Highlights

- MEG measurements at two- and six-months age reveals differential patterning of auditory mismatch activity following VOT contrasts in CV syllables with double oddball paradigm.
- Non-equivalence (TOST) t-testing reveals diminished sensitivity to VOT contrasts wit developmental age. Such that, logistic classification reliability scores for deviant ERFs (i.e., phonemic change detection) are on average 3.6% lower by 6-months of age.
- Conversely, older infants also exhibit enhanced overall auditory mismatch activity considering TOST results demonstrating larger classification reliability scores between evoked responses to oddball stimuli irrespective of VOT contrast.
- Differential MEG findings and predictive modeling of standardized developmental language outcome measurements beyond two year age are discussed in light of NLMe theory of early speech acquisition.

Results

Cross sectional data

Demographics

Results of data analysis for infants (N=72) with both behavioral CDI language outcome measures between 18-30 months and familial Hollingshead SES are reported. Shapiro-Wilk tests confirmed measurements were not normally distributed, thus non-parametric test results are presented. Table 1 summarizes the cross-sectional demographic characteristics of participating families. On average, infants underwent an initial MEG exam around 59.5±6 (M±SD) days-age, presenting with a moderate difference in head size (W = 2.48, p = 0.08, ε^2 = 0.04) between boys and girls. Overall, families were predominately made-up of White-Non Hispanic Latino mothers (61.1%) and fathers (79.2%), and respectively, 91.7% and 79.2% of parents had at least a high-school level-education or equivalent.

TABLE 1. CROSS SECTIONAL DEMOGRAPHICS

	Girls			Boys			χ^2	df	p
N	39			33					
Age (days)	115.0	±	60.0	124.0	±	57.0	0.65	1	0.419
Birth weight (oz)	122.0	±	10.4	118.0	±	15.3	1.23	1	0.267
Head size (cm)	41.2	±	2.1	42.1	±	2.4	3.08	1	0.079*
Maternal education (yr)	16.0	±	1.8	16.0	±	2.3	0.00	1	0.982
Paternal education (yr)	16.0	±	2.7	15.0	±	3.1	1.43	1	0.232
SES	51.9	±	12.9	50.4	±	13.4	0.07	1	0.790

Variable (M±SD) values for N=72 infants ranging in age between 2- and 6-months. Kruskal-Wallis chi-square test and Dwass-Steel-Critchlow-Fligner adjusted p-values for pairwise comparisons between boys and girls.

[The jamovi project (2020). jamovi. (Version 1.2) [Computer Software]. Retrieved from https://www.jamovi.org.

R Core Team (2019). R: A Language and envionment for statistical computing. (Version 3.6) [Computer software]. Retrieved from https://cran.r-project.org/].

Magnetoencephalography

Overall, non-parametric univariate ANOVA results of AUC data irrespective of contrast condition suggested a trend toward differential mismatch evoked response (ER) patterning across age groups (2- vs. 6-months: $\chi^2 = 3.54$, df = 1, $p = 0.06$, $\varepsilon^2 = 0.05$). To further investigate whether mismatch ER patterning across ages is effected by the contrast condition one-sample non-equivalence t-testing (TOST) [Lakens, 2018;Jamovi; R-Core Team] was used to evaluate differences in mismatch detection reliability score measure (AUC) between ages for each classification case (MMN, $MMN_{aspirative}$, $MMN_{plosive}$, $ERF_{deviants}$). Table 2 summarizes the TOST results with a medium sized (Cohen's d = 0.5) smallest effect size of interest (SESOI) for the cross sectional cohort. Non-equivalence test results for mean AUC scores in each

TABLE 2. INDEPENDENT SAMPLES EQUIVALENCE TESTING

			H_0		ΔL		ΔU			
Condition	*Six*	*Two*	t	p	$t_{\Delta L}$	$p_{\Delta L}$	$t_{\Delta U}$	$p_{\Delta U}$	*Rej ΔL*	*Rej ΔU*
MMN	0.51±.04	0.49±.03	-2.29	0.03	-0.16	0.56	-4.42	< .001	no	yes
$ERF_{deviants}$	0.5±.05	0.51±.04	1.59	0.12	3.70	<.001	-0.51	0.12	yes	no

Table shows (M±SD) area under the curve scores for logistic classification of ERF activity following CV-syllables and results of Welch CI testing assuming unequal variance for MMN measurements on infants between two and six-months-age. TOST routines were carried out using a medium sized SEOSI (Cohen's *d*=0.5) at α=0.05.

