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Short communication

Stable auditory processing underlies phonological awareness in typically developing preschoolers

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ABSTRACT

Sound processing is an important scaffold for early language acquisition. Here we investigate its relationship to three components of phonological processing in young children (~age 3): Phonological Awareness (PA), Phonological Memory (PM), and Rapid Automatized Naming (RAN). While PA is believed to hinge upon consistency of sound processing to distinguish and manipulate word features, PM relies on an internal store of the sounds of language and RAN relies on fluid production of those sounds. Given the previously demonstrated link between PA and the auditory system, we hypothesized that only this component would be associated with auditory neural stability. Moreover, we expected relationships to manifest at early ages because additional factors may temper the association in older children. We measured across-trial stability of the frequency-following response, PA, PM, and RAN longitudinally in twenty-seven children. Auditory neural stability at age ~3 years exclusively predicts PA, but this relationship vanishes in older children.

1. Introduction

Language acquisition is a process beginning very early in human life. Several studies have shown that the first steps of this process begin in the womb, where the fetus is already able to hear, recognize and distinguish between sounds (Kisilevsky et al., 2009; Minai, Gustafson, Fiorentino, Jongman, & Sereno, 2017; Moon, Lagercrantz, & Kuhl, 2013). Over time, exposure to the sounds of language allows infants to associate them to a meaning (Saffran & Estes, 2006; Werker & Yeung, 2005; Werker, Yeung, & Yoshida, 2012). Soon after, children learn how to match these sounds and their meanings to their corresponding visual symbols, thus starting the path to reading (Ziegler & Goswami, 2005). The process underlying the sound-to-meaning-to-letters-mapping entails three main skills: the awareness and the ability to manipulate the different sounds of a language, known as *Phonological Awareness* (PA), (Kirby, Parrila, & Pfeiffer, 2003; Scarborough & Brady, 2002), the ability to store the sounds in working or short-term memory, known as *Phonological Memory* (PM), (Scarborough & Brady, 2002; Wagner, Torgesen, & Rashotte, 1999), and the ability to quickly retrieve and produce the sounds associated with a visually presented stimulus, known as *Rapid Automatized Naming* (RAN), (Norton & Wolf, 2012; Scarborough & Brady, 2002). Together, these three skills are collectively known as *Phonological Processing* skills (PP), and are believed to be a key building block for reading.

Given that sound is such an important scaffold for early language development, a child's ability to process sound plays an important role in how well he/she makes the sound-to-meaning association necessary for learning how to read. Consequently, if a child has trouble distinguishing between the sounds of a language, he/she may struggle to develop the awareness of them, to encode them into memory, and to produce them. Previous studies specifically investigated the link between sound processing and phonological processing using the frequency-following response (FFR). FFR is an auditory evoked potential thought to predominantly reflect activity in the auditory midbrain that offers a window into the integrity of sound processing in the brain, revealing how precisely the acoustic features of a sound are encoded (Kraus, Anderson, & White-Schwoch, 2017; White-Schwoch, Nicol, Warrier, Abrams, & Kraus, 2016). Among the many possible measures

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obtainable from the FFR, auditory neural stability, an index of how accurately the nervous system encodes a stimulus over time, is hypothesized to act very early in language and reading development, by impacting the sound-to-meaning associations and, subsequently, the orthographic mapping of language sounds, when reading acquisition begins (Hornickel & Kraus, 2013).

Few studies tested hypotheses on reading subskills that may be associated with the stability of the FFR. A first study on children with reading disabilities found that auditory training that specifically provides a clearer and more stable auditory signal boosts both phonological awareness and auditory neural stability (Hornickel, Zecker, Bradlow, & Kraus, 2012). A second study on typically-developing (TD) school-aged children and children with learning disabilities showed that poor readers (assessed by single-word reading fluency) have a less stable neural response to speech sounds than good readers, independent of resting neurophysiological noise levels (Hornickel & Kraus, 2013). These findings support the idea that auditory stability is important for all PP components. However, the focus of these studies was to understand what underlies reading difficulties in reading-aged children. There is a gap in our understanding of how the auditory system may support acquisition of reading subskills at an early age in typically-developing children.

This study aims to understand how auditory stability might support PA, PM, and RAN when they are just beginning to develop. In particular, we investigate whether auditory neural stability at three years of age is a potential factor underlying the development of all three PP components (prevailing hypothesis) or is important for specific PP components (alternate hypothesis). Under the prevailing hypothesis, PA, PM, and RAN would all show a relationship with auditory neural stability. If the alternate hypothesis is true, we expect that PA would show a stronger reliance on auditory processing compared to RAN and PM. That is because only PA hinges upon the consistency of the auditory system to identify and manipulate speech sounds that allow sound-symbol associations. Moreover, under both hypotheses, we expect all these relationships to be stronger at earlier stages of development, given that, as children get older, additional variables may intervene to temper the association. This would be consistent with two pieces of evidence. On the one hand, auditory neural stability has been shown to be experience-dependent (Krizman, Skoe, Marian, & Kraus, 2014; Skoe, Krizman, Anderson, & Kraus, 2015). On the other hand, PA, PM, and RAN have been shown to diverge from each other as development progresses and children get more experience with a language (Wagner & Torgesen, 1987; Wagner et al., 1999; Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993).

