system of a language) (Popp, 2004, pp. 41). Phonology seems to be an especially important aspect to understand. This is called phonological awareness, and can be defined as assessing the sound structure of a language and being able to manipulate said sounds (Wiig et al., 2012, pp. 69). More practically, it entails the ability to recognise and manipulate compound words; the ability to discriminate syllables and parts of a sentence; and the ability to recognise and create rhyming words. These skills are learnt through hearing children's stories, nursery rhymes and participating in other word play.

Phonological awareness is an important skill to master before school age, as it is a prerequisite for formal reading and writing education: children with deficient phonological awareness tend to have reading and spelling difficulties at early school age (International Reading Association, 1998; Rayner et al., 2001). Indeed, this is also substantiated in neural tracking research. For example, Leong and Goswami (2015) found that children with dyslexia have issues with phonological development, exhibit a reduced sensitivity to amplitude modulation structure of acoustic signals. An amplitude modulation structure describes two simultaneous signals, where one low-frequency signal lines the fluctuations in amplitude of a higher frequency signal. In speech envelopes, these amplitude modulations form linguistic cues (e.g. which part of the sentence receives emphasis, by varying emphasis on syllables). Understanding these linguistic cues is thought to underlie phonological awareness. These findings match another finding concerning children with dyslexia: they show impaired

encoding of speech envelopes between 0 and 2 Hz (Power et al., 2016). This impaired neural tracking of prosody could underlie phonological awareness deficits, as it hinders consequent discrimination of smaller linguistic units, such as phonemes. These findings suggest the theory that there is a relation between the ability to neurally track linguistic units, and phonological awareness level.

The Current Study

Therefore, this research will explore how neural tracking of stress, syllables, and phonemes in typically developing 10-months-olds relates to phonological awareness at early school age (4:0 to 6:11 years old). This aims to shed light on the underpinnings of phonological awareness. It will also explore the relation between SBC and a more comprehensive measure of language ability, as phonological awareness seems to be a language ability that is detrimental to later language and reading abilities, and encompasses the general ability to manipulate language and linguistic units. These results can build further theoretical basis for research into language disorders, such as dyslexia.

Based on previous literature, the tentative hypothesis is drawn that neural tracking significantly predicts phonological awareness at a later age, albeit possibly a small effect. Neural tracking will be measured by calculating SBC in infants upon hearing nursery rhymes. Frequency bands of interests are: stress speech rate at 1-3 Hz; syllabic rate at 3-5 Hz; and phonemic rate at 5-15 Hz (Menn et al., 2022b). Follow-up research between the ages of 4:0 and 6:11 years old will evaluate the phonological awareness abilities, using a subtest of the Clinical Evaluation of Language Fundamentals Preschool-2-NL (CELF Preschool-2^{NL}) (Wiig et al., 2012). This language test contains a subtest of 24 items, examining both the understanding of and ability to manipulate syllable and sentence structure, compound words, and rhyme. In the statistical analysis, several regression models will examine: (1) possible confounding variables, such as age and general language ability, and their relation to phonological awareness scores, and (2) the predictive value of the SBC measures of stress, syllables and phonemes, when correcting for the covariates.

Lastly, this research is related to the ongoing study of Van der Klis and colleagues (2024), which aims to investigate how neural tracking of IDS develops over infancy, and how this relates to children's subsequent vocabulary outcomes. The current study and Van der Klis and colleagues' study are part of the broader BRAVECHILD study (Junge et al., in prep.), examining several relations between biological underpinnings and later language development in childhood.

Methodology

Participants

This study used data from the BRAVECHILD study, conducted by dr. C.M.M. Junge and colleagues (in prep.). This study received ethical approval by the Ethics Committee of the Faculty of Social and Behavioural Sciences of Utrecht University for researching language development at pre-school ages, in relation to neural tracking in infancy. It recruited participants via their earlier participation in Utrecht University's YOUth cohort study (Onland-Moret et al., 2020), which maps the interaction between biological, psychological and environmental processes, and children's behavioural development. The YOUth study provided the sample of EEG recordings from 10-month-olds (N = 1575). The BRAVECHILD study provided the language ability evaluations at ages 3:0 to 6:11 of a subsample of this group that responded to the follow-up research. At least one parent of the participants signed informed consent forms before every recording or testing procedure. Willingness of the children to participate was also monitored informally, and taken into account in the parents' consent. Participants were compensated with a toy after every testing procedure, and parents received a monetary compensation of €10,00.

An inclusion criterion was that the child should be exposed to less than 20% of a language other than Dutch at home, to ensure monolingualism. An exclusion criterion was a general language ability score on the CELF Preschool-2^{NL} lower than two standard deviations, or lower than 70, as this is indicative of developmental language disorder. Based on this criterion, one participant was excluded. After preprocessing of the EEG recordings belonging to this subsample, this resulted in 145 infants to be included in the final sample for statistical analyses. See Table 1 for the descriptive statistics of this sample.

Table 1

Descriptive Statistics of Final Sample.

		N	Range	Mean ± SD
Age in weeks				
	At EEG recording	166	39.00 - 61.00	44.87 ± 4.18
	At CELF	145	243.00 - 359.00	286.66 ± 47.58
SBC		166 (F = 89, M = 77)		
	Stress		-.07 - .14	.10 ± .01
	Syllabic		-.06 - .15	.09 ± .02

	Phonemic	-.07 - .11	.09 ± .01
Normalised SBC	166 (F = 89, M = 77)		
	Stress	-.08 - .36	.14 ± .09
	Syllabic	-.12 - .31	.12 ± .09
	Phonemic	-.08 - .19	.09 ± .04
Phonological Awareness	145 (F = 80, M = 65)		
	Raw scores	5 - 24	20.71 ± 3.16
	z-scores	-4.98 - 1.04	0.00 ± 1.00

Materials

EEG Stimuli

EEG recordings followed the same experimental setup as in Menn et al. (2022b). During EEG recordings, infants were presented with three tasks. The third task was the task of interest for this study. It contained two videos, labelled as 'social' and 'non-social' videos. The social videos showed alternatingly two female researchers singing five Dutch nursery rhymes (respectively: "Dit zijn mijn wangetjes", "De wielen van de bus", "Hansje pansje kevertje", "Twinkel twinkel kleine ster", and "Papegaaitje leef je nog?"), in total lasting 69 seconds. The women were instructed to sing the songs as naturally as possible, including hand gestures and facial expressions. The non-social videos lasted 60 seconds, showing various toys in movement and making sounds, without human interference (earlier used by Jones and colleagues (2015)). The social videos were of interest for SBC analyses.

Language Test

During follow-up research, phonological awareness was tested by administering the CELF Preschool-2^{NL} (Wiig et al., 2012). This is a clinical evaluation that maps a child's language abilities by providing a comprehensive language profile, containing evaluations of both receptive and expressive language abilities (such as vocabulary, grammatical understanding and following instructions). The language profiles provided by the CELF Preschool-2^{NL} are relative to a child's age group, with norm score tables per subtest with separate norm scores for each age segment per two months. A total of 1180 monolingually Dutch children were recruited to compose the norm scores. Additionally, they were typically developing, meaning they were not allowed to have visual, auditive or communicative issues, or an intellectual or physical disability preventing them from understanding and answering the

exercises.

The CELF Preschool-2^{NL} includes eight subtests in total, of which seven were administered. One subtest, Phonological Awareness, was of interest for the current study. It contains 24 items, testing the ability to understand and manipulate (1) syllables and sentence structure, (2) compound words, and (3) rhyme. All three skills were each tested by two tasks, resulting in six tasks, consisting of four items per skill. Due to ceiling effects and different scales for the norm scores per age group, it was decided to use the raw scores in this study.

For further dissection of the concept phonological awareness and how it is evaluated by the CELF Preschool-2^{NL}, see Appendix A.

Procedure

All data was recorded with anonymised participant numbers. The testing started with a continuous EEG recording, containing three tasks; of which the last task was the task of interest, lasting approximately 6 minutes. EEG recordings were done using a 32-channel ActiveTwo BioSemi system, configured to the standard International 10-20 System (channels: 28 lateral channels FP1/2; F7/8; F3/4; AF3/4; FC1/2, FC5/6, C3/4, T7/8, CP1/2, CP5/6, P3/4, P7/8, O1/2, PO3/4, and 4 midline channels Fz, Cz, Pz, Oz). The EEG data were recorded relative to common mode sense and driven right leg (CMS/DRL) electrodes placed near Cz. Continuous EEG was acquired at a 2048Hz sample rate using Actiview (version 7.05).

Infants were placed either on a highchair or on their parent's lap, at approximately 65 cm distance from a 23-inch Full HD IPS LG black computer monitor (refresh rate 60 Hz, 1920 x 1080 resolution). The stimuli were presented a total of three times, alternating between social and non-social videos, with a randomized starting order. Videos were separated by a 1 second black screen. At the start of every video, a trigger number was recorded alongside the neural signal for later preprocessing.