[Lakens, D., Scheel, A. M., & Isager, P. M. (2018). Equivalence Testing for Psychological Research: A Tutorial. Advances in Methods and Practices in Psychological Science, 1(2), 259–269. https://doi.org/10.1177/2515245918770963]

classification case revealed an overall difference between age groups for the critical mismatch detection conditions: acoustic mismatch (MMN) $t_{\Delta L} = -0.16$, $p = 0.56$ and ERFs to deviant ($ERF_{deviants}$) stimuli $t_{\Delta U} = -0.51$, $p = 0.12$. Overall MMN activity to CV segments by 6-months-age (0.41±0.04; M±SD) was enhanced, as shown by a nonsignificant test result against *ΔL*. Critically, by six months-age (0.50±0.05) ERF responses to CV stimuli conveying prototypical VOTs for (/b/ vs. /w/) consonantal onsets was diminished relative to classification scores for two-months-old infants (0.51±0.04). Suggesting a critical change in sensitivity to phonological contrast by six months; namely one attributable to the putative perceptual narrowing facilitating speech acquisition during early infant development (c.f. figure 1).

Canonical correlation analysis (CCA) revealed significant linear relationships between demographic covariates, notably socioeconomic SES was correlated with electrophysiological AUC and language outcome measures M3L and vocabulary size between 18-30 months-age (see table 3).

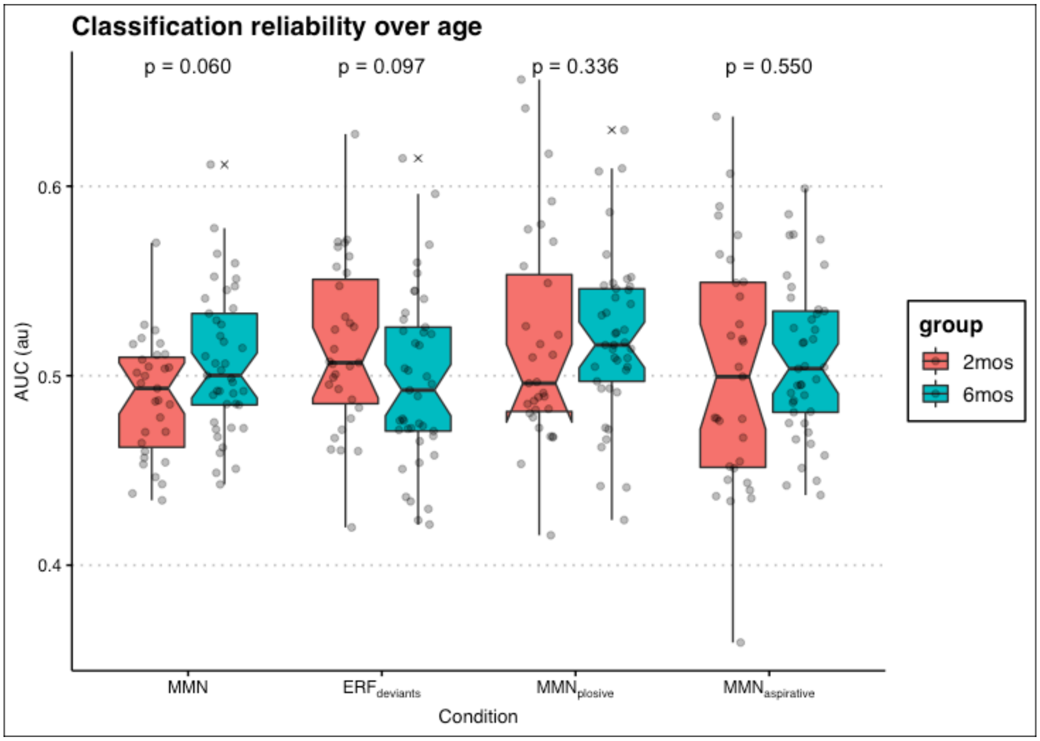

Figure 1. Cross sectional evoked mismatch classification. ROC area under curve (AUC) reliability scores computed for each mismatch condition and evoked responses following deviant (ERFdeviants) consonant-vowel (CV) stimuli. Deviants consisted of opposite extrema VOT tokens (/b/, /w/) contrasted against the standard stimulus consisting of a mid-point VOT CV segment. AUC was computed using k-fold cross validation and logistic regression classifier fit to trial evoked response field (ERF) data for each stimulus type. TOST independent samples testing confirms a likely interaction between factors age and classifier conditioning, such that by six-months-age overall mismatch (MMN) activity and differential deviant ERF (ERFdeviant) patterning exhibit a moderate disassociation. Boxplots summarize group AUC data with results from independent samples t-tests (uncorrected) at (α = 0.05) between groups.