To test these hypotheses, we used a longitudinal approach, measuring across-trail stability from the FFR, and standardized measures of PA, PM, and RAN in children from age 3 to 8 for four consecutive years.

2. Materials and methods

2.1. Participants

Thirty-three children between 3.0 and 4.99 years (mean age = 4.20, SD = 0.53, 17 females) were recruited in the Chicago area and were tested annually for four years (we will refer to the data for each year as Year 1, Year 2, Year 3 and Year 4). Six of the thirty-three participants were excluded: three children (1 female) did not complete neurophysiological testing and three other children (2 female) were removed as outliers (± 2SD) in one of the years. Twenty-seven children (14 female) were considered for the current analyses (Table 1). These children were part of a larger study. They were selected based on their availability of data across 3–4 consecutive years, requirement to test the specific hypothesis of the current study. None of the children had a history of a neurologic condition, a diagnosis of autism spectrum disorder, a risk for learning disabilities, or second language exposure as determined by parental report obtained via questionnaire. Children needed to pass a screening of peripheral auditory function, including normal otoscopy and tympanograms, distortion product otoacoustic emissions at least 6 dB SPL above the noise floor from 1 to 8 kHz, and click-evoked wave V latencies within normal limits (< 6.0 ms) (Skoe et al., 2015). Parents or legal guardians provided informed consent and assent was obtained from the children. This study was approved by Northwestern University's Institutional Review Board. Children were monetarily compensated for their participation.

Each year, testing occurred over ~2.5 h. Longitudinal testing was spaced at approximately one-year intervals (interval duration in year: [Visit 1 – Visit 2] Mean = 1.05, SD = 0.15; [Visit 2 – Visit 3] Mean = 1.05, SD = 0.13; [Visit 3 – Visit 4] Mean = 1.01, SD = 0.05).

2.2. Behavioral assessments

All behavioral assessments were conducted in a quiet, private room and children were allowed to take breaks. Children were comfortable with the testers and were given opportunities to interact with and get to know testers prior to data collection. Raw scores were used for all tests, as age was used as a factor in the regression models (see *Statistics*) and standard scores account for developmental trends. However, behavioral assessments were only administered if they were appropriately normed for the age of the children.

2.2.1. Nonverbal IQ

Nonverbal IQ was assessed using the Matrix Reasoning subtest from the Wechsler Preschool and Primary Scale of Intelligence, 3rd edition (WPPSI-III; Wechsler, 1967, 2003) in Years 1, 2 and 3 and the Wechsler Intelligence Scale for Children, 5th edition (WISC-V; Wechsler, 2014) in Year 4. This change was so that the test items were appropriate for the age of the children in Year 4. In this task, children are shown a pattern or image with a piece missing and asked to choose the correct missing piece from four to five possible options.

2.2.2. Phonological awareness

Phonological awareness (PA) was assessed using the Elision and Blending Words subtests of the Comprehensive Test of Phonological Processing, 2nd edition (CTOPP-2; Wagner et al., 1999) in Years 2, 3, and 4. The Elision subtest required children to create a new, real word by removing a phoneme or syllable from an existing word, while the Blending Words subtest required children to combine syllables or phonemes to make a real word. The arithmetic average of the scores on these subtests was used to calculate PA performance.

2.2.3. Rapid automatized naming

Rapid automatized naming was assessed using the Rapid Digit Naming and Rapid Letter Naming subtests of the Comprehensive Test of Phonological Processing, 2nd edition (CTOPP-2; Wagner et al., 1999, 2013) in Years 2, 3, and 4. The composite of these two scores is termed rapid symbolic naming in the CTOPP manual. The child named four rows of nine numbers (Rapid Digit Naming) or letters (Rapid Letter Naming) out loud as fast as he/she could. The arithmetic average of the time (in seconds) on each subtest was used to calculate RAN performance. Three children could not complete the task in Year 2 due to insufficient knowledge of letters or numbers. These children are excluded from all analyses which use RAN as a variable, but are included for PA analyses.

2.2.4. Phonological memory

Phonological memory was assessed using the Memory for Digits and Nonword repetition subtests of the Comprehensive Test of Phonological Processing, 2nd edition (CTOPP-2; Wagner et al., 1999, 2013) in Years 2, 3, and 4. The Memory for Digits subtest required the children to repeat a series of numbers in the same order in which they heard, while the Nonword Repetition required the children to repeat some made-up word exactly as he or she heard it. The arithmetic average of the scores

Table 1
Children age (M ± SD) and test battery for each year of testing.

	Year 1	Year 2	Year 3	Year 4
Age (M ± SD)	4.17 ± 0.53	5.22 ± 0.57	6.28 ± 0.58	7.29 ± 0.58
click ABR	✓			
Speech FFR (ba - da - ga)	✓	✓	✓	✓
NV IQ Matrix Reasoning	✓	✓	✓	✓
CTOPP Rapid Symbolic Naming		✓	✓	✓
CTOPP Phonological Awareness		✓	✓	✓
CTOPP Phonological Memory		✓	✓	✓

on these subtest was used to calculate PM performance.