For follow-up research, language measures were evaluated between ages 4:0 and 6:11. Researchers visited the child's house and administered the CELF Preschool-2^{NL} (Wiig et al., 2012) mostly in chronological order. Subtests administered were: Sentence Comprehension, Word Structure, Expressive Vocabulary, Following Directions, Recalling Sentences, Word Classes, and Phonological Awareness. Scores were written down manually on a scoresheet, anonymised by a participant number. Some tasks were recorded on an iPod with the parents' permission. These recordings were only used in case of doubt whether a score point should be granted for an item. During the session, parents were instructed not to help their kids, but were allowed to be present.

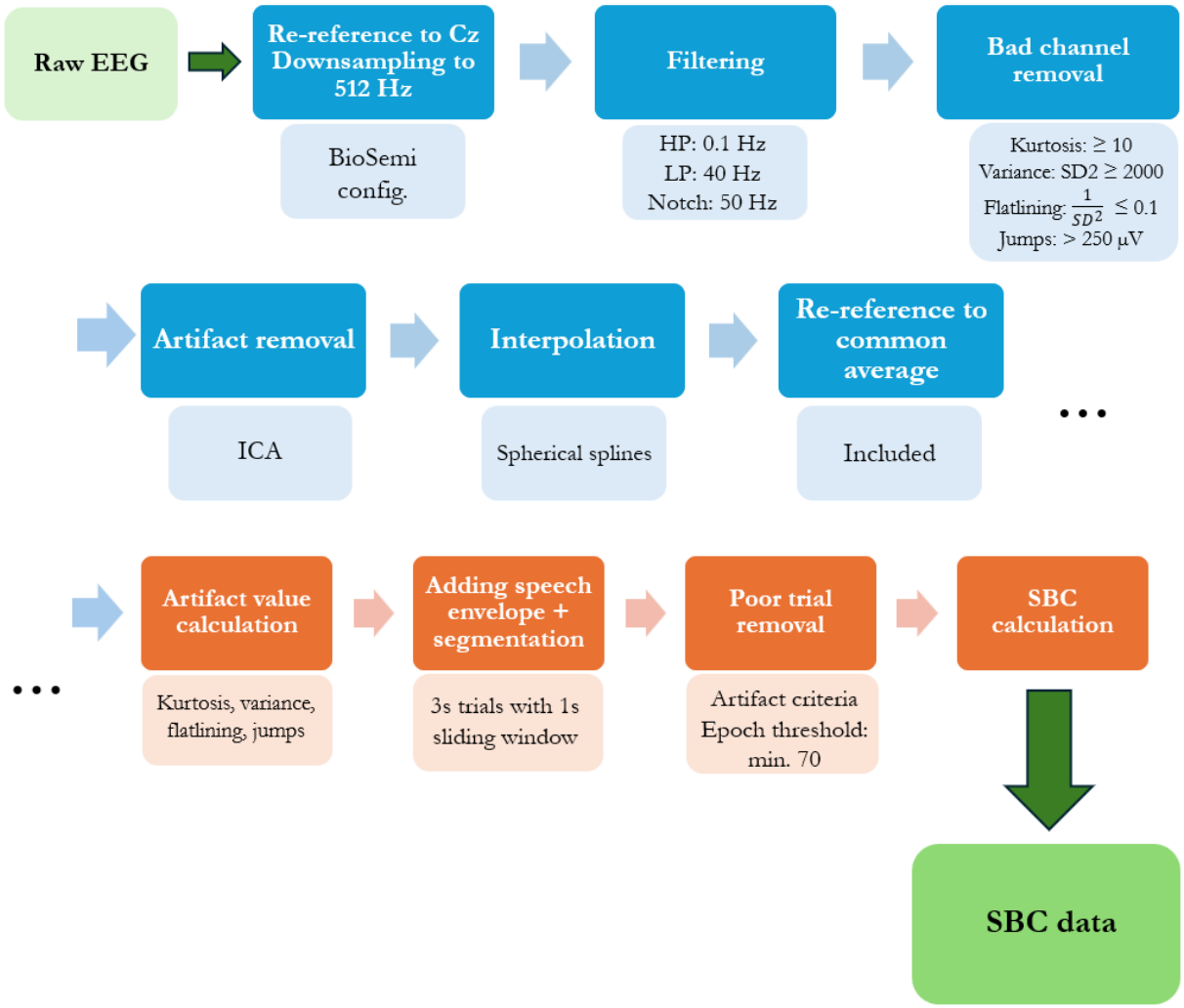
The entire testing session lasted about 2 hours, and breaks were permitted whenever the child or parent deemed it necessary. The subtest of interest, Phonological Awareness, lasted 5-10 minutes. This variation in timing was due to distractibility of the child, as it was often the last subtest to be administered.

EEG Preprocessing

EEG recordings were preprocessed in MATLAB R2021b, using the FieldTrip toolbox (version 20250502) for EEG/MEG analysis (Oostenveld et al., 2011). This was done by using a modified version of Van der Velde et al.'s automated pipeline (2019). The current version is fully automated, meaning no visual inspection or manual corrections were necessary (Chaudhry et al., 2025). A breakdown can be seen below in Figure 1.

Figure 1

Automatic Preprocessing Pipeline for Infant EEG Data.



The first step of the pipeline was to re-reference all EEG data to Cz, as prescribed by BioSemi (n.d.), and resample it to 512 Hz. Then, a 4th-order Butterworth filter was applied with a high-pass filter at 0.1 Hz, a low-pass filter at 40 Hz, and a notch filter at 50 Hz. For artefact rejection, data were cut into 1-second trials and evaluated for kurtosis (≥ 10), variance ($SD^2 \geq 2000$), flatlining ($\frac{1}{SD^2} \leq 0.1$), and jumps (> 250 µV). Consequently, at 40% or more artefactual trials within a channel, the channel was flagged as noisy. Once three or more channels were flagged as noisy, the session was removed from further analysis.

To further clean the data, independent component analysis (ICA) was performed with the EEGLAB toolbox (Delorme & Makeig, 2004), using the iMARA algorithm (Marriott Haresign et al., 2021) and its *runica* function. This algorithm has been trained on infant EEG data, and thus can do without visual inspection of the topographies and flagged artefacts. After this additional examination of artefacts, the artefactual data were removed from the raw data, and the leftover raw data were preprocessed once again. This was done with the same Butterworth filter and values, but with an average re-reference and spherical spline interpolation of missing data. Task trigger numbers were flagged and only social videos were selected from now on.

The data were then cut into 3-second segments with a 1-second sliding window. Artefact values were once again calculated using the previously mentioned criteria, to instate an epoch threshold of a minimum of 70 clean epochs per session. At last, speech-brain coherence was calculated over the remaining sessions.

Speech-Brain Coherence

The speech-brain coherence (SBC) calculation was used as in Menn et al. (2022b). This entails that, firstly, the speech envelope from the social videos was prepared by applying a Hilbert transform with a 4th-order Butterworth filter. Then, both the EEG data and the speech envelope were Fourier-transformed between 1 and 15 Hz to result in two comparable envelopes. SBC was then calculated using the following formula (Bastos & Schoffelen, 2016; Rosenberg et al., 1989; Menn et al., 2022b):

$$\mathrm{coh}_{xy}(\omega) = \frac{|S_{xy}(\omega)|}{\sqrt{S_{xx}(\omega) \cdot S_{yy}(\omega)}}$$

In this formula, $S_{xy}(\omega)$ indicates the normalised cross-spectral density between the speech signal x and the EEG signal y. The frequency is displayed by ω, and $S_{xx}(\omega)$ and $S_{yy}(\omega)$ reflect the power spectra of respectively the speech envelope and the EEG signal.

This formula results in a coherence value between 0 (random synchronisation) and 1 (perfect synchronisation), indicating the consistency of phase difference between the speech signal and the EEG signal at a certain frequency (Peelle et al., 2013).

Lastly, to avoid differences in number of epochs per session influencing statistical outcomes, the SBC values were normalised. This was done by randomly shuffling the neural epochs returned by the preprocessing pipeline along the speech envelope, and calculating random SBC values from this. Then, these random SBC values were subtracted from the observed SBC values. This was divided by the sum of the observed and random values. This calculation resulted in values of negative and positive values. Here, negative values indicated less-than-chance-level coherence, a zero-value indicated chance-level coherence, and positive values indicated above-chance coherence.

To obtain SBC values per frequency band corresponding to a linguistic unit, the normalised coherence values across all electrodes were averaged per frequency band of interest. This resulted in three SBC values per infant: stress rate at 1-3 Hz, syllabic rate at 3-5 Hz, and phonemic rate at 5-15 Hz.

Statistical Analysis

To statistically analyse the relation between SBC values and consequent phonological awareness models, using R (version 4.5.1; R Core Team, 2025), the distributions of the data were first examined to determine which scores would be most useful in a statistical model. Furthermore, exploratory correlation analysis was performed to determine the relation between the separate SBC values, and the different CELF Preschool-2^{NL} scores. This was done to further understand how the SBC values cohere statistically, in addition to conceptually; and to evaluate how phonological awareness scores relate to other linguistic abilities.