TABLE 3. CORRELATIONS

	Age	Head Size	Birth Weight	SES	AUC	M3L
Age (days)	–					
Head circumference (cm)	0.611***	–				
Birth Weight (oz)	-0.079***	0.023	–			
SES	-0.038*	0.013	0.011	–		
AUC	0.042*	-0.020	-0.003	-0.036*	–	
M3L	0.061**	0.016	0.026	0.138***	-0.011	–
Vocabulary size	0.074***	0.025	-0.056**	0.045*	-0.021	0.60***

Linear relationships amongst demographic, electrophysiological (AUC), and CDI language outcome scores for utterance length (M3L) and vocabulary size between 18-30 months-age. Kendall’s tau-b values computed across all classifier conditions (N=1440).* p < .05, ** p < .01, *** p < .001

Longitudinal data

Table 5 summarizes the demographics of th longitudinal cohort: twenty-one infants (12 females) with language outcome measures (CDI) at three-months intervals between 18-30 months-age following up on repeated MEG exams at two (61 ± 5.7; M ± SD days-age) and six (192 ± 7.2) months-age. Families were predominately White-Non Hispanic Latino ethnicities, with 52% of dyads reporting at least with a Bachelors level education. Kruskall-Wallis testing confirmed boys and girls were sampled from families with homogeneous demographic attributes (χ^2's < 2.4).

TABLE 5. LONGITUDINAL DEMOGRAPHICS

	Girls			Boys			χ^2	df	p
N	12			9					
Birth weight (oz)	119.0	±	8.1	112.0	±	14.4	1.48	1	0.230
ΔHead size (cm)	9.2	±	2.3	10.9	±	2.7	1.57	1	0.210
Maternal education (yr)	17.0	±	2.0	16.0	±	2.2	0.06	1	0.800
Paternal education (yr)	17.0	±	2.5	15.0	±	3.0	2.40	1	0.100
SES	55.4	±	11.0	49.3	±	14.0	0.86	1	0.350

Demographic feature (M±SD) values for infants (n=21) that underwent longitudinal repeated MEG examinations at 2- and 6-months-age. Kruskal-Wallis chi-square testing revealed a homogenous sampling of boys and girls and Dwass-Steel-Critchlow-Fligner adjusted p-values for pairwise comparisons between boys and girls.

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Equal variance independent samples confidence interval testing using a medium effect size criteria with Cohen's *d=0.5* indicated a reduction in classification scores for deviant syllables by 6-months age: nonsignificant Welch t-test against ΔU

TABLE 6. PAIRED EQUIVALENCE TESTING

			H_0		ΔL		ΔU			
Condition	*Six*	*Two*	*t*	*p*	$t_{\Delta L}$	$p_{\Delta L}$	$t_{\Delta U}$	$p_{\Delta U}$	*Rej ΔL*	*Rej ΔU*
MMN	0.51±.04	0.49±.03	-1.72	0.09	-0.10	0.54	-3.34	< .001	no	yes
$ERF_{deviants}$	0.49±.04	0.52±.05	1.59	0.12	3.21	0.00	-0.03	0.49	yes	no

Table shows (M±SD) area under the curve scores for logistic classification of ERF activity following CV-syllables and results of Welch CI testing assuming equal variance for repeated measurements on same infant at two and six-months-age. TOST routines were carried out using a medium sized SEOSI (Cohen's *d*=0.5) at α=0.05.
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($t_{(40)}$ = -0.03, p = .49), confirmed that sensitivity to phonological VOT change detection is indeed more nuanced by 6-months. Thus by 6-months-age infants arguably perceived only two distinct CV stimuli varying along VOT along with an unintelligible syllable in the standard position, i.e., a less reliable precept at least as extreme as 0.5 standard deviation in the general population (see table 6).

Modeling

Results from mixed linear modeling (MLM) of RM electrophysiology data in relation to CDI language outcomes between 18-30 months for longitudinal cohort are presented here (see table 7). Model yields confirmed CDI VOCAB was effected by SES ($F_{(1, 813)}$ =87.46, p<0.001), AGE ($F_{(1, 813)}$ =43.31, p<0.001), HEAD SIZE $F_{(1, 813)}$ =51.57, p<0.001) and BIRTH WEIGHT $F_{(1, 813)}$ =82.87, p<0.001). VOCAB was also influenced by paternal education: mother ($F_{(1, 814)}$ =19.74, p<0.001) and father's