2.2.5. Neural stability assessment

All electrophysiological recordings were conducted in an electrically shielded, sound-attenuated booth (IAC Acoustics, Bronx, NY) while children watched a film of their choice. Stimuli were presented monaurally to the right ear using an insert earphone (ER-3A, Etymotic Research, Elk Grove Village, IL), while the left ear was left unoccluded so children could hear the film soundtrack at a level insufficient to mask the stimuli (< 40 dB SPL).

All recording sessions began and ended with a standard click ABR (100 μS rarefacting square wave, rate of 31.3/s, 80 dB SPL) consisting of 2000 sweeps to ensure proper functioning of equipment, normal auditory brainstem response latency, and that ear insert depth did not change over the course of the recording.

2.2.6. Stimuli

Frequency-following responses (FFRs) were recorded to three voiced 170 ms six-formant stop consonant-vowel stimuli ([ba], [da], and [ga]). All stimuli were synthesized at 20 kHz using a Klatt-based formant synthesizer (Klatt, 1980) with voicing beginning at 5 ms followed by a 50 ms consonant-vowel transition and a 120 ms steady-state vowel. Further acoustical specifications of the three syllables can be found in White-Schwoch and Kraus (2013) and White-Schwoch et al. (2015). All stimulus presentation was controlled using E-Prime version 2.0 (Psychology Software Tools, Inc., Sharpsburg, PA). Stimuli were presented in alternating polarities at 80 dB SPL with an 81 ms interstimulus interval.

2.2.7. Recordings

FFRs were recorded using a BioSemi Active2 system (BioSemi, Amsterdam, The Netherlands) with ActiABR module via LabView 2.0 (National Instruments, Austin, TX). An active non-inverting electrode was placed at Cz, inverting references were placed on the right and left earlobes, and Common Mode Sense (CMS) and Driven Right Leg (DRL) and were placed at Fp1 and Fp2, respectively. Responses were digitized at 16.384 kHz with an online bandpass filter of 100–3000 Hz (20 dB/decade roll-off). Offset voltage was kept under ± 50 mV. FFRs collected via the ipsilateral vertical recording montage (Cz to right earlobe) were processed offline. This included amplification in the frequency domain for 20 dB per decade for 3 decades below 100 Hz in MATLAB (The Mathworks, Inc., Natick, MA, USA) using custom software in order to counter the online bandpass filter for these lower frequencies. Responses then underwent offline bandpass filtering from 70 to 2000 Hz, using a Butterworth filter with a 12 dB/octave rolloff and a zero-phase shift. The responses were epoched relative to stimulus onset (0 ms) from −40 to 210 ms, and baseline corrected. Any responses greater than ± 35 μV were rejected. Final responses consisted of 2000 artifact-free sweeps of each polarity. Responses to the two polarities were averaged, giving 4000 total sweeps per stimulus.

2.2.8. Analysis

The response stability measure was calculated from 20 to 60 ms, which corresponds to the consonant-vowel transition of each stimulus (Hornickel & Kraus, 2013; Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009). It was calculated for each participant by randomly selecting 2000 sweeps of the response, and creating the subaverage of the response using those sweeps. The remaining 2000 sweeps formed another subaverage. These two subaverages were then correlated with a Pearson's correlation. This process was repeated 300 times with a new random sample of sweeps every time, and the average of these 100 correlations was used as the measure of response stability (see Fig. 1a and b for examples of highly stable and unstable responses). This procedure was performed separately on the responses to the three stimuli, r-values were converted using a Fisher transform, and the three resulting Z-scores were averaged to produce the neural stability score for statistical analyses. Seven children displayed noisy data (outliers for either neural stability, pre-stimulus RMS, or SNR across the response) across years: 2 children in Year 2, 5 in Year 3 (2 of them were the same from Year 2), and 5 in Year 4 (3 of them were the same from previous years). In all cases, the neural stability composite measure was computed considering only the non-noisy data for that individual.

3. Statistical analysis

Descriptive statistics (Mean and Standard Deviations) for all the behavioral tests administered are reported in Table 2.

A Repeated Measures ANOVA was performed to test for any change in auditory neural stability, PA, PM and RAN across the years of testing.

Hierarchical three-step linear regressions were employed to separately predict phonological awareness, rapid automatized naming, and phonological memory in Years 2, 3, and 4. The first step of each regression considered age of testing and raw scores of nonverbal IQ as predictors. The second step added response stability from Year 1. The third step added response stability from consecutive years up until the same year of the dependent variable considered. As an example, we ran a regression to predict PA in Year 2. We used Year 2 age and IQ as the first step, Year 1 Neural stability as the second step, and added Year 2 Neural stability in the third step. This process was repeated for Years 3 and 4 for PA, RAN and PM. We were focused on the added predictive contribution of the second step, which indicated the role of neural stability and on any significant R^2 changes from step 2 and step 3 to explore the specificity of the earliest measure of neural stability Statistics were computed using SPSS (SPSS, Inc., Chicago, IL). Pearson correlations were performed to investigate the relationship among auditory neural stability, PA, PM and RAN within and across each year of testing. Bivariate Pearson correlations between neural stability and phonological skills across each year of testing were also performed.