Then, to determine the relation between neural tracking at 10 months old and phonological awareness at early school age (4:0-6:11), several linear regression models were fitted on the SBC values of the 10-month-olds and the CELF Preschool-2^{NL} scores of their later selves. To avoid ceiling effects of the Phonological Awareness scores, the raw scores were standardised by calculating a *z*-score for each value. For SBC values, the normalised SBC values were used. In the following model descriptions, phonological awareness *z*-scores are indicated as PA_z, normalised SBC values as SBC_x, and covariates as C_x.

Model 1: $PA_z = C_{EEGage} + C_{CELFage}$

$$\text{Model 2: } PA_z = C_{EEGage} + C_{CELFage} + C_{\text{general language ability}}$$

$$\text{Model 3: } PA_z = SBC_{stress} + SBC_{syllabic} + SBC_{phonemic} + C_{EEGage} + C_{CELFage} + C_{\text{general language ability}}$$

In this model structure, Model 1 posed as a baseline model, determining the predictive power of age in weeks at the two testing points. In this model, the two ages were taken into account, to age-norm the SBC values, and to correct for ceiling effects of the CELF. The results of this model would indicate whether these variables should be taken into account as covariates. Model 2 added the age-normed score for general language ability from the CELF Preschool-2^{NL}. This was done due to moderate correlation between this score and the Phonological Awareness norm scores (see Table 2), to once again evaluate its covariance with the outcome. In Model 3, the additive value in predictive power of the three normalised SBC values was evaluated for amount of contribution. The same covariates were assumed as in Model 2, to control for confounding factors and ensure finding the unique contribution of neural tracking to phonological awareness. Finally, the assumptions of each model were tested, to evaluate the validity of each model interpretation.

Two additional models were tested to further explore the relations between the SBC values, phonological awareness and age. These are discussed in Appendix B.

Results

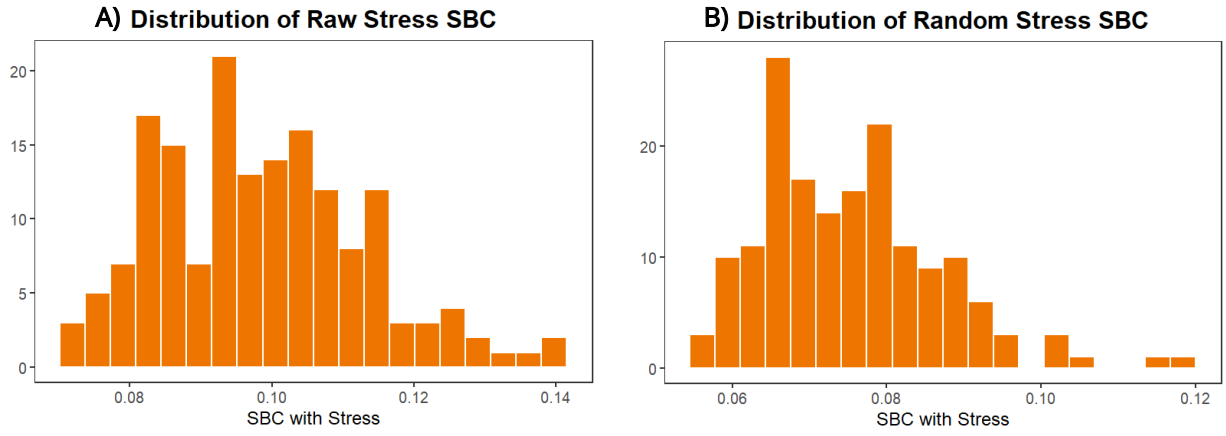
Standardisation of Raw Data

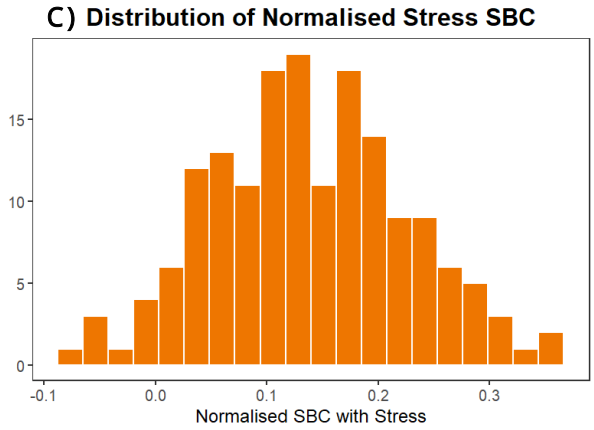
As described in the methodology, the SBC and phonological awareness scores in the regression models were standardised. In this section, data distribution graphs will support why this choice was made.

Concerning the SBC values, three types of data were available: the raw coherence scores, normalised coherence scores, and randomly shuffled coherence scores (which were used in the normalisation formula). In the Figures 2, 3, and 4 below, the distribution of the SBC values can be seen. For all three linguistic units, it can be seen that the raw scores are relatively left skewed. The scores are also relatively low, ranging mostly from .08 to .10. The randomly shuffled data contains the same epochs as in the raw data, but shuffled randomly to the speech envelope. This created lower SBC values than the raw scores, which is a positive finding. It suggests that generally, observed SBC values are higher than randomly at chance obtained data. This suggestion is confirmed in the distributions of the normalised data, where a score of 0 indicates chance-level SBC, and a positive value shows above chance-level SBC. For all linguistic units, the majority of the values correspond to positive values, albeit low positive values.

Figure 2

Spread of SBC Values with Stress for Different Scores.

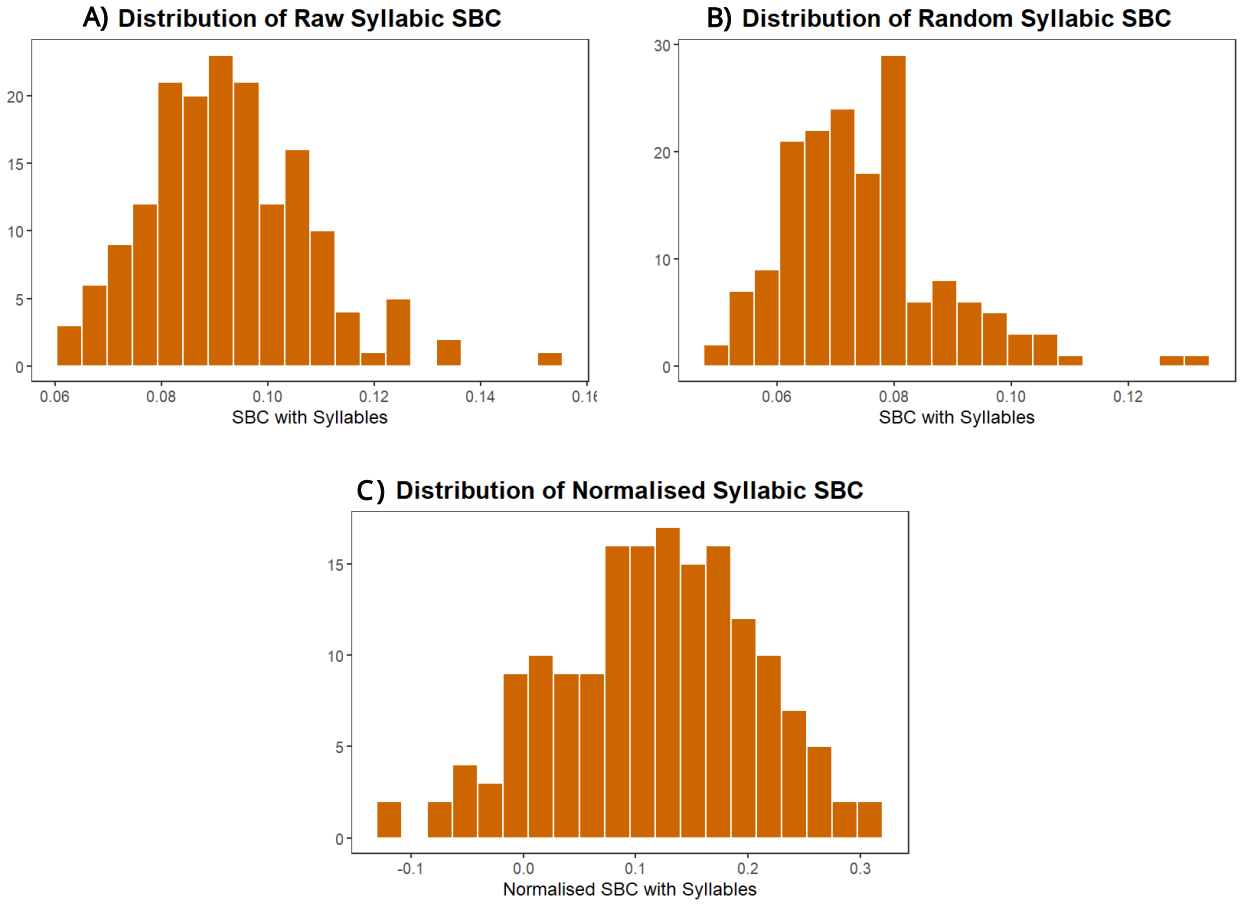




Note. Figures show the distribution of 166 data points of 10-month-olds across SBC values. In graphs A and B, the x-axis shows coherence values with a range of 0-1. Graph C shows normalised scores, with the x-axis ranging from negative to positive values, and a score of 0 corresponding to chance-level. A positive value indicates above chance-level coherence.