Table 7

	Effect/parameter	β	SE	95% CI Lower	95% CI Upper	df	t	*p*
Vocabulary size	AUC	-2.21	3.26	-8.61	4.19	813.99	-0.68	0.499
	SES	-4.16	0.43	-5.00	-3.32	814.29	-9.67	< .001
	Age	0.71	0.11	0.50	0.92	814.19	6.66	< .001
	Head size	-21.27	2.92	-27.00	-15.55	814.24	-7.28	< .001
	Birth weight	-3.05	0.32	-3.67	-2.42	813.99	-9.59	< .001
	Maternal education	12.24	2.72	6.90	17.57	815.19	4.49	< .001
	Paternal education	20.18	1.95	16.36	24.00	814.64	10.36	< .001
	M3L	25.44	1.47	22.55	28.33	817.38	17.26	< .001
	AUC ✻ SES	-1.11	0.29	-1.68	-0.53	813.98	-3.77	< .001
	SES ✻ Age	-4.92E-04	0.00	-0.01	0.01	813.98	-0.14	0.892
	AUC ✻ Head size	1.53	2.95	-4.26	7.31	814.01	0.52	0.606
	AUC ✻ Age	-0.11	0.11	-0.34	0.11	814.03	-0.98	0.329
	Maternal ✻ Paternal education	-4.05	0.75	-5.53	-2.57	814.11	-5.37	< .001
	SES ✻ Gender (M-F)	-2.84	0.52	-3.86	-1.82	814.02	-5.44	< .001
M3L	AUC	-0.03	0.07	-0.16	0.10	814.04	-0.46	0.647
	SES	-0.01	0.01	-0.03	0.01	741.67	-0.94	0.348
	Age	0.00	0.00	0.00	0.01	801.35	1.38	0.167
	Head size	-0.10	0.06	-0.22	0.02	789.03	-1.70	0.090
	Birth weight	0.03	0.01	0.02	0.04	805.10	4.42	< .001
	Gender (M-F)	0.34	0.14	0.07	0.61	815.13	2.43	0.015
	Maternal education	0.56	0.05	0.46	0.66	715.08	10.91	< .001
	Paternal education	0.14	0.04	0.06	0.22	655.41	3.40	< .001
	Vocabulary size	0.01	5.52E-04	0.01	0.01	88.98	19.68	< .001
	AUC ✻ SES	0.01	0.01	0.00	0.02	816.84	1.56	0.119
	SES ✻ Age	1.55E-06	7.35E-05	-1.42E-04	1.46E-04	813.65	0.02	0.983
	AUC ✻ Head size	0.10	0.06	-0.02	0.22	814.52	1.67	0.096
	AUC ✻ Age	0.00	0.00	-0.01	4.26E-05	815.35	-1.94	0.053
	Maternal ✻ Paternal education	0.10	0.02	0.08	0.13	815.15	6.91	< .001
	SES ✻ Gender (M-F)	0.05	0.01	0.03	0.07	816.72	4.96	< .001

Linear mixed model fitting using REML. Table shows fixed effects parameters for CDI language outcome measures of Vocabulary size and mean length of three longest utterances (M3L) between 18-30 months-of-age. Modeling was done assuming a random intercept for prospective CDI measurement timepoints yielding likelihood ratio tests for vocabulary size (AIC=10314.86, LRT=545.35, *p*< .001, ICC=0.73) and M3L (AIC=3420.62, LRT=26.83, *p*< .001, ICC=0.08) at five CDI intake timepoints. Fixed effects omnibus F distribution testing was carried out using Satterthwaite method for degrees of freedom, yielding converging models for vocabulary (AIC=9825.44, R^2=0.83conditional) size and M3L (AIC=3263.77, R^2=0.75).

education in years ($F_{(1, 814)}$ =102.85, p<0.001) educational level. Crucially the influence of SES on vocabulary development was moderated by not only AUC ($F_{(1, 814)}$ =14.19, p<0.001) but also GENDER ($F_{(1, 814)}$ =29.56, p<0.001) .

moderated by SES and AUC ($F_{(1, 1419.01)}$ =3.46, p=0.063), M3L was only affected by an interaction between age and AUC ($F_{(1, 1419.01)}$ =3.70, p=0.055). Notably, whereas M3L was moderated by an interaction between parental education levels ($F_{(1, 1419.24)}$ =8.71, p=0.055). CDI vocabulary was effected by both SES ($F_{(1, 1419.03)}$ =17.54, p<0.001) and AGE ($F_{(1, 1419.17)}$ =26.13, p<0.001) and crucially, the influence of SES was marginally modulate by AUC ($F_{(1, 1419.01)}$ =3.46, p=0.063). Conversely, M3L was only effected by BIRTH WEIGHT ($F_{(1, 805)}$ =19.52, p<0.001), GENDER ($F_{(1, 591)}$ =8.15, p=0.015), and the interaction between paternal education levels ($F_{(1, 815)}$ =47.71, p<0.001). Also, the effect of GENDER on CDI M3L was moderated by SES ($F_{(1, 817)}$ =24.60, p<0.001).

Conclusion

Despite an enhancement in overall auditory mismatch activity by six-months-age (MMN condition), in light of early language acquisition, older infants presented with reduced auditory sensitivity to phonemic VOT contrast in syllabic stimuli. We argue that a reduction in auditory discrimination. Findings provide electrophysiological evidence for underlying neurological organization facilitating theoretical account of perceptual narrowing envisaged by NLMe to underlie infant language learning.