4. Results

4.1. Auditory neural stability and phonological processing skills mature overtime

To test for changes in neural stability across the four years of this study, we employed an RMANOVA considering the mean of ages across the four consecutive years as a covariate, to account for slightly test-retest delays. The results show a main effect of Year of testing

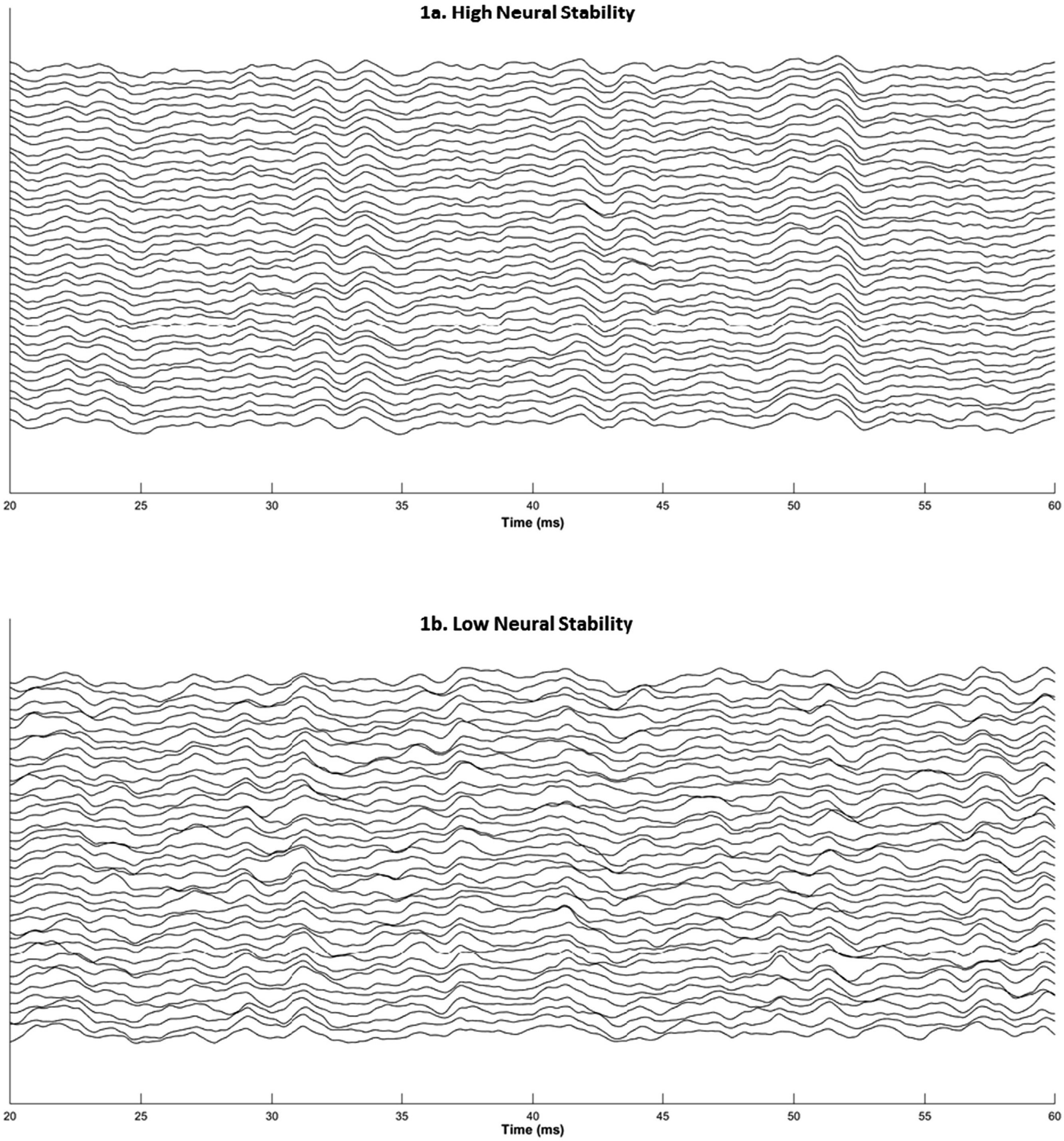

Fig. 1. (a and b) Examples of an FFR with high and low neural stability, respectively. The transition time period (20–60 ms) of the FFR in response to a /da/ is displayed for two example subjects. In each panel, forty samples of 2000-sweep subaverages are overlaid, giving a visual indicator of what it means to have high or low neural stability of the FFR.

(Difference Mean Year 4-Mean Year 1 is 0.017; $F = 3.265$, $p = 0.026$, $\eta^2 = 0.116$) with neural stability increasing over time. To explore changes in the phonological processing skills we performed 3 separate RMANOVAs. The results show a main effect of Year of testing across all 3 phonological processing skills, as for PA (Difference Mean Year 4-Mean Year 2 = 10.87; $F = 89.314$, $p < 0.001$, $\eta^2 = 0.775$), as for PM (Difference Mean Year 4-Mean Year 2 = 2.685; $F = 16.661$, $p < 0.001$, $\eta^2 = 0.391$), as for RAN (Difference Mean Year 4- Mean Year 2 = 18.95; $F = 44.580$, $p < 0.001$, $\eta^2 = 0.660$), with all three improving as the children got older. See Fig. 2 for developmental trajectory of auditory neural stability and phonological processing skills across the 4 years of testing.