Figure 3

Spread of SBC Values with Syllables for Different Scores.

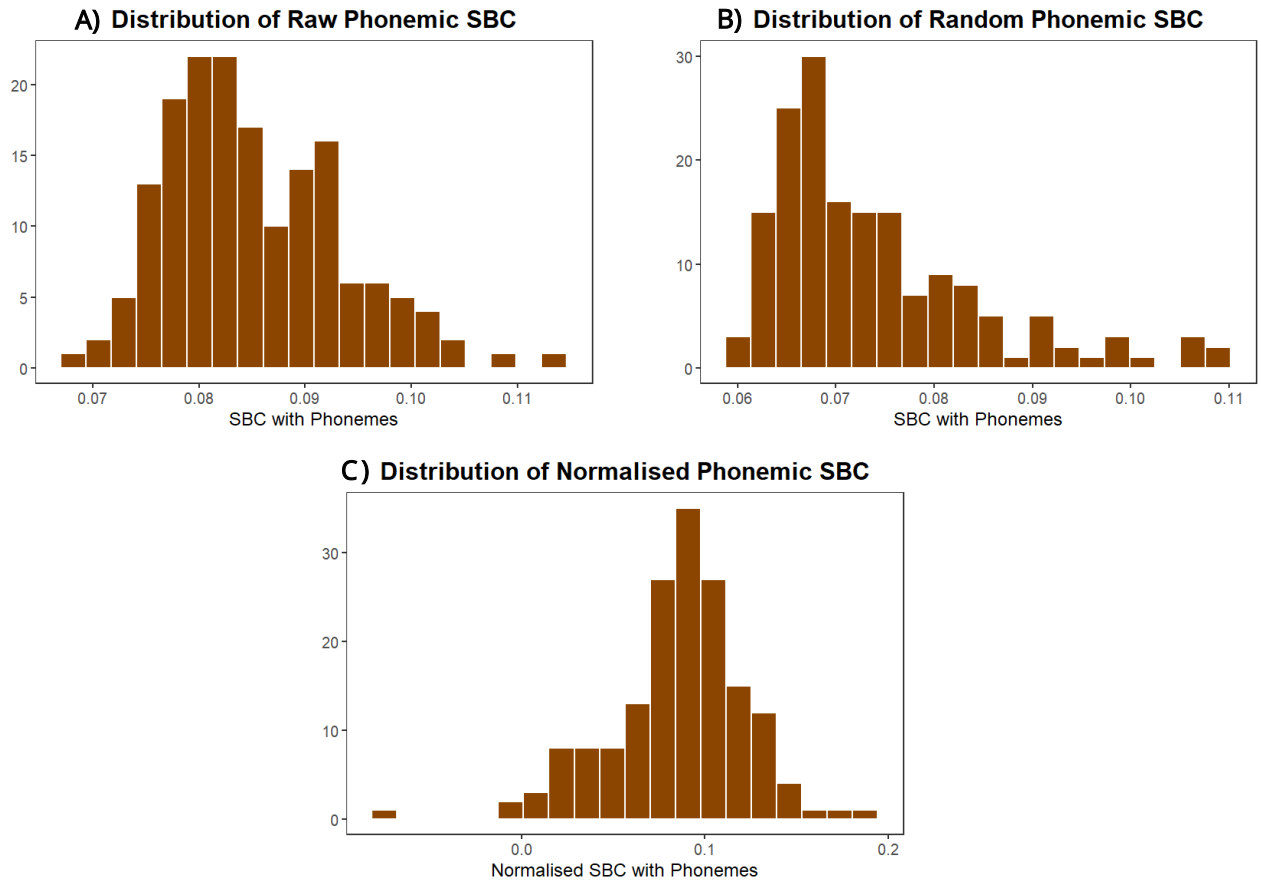


Note. Figures show the distribution of 166 data points of 10-month-olds across SBC values. In graphs A and B, the x-axis shows coherence values with a range of 0-1. Graph C shows normalised scores, with the x-axis

ranging from negative to positive values, and a score of 0 corresponding to chance-level. A positive value indicates above chance-level coherence.

Figure 4

Spread of SBC Values with Phonemes for Different Scores.



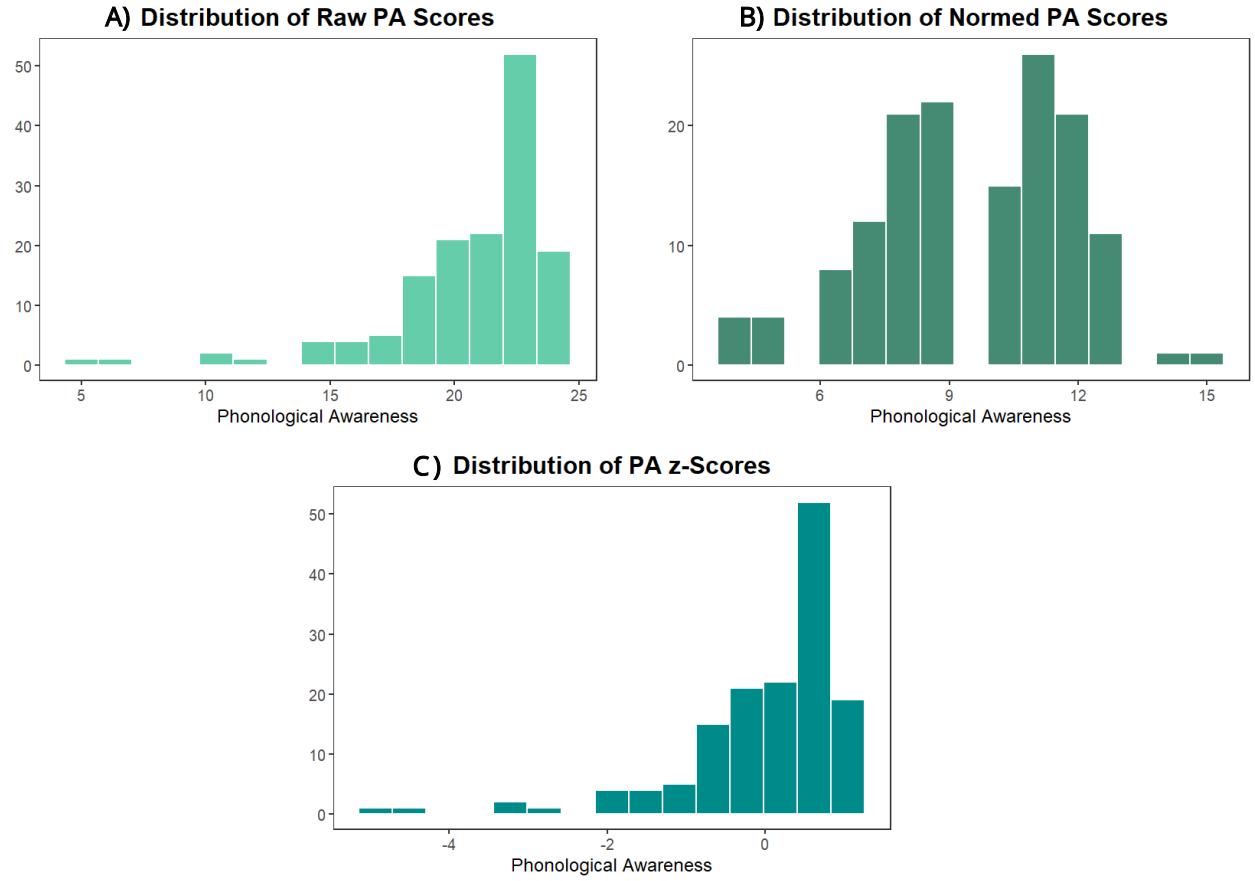
Note. Figures show the distribution of 166 data points of 10-month-olds across SBC values. In graphs A and B, the x-axis shows coherence values with a range of 0-1. Graph C shows normalised scores, with the x-axis ranging from negative to positive values, and a score of 0 corresponding to chance-level. A positive value indicates above chance-level coherence.