4.2. Phonological awareness

PA was predicted by age and nonverbal IQ in the first step of the regression in Year 2 ($R^2 = 0.419$, $F_{(2,24)} = 8.647$, $p = 0.001$) and Year 3 ($R^2 = 0.434$, $F_{(2,23)} = 8.815$, $p = 0.001$), but not Year 4 ($R^2 = 0.143$, $F_{(2,24)} = 2.005$, $p = 0.157$). Adding neural stability in the second step predicted an additional 9.9% of variance in Year 2 ($F_{(3,23)} = 8.228$,

Table 2
Descriptive statistics for all behavioral tests considered. Mean ± Standard Deviation for both raw scores and percentiles are reported.

	N	Mean ± SD raw scores	Mean ± SD percentiles
Year 1 (Age = 4.17 ± 0.53, Min = 3.08; Max = 4.92)			
WPPSI - Object assembling (3 yrs old)	11	18.636 ± 9.688	75 ± 27.583
WPPSI - Matrix Reasoning (4 yrs old)	16	13.125 ± 4.113	74.687 ± 18.635
Year 2 (Age = 5.22 ± 0.57, Min = 4.09; Max = 6.01)			
WPPSI - Matrix Reasoning	27	15.814 ± 5.677	69.170 ± 28.312
CTOPP - Phonological Awareness	27	13.37 ± 4.09	64.093 ± 16.421
CTOPP - Rapid Automatized Naming	24	42.475 ± 14.688	62.354 ± 23.028
CTOPP – Phonological Memory	27	13.259 ± 2.242	54.148 ± 19.655
Year 3 (Age = 6.28 ± 0.58, Min = 5.03; Max = 7.16)			
WPPSI - Matrix Reasoning	26	21.077 ± 6.039	77.807 ± 30.701
CTOPP - Phonological Awareness	27	19.57 ± 5.32	64.370 ± 18.38
CTOPP - Rapid Automatized Naming	24	30.083 ± 7.301	57.021 ± 14.99
CTOPP – Phonological Memory	27	14.556 ± 2.379	50.703 ± 20.580
Year 4 (Age = 7.29 ± 0.58, Min = 6.01; Max = 8.12)			
WPPSI - Matrix Reasoning	27	16.444 ± 3.619	72.574 ± 25.679
CTOPP - Phonological Awareness	27	24.24 ± 3.16	65.148 ± 20.615
CTOPP - Rapid Automatized Naming	24	23.521 ± 5.523	47.875 ± 18.55
CTOPP – Phonological Memory	27	15.944 ± 2.127	52.111 ± 22.633

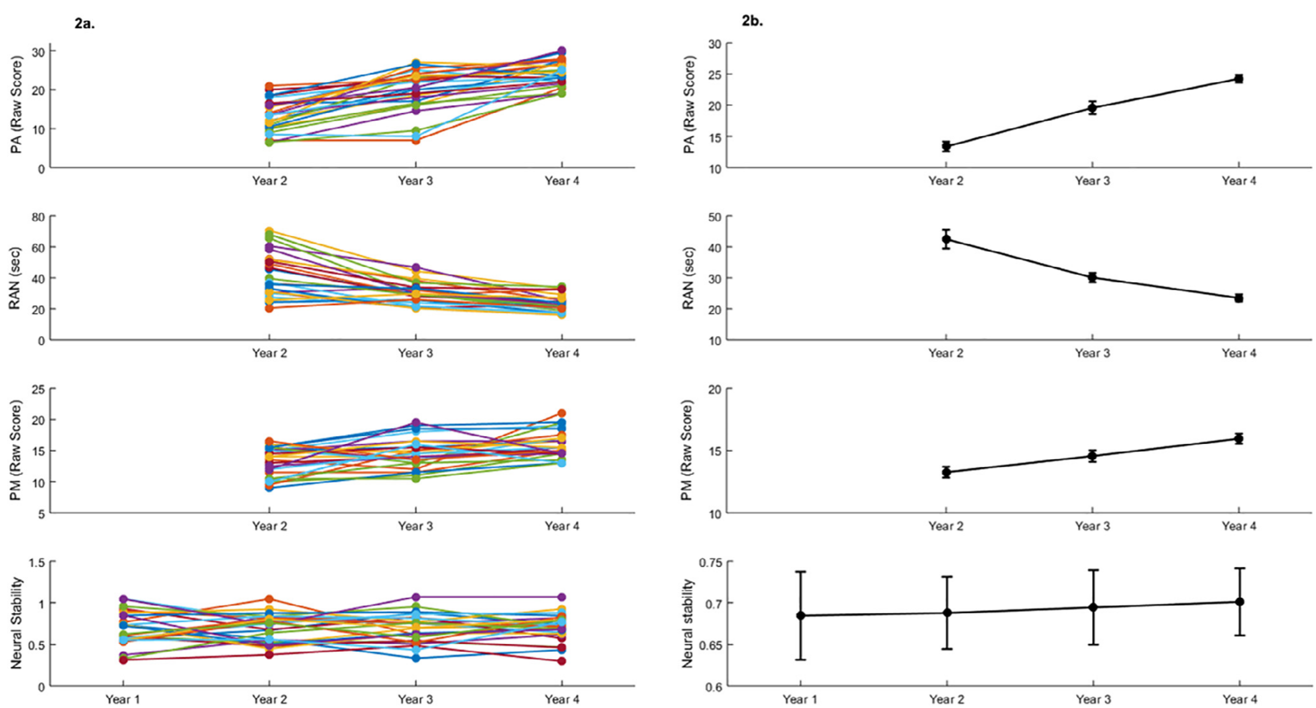

Fig. 2. (a) Performance for each child on Phonological Awareness (Line 1), Rapid Naming (Line 2), Phonological Memory (Line 3) across Year 2, Year 3 and Year 4 are plotted. Raw scores are shown. Auditory neural stability (Line 4) for each child is plotted across Year 1, Year 2, Year 3, and Year 4. (b) Mean developmental trajectory for PA (Line 1), RAN (Line 2), PM (Line 3), and Auditory neural stability (Line 4) across the four years of testing is plotted.

$p = 0.001$) and an additional 10% in Year 3 ($F_{(3,22)} = 8.405$, $p = 0.001$). In Year 4 the predictive power of the model does not statistically improve ($F_{(3,23)} = 2.195$, $p = 0.116$). Adding neural stability for consecutive years in the third step did increase the amount of variance explained in previous steps in Year 2 ($\Delta R^2 = 0.035$, $F_{(4,22)} = 6.798$, $p = 0.001$), however among Neural stability predictors the only β that resulted to be significant is the one related to Neural stability Year 1. The same pattern of results is for Year 3 ($\Delta R^2 = 0.028$, $F_{(5,20)} = 5.134$, $p = 0.003$). As for Year 4, the addition of neural stability for consecutive years in the third step did not increase the amount of variance explained in previous steps ($\Delta R^2 = 0.096$, $F_{(6,20)} = 0.730$, $p = 0.632$).

See Table 3 for full regression results and Fig. 3 for a representation of the regression results.

4.3. Rapid automatized naming

RAN was not predicted by age and nonverbal IQ in Year 2 ($R^2 = 0.094$, $F_{(2,21)} = 1.090$, $p = 0.355$), Year 3 ($R^2 = 0.084$, $F_{(2,20)} = 0.914$, $p = 0.417$), or Year 4 ($R^2 = 0.118$, $F_{(2,21)} = 1.411$, $p = 0.266$). Adding neural stability in the second step of this regression did not increase the amount of variance explained by the model in Year 2 ($\Delta R^2 = 0.069$, $F_{(3,20)} = 1.298$, $p = 0.303$), Year 3 ($\Delta R^2 = 0.055$, $F_{(3,19)} = 1.017$, $p = 0.407$), or Year 4 ($\Delta R^2 = 0.028$, $F_{(3,20)} = 1.143$, $p = 0.356$). Adding neural stability for consecutive years in the third step did not increase the amount of variance explained in previous steps in Year 2 ($\Delta R^2 = 0.049$, $F_{(4,19)} = 1.279$, $p = 0.313$), Year 3 ($\Delta R^2 = 0.099$, $F_{(5,17)} = 1.058$, $p = 0.417$), or Year 4 ($\Delta R^2 = 0.059$, $F_{(6,17)} = 0.730$, $p = 0.632$). See Table 4 for full regression results.

Table 3
Full regression results of neural stability predicting phonological awareness in subsequent years.

	Phonological Awareness					
	Year 2 (age 5)		Year 3 (age 6)		Year 4 (age 7)	
Predictors	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	0.419**		0.434**		0.143	
Age		0.263		0.426*		−0.119
NV IQ		0.476*		0.407*		0.390~
Step 2	0.099**		0.1*		0.079	
Age		0.174		0.351*		−0.186
NV IQ		0.559**		0.469**		0.479*
Neural stability Year 1		0.326*		0.328*		0.298
Step 3	0.035		0.028		0.096	
Age		0.102		0.327		−0.289
NV IQ		0.566**		0.484**		0.548*
Neural stability Year 1		0.423*		0.459*		0.479~
Neural stability Year 2		−0.217		−0.025		0.126
Neural stability Year 3				−0.197		−0.268
Neural stability Year 4						−0.200
Total R^2	0.553		0.562		0.318	

4.4. Phonological memory

PM was not predicted by age and nonverbal IQ in Year 2 ($R^2 = 0.153$, $F_{(2,24)} = 2.166$, $p = 0.137$), Year 3 ($R^2 = 0.082$, $F_{(2,23)} = 1.028$, $p = 0.374$), or Year 4 ($R^2 =$, $F_{(2,24)} = 1.281$, $p = 0.296$). Adding neural stability in the second step of this regression did not increase the amount of variance explained by the model in Year 2 ($\Delta R^2 = 0.015$, $F_{(3,23)} = 1.543$, $p = 0.230$), Year 3 ($\Delta R^2 = 0.009$, $F_{(3,22)} = 0.738$, $p = 0.541$), or Year 4 ($\Delta R^2 = 0.007$, $F_{(3,23)} = 0.884$, $p = 0.464$). Adding neural stability for consecutive years in the third step did not increase the amount of variance explained in previous steps in Year 2 ($\Delta R^2 = 0.013$, $F_{(4,22)} = 1.213$, $p = 0.334$), Year 3 ($\Delta R^2 = 0.081$, $F_{(5,20)} = 0.831$, $p = 0.543$), or Year 4 ($\Delta R^2 = 0.049$, $F_{(6,20)} = 0.599$, $p = 0.728$). See Table 5 for full regression results.