Concerning phonological awareness scores, the CELF Preschool-2^{NL} provided several scores to be used, namely: raw scores, age-normed scores and percentile scores. Percentile scores were not deemed useful in this experimental setup. The distributions of the raw and age-normed scores were examined. Figure 5 shows the distribution of the different types of scores. Even though the age-normed scores provided by the CELF Preschool-2^{NL} seemingly show the most evenly spread data points, an important consideration must be mentioned. As more elaborately described in Appendix A, the age-normed scores are scaled anew per age

segment of two months. This leads to a different maximum score per age segment. It especially minimises the effect for older children, as the maximum score decreases, the older a child is at the moment of testing. Therefore, it was decided to scale the raw scores to create a *z*-score that was used for statistical analysis.

Figure 5

Distribution of Phonological Awareness for Different Scores.



Note. Figures show the distribution of 145 data points of 4:0-6:11 year-olds across phonological awareness scores. (a) Distribution of raw scores, with a range of 0-24. (b) Distribution of age-normed scores, with a differing range per age segment of two months. At 4:0, the range is 1-19; at 6:11, the range is 1-11. (c) Distribution of phonological awareness *z*-scores, where 0 corresponds to $\bar{x} = 20.71$.

Exploratory Correlation Analysis

To firstly broaden the understanding of the relations between Phonological Awareness scores and other language measures, and the SBC values, Pearson correlations were calculated, with $\alpha = .05$.

As can be seen in Table 2, age-normed phonological awareness scores correlated

moderately with other language normed scores. It shows that phonological awareness is a skill that is not only conceptually, but also statistically closely related to other linguistic skills. Theoretically, phonological awareness can be viewed as a rather comprehensive ability, as semantic and vocabulary knowledge is required to for example understand sentence structure or compound words. This has now also been shown statistically. This finding also underlines the need to test for general language ability as a confounding factor.

Table 2

Pearson Correlations Between Age-Normed Scores of the CELF Preschool-2^{NL}.

	r with Phonological Awareness	*p*
Core Language Score	.313	.015*
Expressive Language Index	.315	.012*
Receptive Language Index	.253	.016*
Language Content Index	.307	.031*
Language Structure Index	.313	.016*

Note. Score names correspond to the English version of the CELF Preschool-2.
* Significant at p < .05.

Among the observed SBC values, correlations are moderate and significant (see Table 3). This fits the conceptual relationship, because to follow stress rate, one needs to distinguish syllables; and to follow syllabic rate, one needs to distinguish phonemes. As this could lead to multicollinearity, correlations between the normalised values were also checked. This resulted in one significant value, namely $r = .16$, $p = .05$, for the relation between stress and syllabic rate. These frequency bands were previously found to be related to later language skills (e.g. Menn et al., 2022a). Their intercorrelation can be explained by the fact that infants are typically good at neurally tracking low frequency bands (e.g. Attaheri et al., 2024).

Table 3

Pearson Correlations Between SBC Values.

	1	2	3	4	5	6
1. Stress	-					
2. Syllables	.38*	-				
3. Phonemes	.38*	.45*	-			
4. Normalised Stress				-		

5. Normalised Syllabic	.16*	-	
6. Normalised Phonemic	.03	.02	-

* Significant at p < .05.

Lastly, to estimate the coherence between SBC values and phonological awareness scores, semi-partial Pearson correlations were calculated, while correcting the SBC values for age at EEG testing (see Table 4). Interestingly, correlations did not differ between raw phonological awareness scores and their *z*-scores. Rather, whether SBC values were normalised did influence the strength of the correlation. However, the direction of the correlation did not change, and none of the correlations were significant. This effect was not visible for the age-normed scores. Similarly, none of those correlations were significant. Using simple correlations, phonological awareness scores and SBC values were not statistically related.

Table 4

Semi-Partial Correlations Between SBC Values and Phonological Awareness.

	PA: raw scores[a]	PA: *z*-scores[a]	PA: age-normed scores[a]
Stress rate	-.038	-.038	-.028
Syllabic rate	-.020	-.020	-.003
Phonemic rate	.079	.079	.098
Normalised Stress rate	-.105	-.105	-.043
Normalised Syllabic rate	-.101	-.101	-.147
Normalised Phonemic rate	.020	.020	-.012

Note. All abovementioned correlations were non-significant, with .06 < *p* < .97.
[a] Corrected for age at EEG measurement.

Multiple Linear Regression Models

Despite abovementioned correlations, assumptions for linear regression were met for all models that will be discussed below.

Model 1: Age as Predictors

Model 1 was a significant baseline model, showing that age of EEG recording and age at CELF testing significantly predicted phonological awareness scores ($F(2, 143) = 17.450$, *p*

< .001). The effect was small, however, with R^2 = .196 (adjusted R^2 = .185; *RSE* = .903). Nevertheless, it underlined the need to include age as covariates in the following models. A model summary can be seen in Table 5. Note that the low intercept does not indicate a negative raw score of phonological awareness, but rather a negative *z*-score, based on a mean raw score of $\bar{x}$ = 20.71 (see Table 1 and Figure 5 for specifics on the distribution of the raw scores and *z*-scores of phonological awareness).

Table 5

Phonological Awareness Predicted By Age (Model 1).

	Estimate	*SE*	*t*-value	*p*
Intercept	-5.979	1.237	-4.833	< .001 **
EEG age	.053	.019	2.768	.006 *
CELF age	.012	.002	5.887	< .001 **

**Significant at p < .05.*

***Significant at p < .001.*

Model 2: Age and General Language Ability as Predictors

Model 2 also was a significant model ($F(3, 142) = 18.630$, $p < .001$), adding to Model 1 by showing the contribution of general language ability in predicting phonological awareness. The predictive power of the model was small to moderate, and therefore slightly higher than Model 1, as R^2 = .283 (adjusted R^2 = .267; *RSE* = .856). This can be attributed to general language ability as a predictor. Its estimated contribution was small at ß = .025, but significant ($p < .001$). Therefore, general language ability should also be included in the final model as a covariate. See Table 6 below for a model summary.

Table 6

Phonological Awareness Predicted By Age and General Language Ability (Model 2).

	Estimate	*SE*	*t*-value	*p*
Intercept	-8.813	1.359	-6.487	< .001 **
EEG age	.048	.018	2.654	.008 *
CELF age	.013	.002	6.787	< .001 **
General language ability	.025	.006	4.133	< .001 **

**Significant at p < .05.*

***Significant at p < .001.*

Model 3: SBC Values as Predictors With Covariates

Lastly, Model 3 was a also significant model ($F(6, 139) = 9.670$, $p < .001$); see Table 7 for a model summary. However, its predictive power was still small to moderate, with $R^2 = .295$ (adjusted $R^2 = .264$, $RSE = .858$). Also, none of the normalised SBC values significantly predicted phonological awareness at a later age, even though the estimated ß-coefficient is relatively large in comparison to the covariates' ß-coefficients. However, in Figure 2 it becomes clear that the linear effect is fairly weak. Since the SBC values were not multicollinear, and the standard errors of the values in Model 3 were quite large, it can be assumed that there is no (significant) relation between SBC and consequent phonological awareness. Note that both SBC values and phonological awareness scores were standardised, meaning that the value of the intercept is modified by both scores ranging from negative to positive values (see Table 1 for specifics). However, the direction of the relations between the predictors and the outcome can be interpreted as usual.

Table 7

Phonological Awareness Predicted By Normalised SBC Values and Covariates (Model 3).

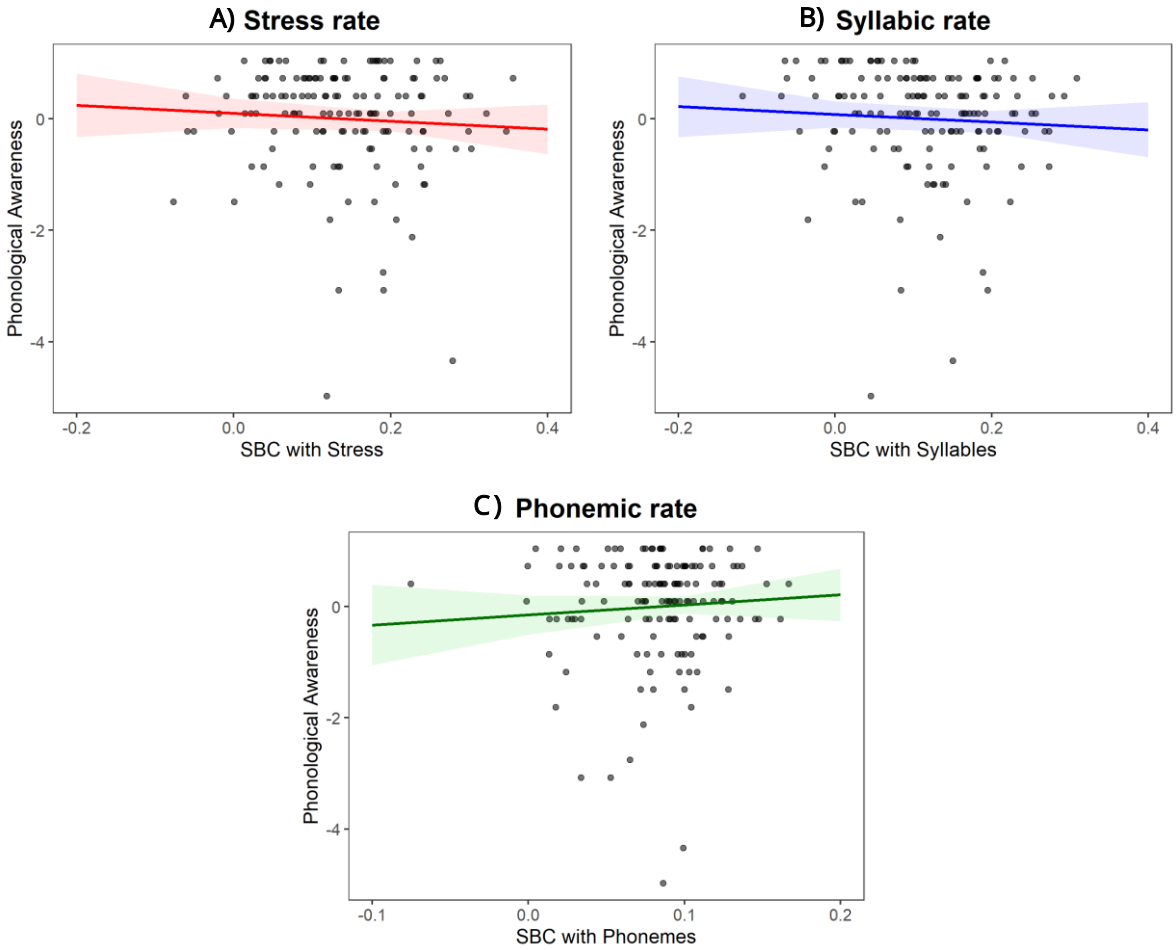
	Estimate	*SE*	*t*-value	*p*
Intercept	-8.746	1.383	-6.326	< .001 **
SBC Stress	-.719	.821	-.875	.383
SBC Syllabic	-.692	.842	-.822	.413
SBC Phonemic	1.815	1.959	.927	.356
EEG age	.048	.018	2.612	.009 *
CELF age	.013	.002	6.667	< .001 **
General language ability	.025	.006	4.127	< .001 **

** Significant at p < .05.*

*** Significant at p < .001.*

Figure 6

Unique Contributions of SBC Values in Model 3.



Note. Figures show the predictor's unique contribution to the outcome variable, when holding all other predictors constant. SBC scores (x-axis) represent normalised SBC values and phonological awareness scores (y-axis) represent *z*-scores. None of the shown relations are significant, with $p > .36$ for all values. (a) Unique contribution of stress rate (1-3 Hz) was estimated at ß = -.719. (b) Unique contribution of syllabic rate (3-5 Hz) was estimated at ß = -.692. (c) Unique contribution of phonemic rate (5-15 Hz) was estimated at ß = 1.815.

Discussion

In summary, this study shows that, in a sample of 145 typically developing children, phonological awareness at preschool age (4:0-6:11 years old) is moderately positively predicted by age and general language ability, but not by speech-brain coherence at 10 months old. SBC was tested by having an infant watch a video of three minutes, in which five well-known nursery rhymes were sung. Phonological awareness was tested through a supplementary evaluation of the CELF Preschool-2^{NL}, consisting of 24 items. Exploratory correlation analysis showed significant correlations between several language indexes within the CELF Preschool-2^{NL}, indicating that phonological awareness is a comprehensive score, calling upon other already obtained linguistic abilities. However, no significant Pearson correlations were found between phonological awareness scores and SBC values, with or without standardisation of both scores. As results from the linear regression were likewise, the tentative hypothesis of a positive relation is rejected. Nonetheless, the non-existence of this relationship in the current data is not generalisable, as several factors about the methodological approach could have negatively influenced the results. Especially for speech-brain coherence research, considering the methodological approach when interpreting findings is vital, as it is not sure whether this coherence shows top-down processes or rather bottom-up processes (Kolozsvári et al., 2021).

The first factor of influence is time. The stimuli that were used to measure the speech-brain coherence lasted a total of three minutes. Even though they consisted of nursery rhymes – which are highly rhythmic and contain IDS, facilitating neural tracking (Menn et al., 2022a; Attaheri et al., 2022) –, it might have been too little time to show neural tracking of language that does significantly relate to language development. Furthermore, the time between the two points of testing was relatively large. EEG measurements were taken around 10 months of age, with the youngest being 9 months of age, while the CELF measurements were largely around 5:6 years, with the oldest being 6:11 years. As a child develops drastically in that time period (Hurford, 1991), it may have simply been too large of an interval; therefore concealing a more subtle effect that might be present when examined at a smaller interval.

Relating to time, another factor of influence could have been that children were assessed to be typically developing at moments of testing. However, children could have had developmental disorders such as dyslexia, which can only be tested once these children can read – typically from 7 years on. In this sample, children were too young to have had formal reading education, as they were all of pre-school age. Therefore, children were included that

could have proven to have dyslexia at a later age. This particularly clouds the relation between speech-brain coherence and phonological awareness, because it has been shown that phonological awareness skills are particularly low in children with dyslexia (International Reading Association, 1998; Rayner et al., 2001).

Thirdly, using the CELF Preschool-2 as an instrument to measure phonological awareness could have been a flawed choice; see Appendix A for a more thorough dissection of this issue. While it is a validated and reliable instrument to examine a child's language ability, it is mostly used to gain an understanding of an individual child's language deficits. Some difficulties arise when administering this test to a large group. Firstly, the Phonological Awareness subtest is a supplementary evaluation, commonly assessed when reading and writing abilities do not develop as expected in a child (Wiig et al., 2012). It is a relatively short evaluation of 24 items, especially since the three specific skills are each only assessed by eight items. It can be argued, therefore, that this subtest is an incomplete way to identify a child's phonological awareness. Additionally, the concept of phonological awareness includes sentence comprehension, understanding word structure, being able to follow instructions, and to express this understanding in the required manner. Therefore, it relates to various other skills that are tested in the language profile that the CELF Preschool-2 provides. One could argue that it therefore resembles a comprehensive score of skills required to manipulate language in the appropriate way. Since this measure of phonological awareness entails so many aspects and is not significantly related to speech-brain coherence, it could be hypothesised that neural tracking relates to the individual skills, but not to the overarching skill.

Lastly, the EEG data of the 10-months-olds was cleaned by an automated EEG preprocessing pipeline (Chaudhry et al., 2025) that has not been validated in further studies. While it was based on reliable algorithms, such as the iMARA algorithm (Marriott Haresign et al., 2021) and the baseline pipeline of Van der Velde and colleagues (2019), it runs the risk of having over-cleaned the data by combining these steps. Infant EEG data is especially noisy, and can therefore easily be cleaned too conservatively, therefore removing actual effects from the data (Noreika et al., 2020). Even though the steps in this pipeline are theoretically substantiated, it might have influenced the current results negatively.

Theoretical Interpretation

Despite limitations in its methodological approach, these findings, if assumed to be true, have two theoretical implications.

Firstly, it might show that the neurophysiological mechanisms related to phonological awareness develop after the first year of life. One could argue that in order to understand and manipulate language units of any size (be that syllables, words or sentences), i.e. in order to have phonological awareness, one needs to be able to discriminate phonemes. However, the general consensus in linguistic development research is that children learn a language from larger linguistic chunks to the smallest possible units (Galle & McMurray, 2014). The non-significant results could therefore be explained by the lack of neurophysiological ability to discriminate phonemes. While phonemic neural tracking was the only frequency band out of the three speech-brain coherence measures to have a positive contribution in Model 3, it was still a non-significant effect, suggesting that phonemic tracking at 10 months old does not significantly predict phonological awareness. This could be explained by previous literature, showing that phonetic encoding is relatively weak in infancy, and only arises significantly in later childhood (Di Liberto et al., 2023; Feldman et al., 2021). This would then indicate that while the current results were negative, a relation between neural tracking and phonological awareness might still exist under different circumstances.

Another question that can be posed is whether these results show that neural tracking is based on acoustic cues or rather top-down, knowledge driven tracking. Thus far, speech-brain coherence research has only shown a significant relation between neural tracking of language at 10 months old and later language ability for the stress rate, which corresponds to 1-3 Hz (Menn et al., 2022b). Syllabic rate (approximately 3-5 Hz) has also been shown to be significantly tracked by infants at 10 months old, but has not yet been linked to later language development (Çetinçelik et al., 2024). Findings on phonemic and its related phonetic encoding are most ambiguous. A study Di Liberto and colleagues (2023) showed that 4-months-olds show the strongest acoustic, yet the weakest phonetic encoding. From 7 months on, this phonetic encoding increases into a significant effect. They discuss that phonetic encoding increases greatly during the first year of life. Nonetheless, two critical notes should be placed with these findings. Firstly, they assessed low-frequency neural tracking, ranging from 0.1-8 Hz, of which they extracted a “phonetic feature vector”. However, in the current and other studies, it is suggested that that phonemic units correspond to a frequency of approximately 20 Hz in ADS (Leong & Goswami, 2015), or approximately 15 Hz in IDS (Menn et al., 2022b). While Di Liberto and colleagues (2023) found significant neural tracking, this result could be explained by their focus on low-frequency tracking of possibly larger linguistic units. Additionally, studies that do show significant phonetic encoding in infancy, have not attempted to link it to language development. Aligning these considerations with the current

results, it rather seems that neural tracking at 10 months old is still largely acoustically driven, especially for smaller linguistic units. Since phonological awareness requires phonemic knowledge and the ability to understand and manipulate several linguistic units, it would require more thorough and especially more top-down driven neural tracking of language. Judging by the current results, this requirement does not seem to be met before the first year of life. However, as Gillis and colleagues (2022) concluded: neural tracking is inevitably an interplay between acoustic and linguistic cues, as one needs to interpret the acoustic cues to evaluate them as linguistic cues. Therefore, a definitive, binary answer to this debate might be impossible, and rather a dynamic answer should be researched.