4.5. Reciprocal relationship between neural stability and phonological skills across years

We examined the reciprocal relationships between neural stability and phonological skills across each year of testing. The strength of correlations between PA and RAN for Year 2, Year 3, and Year 4 decreased over time. The correlation was moderately strong in Year 2 ($r = -0.449$, $p = 0.028$, $n = 24$), but there was no significant correlation in Year 3 ($r = -0.276$, $p = 0.191$, $n = 24$), or Year 4 ($r = 0.093$, $p = 0.666$, $n = 24$). Correlations between PA and PM for Year 2, Year3, and Year 4 also decreased over time. The correlation was moderate but just trending in Year 2 due to one subject with a high PA score ($r = 0.333$, $p = 0.090$) and there was no significant correlation in

Table 4
Full regression results of neural stability predicting rapid automatized naming in subsequent years.

	Rapid Automatized Naming					
	Year 2 (age 5)		Year 3 (age 6)		Year 4 (age 7)	
Predictors	ΔR^2	β	ΔR^2	β	ΔR^2	B
Step 1	0.094		0.084		0.118	
Age		−0.177		−0.287		−0.102
NV IQ		−0.19		−0.016		0.34
Step 2	0.069		0.055		0.028	
Age		−0.122		−0.24		−0.076
NV IQ		−0.254		−0.068		0.292
Neural stability Year 1		−0.271		−0.243		−0.175
Step 3	0.049		0.099		0.059	
Age		−0.083		−0.251		0.043
NV IQ		−0.267		−0.113		0.229
Neural stability Year 1		−0.387		−0.166		−0.118
Neural stability Year 2		0.250		0.369		−0.121
Neural stability Year 3				−0.413		−0.296
Neural stability Year 4						0.357
Total R^2	0.212		0.237		0.205	

Table 5
Full regression results of neural stability predicting phonological memory in subsequent years.

	Phonological Memory					
	Year 2 (age 5)		Year 3 (age 6)		Year 4 (age 7)	
Predictors	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	0.153		0.082		0.096	
Age		0.403		0.115		0.317
NV IQ		−0.027		0.235		−0.125
Step 2	0.015		0.009		0.007	
Age		0.369		0.092		0.297
NV IQ		0.005		0.254		−0.099
Neural stability Year 1		0.126		0.101		0.088
Step 3	0.013		0.081		0.049	
Age		0.325		0.181		0.351
NV IQ		0.009		0.214		−0.144
Neural stability Year 1		0.185		0.176		0.056
Neural stability Year 2		−0.133		0.258		−0.247
Neural stability Year 3				−0.341		0.077
Neural stability Year 4						0.228
Total R^2	0.181		0.172		0.152	

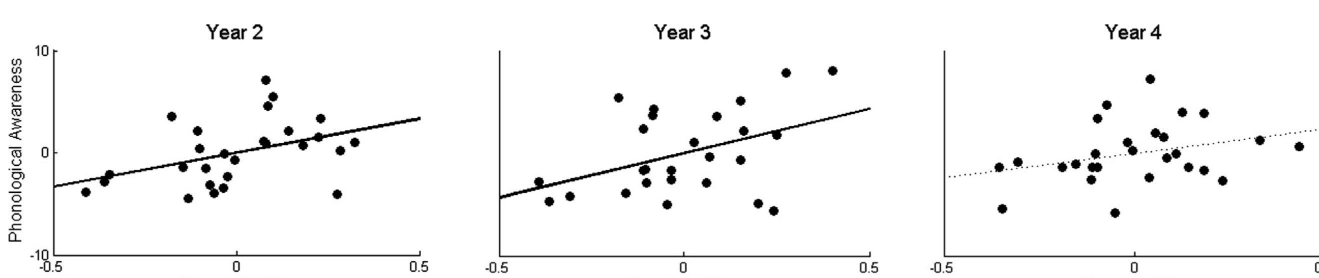

Fig. 3. The effects of neural contributors on phonological awareness with the effects of age and IQ partialed out. Unstandardized residuals of year-1 neural stability regressed upon age and IQ are plotted against unstandardized residuals of PA regressed upon age and IQ for each year. Fig. 2a–c show year-1 (age 4) neural stability versus PA in Years 2, 3, and 4 (ages 5, 6, and 7), respectively. Regression lines are plotted, with a solid line indicating statistical significance ($p < 0.05$), and a dotted line indicating no statistical significance ($p > 0.05$). Neural stability has decreasing predictive power as the children get older, and is an insignificant predictor by the time children reach age 7.

Table 6
Bivariate Pearson correlations between neural and behavioral measures. R values are reported.