Limitations of the Study

In brief, the inconclusive results of this study do not provide a definitive answer to the broader conceptual question due to limitations of the experimental setup. While sample size is commonly a limitation to the interpretability of the results, it is not an issue in this study. However, other factors mentioned before were of influence.

Firstly, stimuli used for EEG were of short duration and high familiarity. Not only could the infants have known the nursery rhymes before the session, but the same video was also shown three times within six minutes. This familiarity could be of negative influence when exploring a relation between neural tracking and naturalistic language input.

Secondly, this relation was examined in a sample of typically developing children. However, language disorders such as dyslexia cannot be evaluated before a child can read. It was therefore unknown how many children in this sample would later show signs of dyslexia.

Thirdly, the construct of phonological awareness was measured by one instrument, the CELF Preschool-2^{NL}, which could be argued to be flawed. It might have been more thorough to include several measures of phonological awareness, such as a translated version of the Phonological Awareness Test (PAT-2:NU; Robertson & Salter, 2018) or the Dynamic Indicators of Basic Early Literacy Skills (DIBELS; University of Oregon, 2021); or a Dutch alternative, such as the Toetspakket Beginnende Geletterdheid (Aarnoutse et al., 2023). Alternatively, any of the newly suggested instruments individually could have been a more valid evaluation of true phonological awareness than the CELF Preschool-2^{NL} measure.

Future Research

Nevertheless, these inconclusive results provide suggestions for future research into the relationship between neural tracking of language and later phonological awareness.

Firstly, it would be informative to examine this relationship at different ages. Primarily, theoretical argumentation suggests that neural tracking of phonemes needs to be significant, to relate it to a phonological skill. Therefore, research is necessary into when phonemic tracking has developed significantly. Specifically, it would be informative to test this at fixed time intervals, starting around the end of the first year of life, until a child can talk (ca. 2 years of age). EEG recordings every few months can consequently give insight into the developmental trajectory of this neurophysiological mechanism. As language input changes significantly during this time period, one could question which stimuli would be suitable in such a study; whether it should possibly differ per measurement. However, this would pose large difficulties for comparisons between the time points. As this is the most important point of analysis for the suggested study, equal stimuli would be necessary. In order to offer more varying stimuli so that familiarity does not overshadow an otherwise present effect, it would be useful to have the children watch a longer video, similar to an episode of a children's television show: where IDS is used, but significantly more input is received that can be neurally tracked. Once it is then known when phonemic tracking is significant, the relationship between neural tracking and phonological awareness can be re-examined. This can be through a similar setup as in this study, where neural tracking is measured at an age where all linguistic units are tracked significantly, and phonological awareness at early school age. Additionally, it would also be interesting to add another time point before all linguistic units are tracked significantly, as a control variable. This experimental setup could then provide a definitive conclusion on whether this supposed relation is factual or falsified.

Secondly, it would be interesting to examine this relationship in a sample of children with a risk for dyslexia, and a sample of children unlikely to have dyslexia; as dyslexia was previously related to phonological awareness deficits (Rayner et al., 2001). This could be done by examining whether at least one of the parents have been diagnosed with dyslexia, as this significantly increases the risk for dyslexia in a genetically related child (Andreola et al., 2021). If both sample sizes are similar or equal, comparison between the two groups could shed light onto differences in speech-brain coherence, differences in phonological awareness, and differences in the relation between these two concepts. These results might be more informative than studies with a typically developing sample, as it is still unsure whether neural tracking is a mechanism that is cognitively employed by all people, or simply in situations where it is difficult to understand the language (e.g. Hambrook & Tata, 2019). If children with a risk for dyslexia prove to show a significant relation between neural tracking and phonological awareness, and the typically developing group would not, these results

would argue in favour of neural tracking being a mechanism for selective attention, rather than a general mechanism for language processing. Additionally, these findings would have implications for dyslexia research and a deepened understanding of the impaired abilities in dyslexic children.

Lastly, it could be interesting to compare different mother tongues in children. Power and colleagues (2016) suggested that the relation between neural tracking and language processing might be different per language, as languages are differently structured. They mention that English is a stress-timed language, whereas Spanish is a syllable-timed language. Examining the responses to both languages for a native speaker can answer the question whether neural tracking responses are similar in all children, suggesting a universal innate mechanism, or rather dependent on the language input, suggesting a more random, possibly learnt mechanism. Specifically for the relation between neural tracking and phonological awareness, this could be informative, as phonological awareness is based on the sound structure of a language (Wiig et al., 2012, pp. 69). Comparing differently structured languages could therefore provide more insight into the development of phonological awareness, and potentially suggest a re-examination of the definition of the concept, depending on the linguistic context.

Conclusion

Concluding, the exploration of the relation between neural tracking at 10 months old and phonological awareness at pre-school age (4:0-6:11 years) was inconclusive. Age and general language ability were shown to predict phonological awareness, but speech-brain coherence measures were not significant. To ensure validity of these findings, it would be informative to examine this relationship with a smaller age gap, where speech-brain coherence is evaluated somewhere after the first year of life. However, to convincingly draw conclusions on this relationship, further research is necessary.

AI statement

I hereby declare to have used OpenAI ChatGPT (version 5.0; 2025) to facilitate the search for relevant, academic sources. I have verified their reliability through other, scientific databases and checking for peer review. I have also used ChatGPT 5.0 for inspiration on the right statistical analyses. Once again, I verified the approaches with scientific sources and my supervisors, to ensure substantiated methods.

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Appendix A

Phonological Awareness and How It Is Assessed

Phonological awareness is the explicit understanding of linguistic phonology, which entails the speech structure and sound system of a language (Popp, 2004, pp. 41), and the ability to apply this knowledge in manipulating language. Practically, this entails assessing the sound structure of words, and consequently being able to manipulate said speech sounds (Wiig et al., 2012, pp. 112). Children learn to recognize and manipulate compound words, discriminate syllables and parts of a sentence, and recognise and create rhyming words. These manipulations show an understanding of word structures, syllables, and phonemes (Noiray et al., 2019a).

Phonological awareness is tightly related to the language development of a child, namely to reading and writing ability, articulation, and auditive processing related to word production and knowledge (Wiig et al., 2012, pp. 113). Phonological awareness development interacts with children's speech motor organisation and therefore develops throughout the first two years of life as children learn to make sounds, and eventually speak a language (Noiray et al., 2019a). At age 3, phonological awareness is established enough for proper coarticulation of phonemes (Noiray et al., 2018; Noiray et al., 2019b). Difficulty with phonological awareness is therefore related to early signs of language difficulties or disabilities, as a positive correlation has been found between deficient phonological awareness and reading and spelling difficulties such as dyslexia (International Reading Association, 1998; Rayner et al., 2001).

Because of this fact, it is evaluated in children with early markers of reading and language disabilities, before children start formal reading education, at ages 4:0-6:11. This evaluation shows to what extent their language is not developing as expected. This typically concerns children with a language disorder, multilingual children, children with (prior) hearing problems, and children who have not had preparatory reading activities in preschool settings. One of the ways to evaluate phonological awareness is by administering the CELF Preschool-2 (Wiig et al., 2012), which results in a language profile of the child relative to its age group. For the Dutch version (CELF Preschool-2^{NL}), the comparing norming sample has been acquired by administering the CELF Preschool-2^{NL} to 1100 children between ages 3:0-6:11 in all areas within a linguistic region; i.e. the Netherlands and Flanders.

One of its subtests is Phonological Awareness, which is a subtest that may only be administered from 4:0 years on, because it is a skill that develops through linguistic play,

which children encounter at the latest in kindergarten. Its score is therefore normed to a subsample of 4:0-6:11 years, with separate norm scores for each age segment per two months. The subtest is also supplementary to the general language profile composed by the CELF Preschool-2, as it is a skill that is linked to reading prerequisites typically attained in early primary school. It would therefore not be a comprehensive language profile if it were included, as it is not a realistic standard for children below age 4:0.