	Neural Stability Year 1	Neural Stability Year 2	Neural Stability Year 3	Neural Stability Year 4	RAN Year 2	RAN Year 3	RAN Year 4	PA Year 2	PA Year 3	PA Year 4	PM Year 2	PM Year 3	PM Year 4
Neural Stability Year 1	1												
Neural Stability Year 2	0.392*	1											
Neural Stability Year 3	0.507**	0.508**	1										
Neural Stability Year 4	0.308	0.610**	0.615**	1									
RAN Year 2	-0.246	0.108	0.069	0.000	1								
RAN Year 3	-0.270	0.076	-0.084	0.092	0.688**	1							
RAN Year 4	-0.258	-0.105	-0.242	0.049	0.598**	0.685**	1						
PA Year 2	0.285	-0.184	-0.330	-0.292	-0.449*	-0.293	0.097	1					
PA Year 3	0.331	-0.012	0.005	-0.006	-0.374	-0.276	-0.101	0.680**	1				
PA Year 4	0.154	0.099	-0.123	0.025	-0.182	0.065	0.093	0.441*	0.451*	1			
PM Year 2	0.180	-0.145	0.046	-0.011	-0.287	0.024	0.052	0.333	0.404*	0.283	1		
PM Year 3	0.078	0.137	-0.065	-0.011	-0.353	-0.035	0.016	0.465*	0.259	0.387*	0.394*	1	
PM Year 4	0.157	-0.130	0.128	-0.024	-0.003	0.126	0.156	0.241	0.201	0.088	0.570**	0.322	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

High	0.4 - 0.7
Moderate	0.3 - 0.399
Low	< 0.299

Year 3 (r = 0.259, p = 0.193), or Year 4 (r = 0.088, p = 0.663). Correlations between PM and RAN were not significant in any year: Year 2 (r = −0.287, p = 0.175), Year 3 (r = −0.035, p = 0.870), and Year 4 (r = 0.156, p = 0.465). See Table 6 for details about all the bivariate correlations performed.

5. Discussion

Our results suggest that PA, but neither RAN nor PM, may be in part influenced by auditory neural stability in typically-developing preschool children. Neural stability predicted PA up to two years out, but did not predict RAN and PM in typically-developing preschool-aged children. Neural stability, an index of how accurate a brain is in coding a speech stimulus over repeated trials, specifically related initially with PA ability. It is not surprising that a consistency in how a speech sound is processed each time it is heard would facilitate the awareness of the sounds of one's language. Noteworthy is that this association was specific for early, when the children are at the first stages of language development. From previous study we know that neural stability is experience-dependent, and it has a complex maturational path, punctuated by periods of change and periods of stability (Krizman et al., 2014; Skoe et al., 2015; Thompson ARO Abstract). With respect to this, early childhood appears to be a dynamic time where continuous and repeated enhancements happen over time. In our study, the measure of neural stability collected as earlier as when children were 3 revealed to be the most effective index able to capture within-individual variability associated with successful PA development.

Neural stability was not connected to PA in Year 4. This may be because PA is no longer strongly related to auditory processing as the children get older. Perhaps as children learn to read, the strategies used in PA change from purely auditory to a more complex reliance upon visual and memory factors. It is also possible that additional variables have begun to influence PA, such as the exposure to written language and its orthography in addition to the potential impact of any training or experiences (Wagner et al., 1999).

5.1. Limitations

One limitation of our study is its modest sample size. Although we had four years of longitudinal data, our sample size is smaller than previous behavioral studies tracking the development of phonological processing skills. While it is interesting that our behavioral data, in general, replicated previous findings, it will be important to replicate our results in a larger population—particularly those pertaining to neural stability. Another limitation of is that we only enrolled typically developing children. The relationships between PA, PM, RAN and neural stability may be different in a cohort of children with a reading impairment.

5.2. Theories and future work

Despite its limitations we hope to address in future studies involving a larger population, the current study supports the notion that PA, PM and RAN are distinct subskills and, for the first time, extends this evidence to preschool age. Thanks to our longitudinal dataset of four consecutive years, we determined that neural stability relates to PA development at its early stages and can potentially help in identifying children at risk for reading disabilities when they are three years old.

This study also raises questions about the mechanism behind neural stability's relationship to PA. Further work needs to examine this, potentially through interventions that can enhance neural stability. It has already been shown that timing of the FFR can be altered through training (Anderson, White-Schwoch, Parbery-Clark, & Kraus, 2013; Russo, Nicol, Zecker, Hayes, & Kraus, 2005). In addition, assistive-listening devices in the classroom have been shown to improve reading and neural stability (Hornickel et al., 2012). When considering these interventions, the impact of noise on FFRs must also be considered, as this may affect measurements of the FFR across development (Musacchia et al., 2018). Investigating complex FFR metrics such as pitch perception may also reveal exciting correlations with pre-reading skills (Jeng et al., 2010; Patel & Iversen, 2007). These studies indicate that targeted interventions could be used to enhance neural stability in young children and corresponding increases in pre-reading abilities.

The present study may hint at a relationship between auditory neural stability and phonological processing at an early age. Increasing the sample size and continuing to follow the children in this study longitudinally would give us the opportunity to monitor their reading development as it relates to their neural response to sound at early ages, perhaps discovering distinct patterns between auditory processing and phonological skills at older ages.

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