The subtest Phonological Awareness consists of 6 tasks, each comprising 4 items. In subsequent order, it tests understanding of (1) sentence structure, (2) compound words, (3) syllable structures, and (4) rhyme.

Task A examines the understanding of compound words. An audio file is played where two words are spoken separately, with a few seconds of silence between, and it is up to the child to form a compound word with them. In the items, the words are already spoken in the correct order: the child needs to understand that these words can be used together to form a new word with a different meaning.

Task B requires the child to form meaningful words with the separate syllables they hear. These are once again heard from a pre-recorded audio file, provided by the CELF Preschool-2. This varies from two items with two-syllable-words, to two items with three-syllable-words.

In Task C, the examiner naturally reads aloud a sentence, that the child has to repeat. Additionally, it is asked to clap their hands for every word that they speak. This is repeated four times.

Task D is similar, where the child has to clap their hands for every syllable in the word that they repeat. This varies between two items with two-syllable-words, and 2 items with three-syllable-words.

Lastly, Task E and F measure rhyming skills. Task E poses four items of two words, of which the child has to determine whether they rhyme or not. Task F requests the child to think of a word that rhymes with the word the examiner tells them. This may also be a non-existing word, as long as it phonologically matches the previous word.

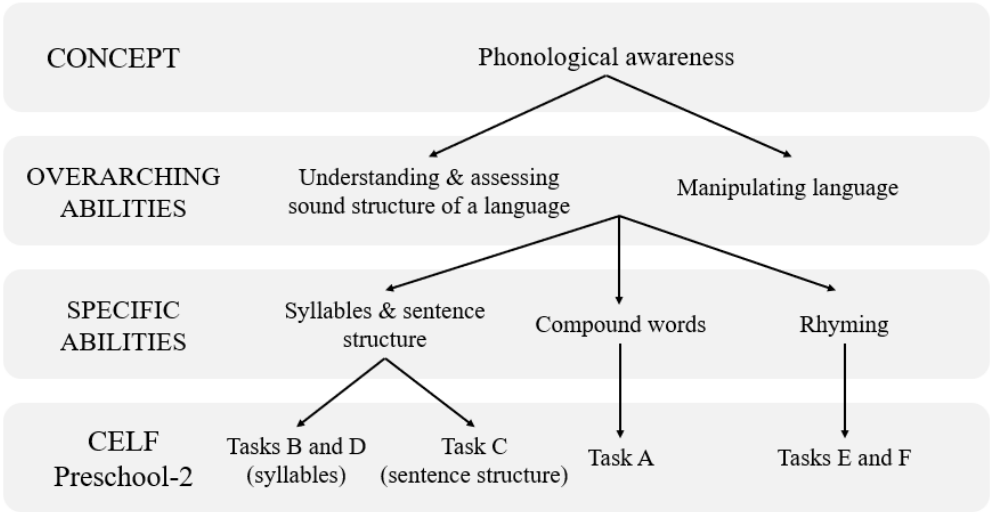
The score for this subtest is afterwards calculated as a raw score, an age-normed score, and a percentile score. The raw score has a minimum of 0 and a maximum of 24. This raw score should then be looked up in the table corresponding to the child's age in years and months. The normed scores get stricter the older a child is, meaning that at 4:0 the highest norm score corresponds to 17, whereas at 6:11, the highest norm score corresponds to 12. In the same tables, a percentile score is matched with the raw and normed score. In all age

groups, percentile scores range from 0,1 to 99,9.

In my view, these tasks form a comprehensive test of phonological awareness (see below, Figure 1). Phonological awareness can be seen as consisting of two overarching abilities, subdivided into three more specific abilities. As overarching abilities, it contains (1) the understanding and assessing of the sound structure of the heard language, and (2) the ability to manipulate language based on this understanding. The understanding is tested in tasks C, D and E, where the child passively hears words or sentences, and has to return the structure of the language (i.e. word segmentation, determining syllables in a word, and noticing familiarity in sounds of rhyme). The ability to manipulate the language is tested in tasks A, B and F. The child receives loose words or sounds as input, and has to create something new and/or meaningful (i.e. creating compound words, creating a word from syllables, and coming up with rhyme words). These tasks also encompass all three specific abilities, being: recognising and manipulating compound words (task A), discriminating and using syllables and parts of a sentence (respectively tasks B and D, and C), and recognising and creating rhyme words (tasks E and F). It can therefore be seen as an adequate measure of phonological awareness, as a supplementary evaluation.

Figure 7

Conceptual Subdivision of Phonological Awareness.



I do agree that the Phonological Awareness subtest is not part of the general language profile the CELF Preschool-2 can provide, because there are some critical notes to be mentioned. Firstly, one could argue that each specific ability is tested very briefly, as each task contains only four items. Additionally, in my observation, the items within tasks do not seem to differ much in difficulty, preventing the examiner from determining the exact level of

proficiency in a certain ability. This similarity in level of tasks forms another issue for the age group this subtest can be administered in. It is designed for 4:0-6:11 year old children, which is still a span of almost three years difference. The age-normed scores mostly solve this issue, but it can be noted that for children nearing the maximum age by months, a difference in ability might be harder to spot, as most children will score near the ceiling because of the relative simplicity of the tasks. Also, comparison between ages is complicated, due to different scaling of the norm scores. Lastly, one could argue that presenting the compound words and the syllables to be matched in chronological order is not a true test of understanding these units – as the order in which they are heard, even if the break between them is unusually long, can be too familiar and therefore rely on knowledge, rather than understanding and application of prior knowledge.

Concluding, it seems wise to only consider the measure of phonological awareness as one composite score to assess the overarching abilities; to pay attention to the age normed scores of this measure; and to keep in mind that it is an indication of phonological awareness levels, not a direct or extensive measure of it.

Appendix B

Additional Exploratory Regression Models

Additional Methods

To further explore the relation between speech-brain coherence and phonological awareness, two additional regression models were tested. They could be described as follows:

$$\text{Model 4: } PA_z = SBC_{stress} + SBC_{syllabic} + SBC_{phonemic} + C_{EEGage} + C_{CELFage}$$

$$\text{Model 5: } PA_z = SBC_{stress} * C_{EEGage} + SBC_{syllabic} * C_{EEGage} + SBC_{phonemic} * C_{EEGage} + C_{CELFage} + C_{general\ language\ ability}$$

In Model 4, Model 3 is refitted without the Core Language Score (i.e. general language ability) as a covariate. This decision was made because (1) the Core Language Score is as significant predictor of phonological awareness scores; (2) the Core Language Score and Phonological Awareness score correlate moderately and significantly (see Table 2); and (3) the Phonological Awareness subtest indirectly tests skills that comprise the Core Language Score, meaning the addition of this score as a predictor could overshadow the actual predictive effect of SBC values on phonological awareness scores.

Model 5 is another variant on Model 3, but examining a different significant covariant, namely age at EEG testing. Conceptually, it is illogical that the age at which the EEG was taken, predicts later phonological awareness scores. Therefore, EEG age was added as an interaction effect for each SBC value, to limit its predictive power to solely controlling the SBC values for age.

Additional Results

Neither models showed a significant contribution of SBC values to phonological awareness scores, as can be seen in Tables 8 and 9 below. Both models were once again significant (Model 4: $F(5, 140) = 7.354$, $p < .001$; Model 5: $F(9, 136) = 6.343$, $p < .001$), which could be credited to the covariates' significant contribution to the model. Also, both models had a similarly moderate effect: for Model 4, $R^2 = .208$, adjusted $R^2 = .180$, and $RSE = .906$; and for Model 5, $R^2 = .296$, adjusted $R^2 = .249$, and $RSE = .867$. Since the effects did not differ much in strength, but the amount of predictors and type of predictors did change, it underlined the lack of predictive power from the SBC values.

Table 8

Phonological Awareness Predicted By Normalised SBC Values, Without General Language Ability (Model 4).

	Estimate	*SE*	*t*-value	*p*
Intercept	-5.826	1.254	-4.646	< .001 **
SBC Stress	-.738	.867	-.851	.396
SBC Syllabic	-.863	.887	-.972	.413
SBC Phonemic	1.057	2.059	.513	.608
EEG age	.053	.019	2.762	.007 *
CELF age	.012	.019	5.752	< .001 **

**Significant at p < .05.*
***Significant at p < .001.*

Table 9

Phonological Awareness Predicted By Normalised SBC Values and Interactions (Model 5).

	Estimate	*SE*	*t*-value	*p*
Intercept	-8.746	1.383	-6.326	< .001 **
SBC Stress	-.719	.821	-.875	.383
SBC Syllabic	-.692	.842	-.822	.413
SBC Phonemic	1.815	1.959	.927	.356
CELF age	.013	.002	6.667	< .001 **
General language ability	.025	.006	4.127	< .001 **
Interactions				
Stress * EEG age	-.026	.221	-.118	.906
Syllabic * EEG age	.019	.245	.076	.939
Phonemic * EEG age	-.209	.494	-.423	.673

**Significant at p < .05.*
***Significant at p < .001.*