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Early language processing efficiency predicts later receptive vocabulary outcomes in children born preterm

Virginia A. Marchman^{a,1}, Katherine A. Adams^a, Elizabeth C. Loi^b, Anne Fernald^a, and Heidi M. Feldman^b

Virginia A. Marchman: marchman@stanford.edu; Katherine A. Adams: 1kattams@gmail.com; Elizabeth C. Loi: eloi@stanford.edu; Anne Fernald: afernald@stanford.edu; Heidi M. Feldman: hfeldman@stanford.edu

^aDepartment of Psychology, 450 Serra Mall, Stanford University, Stanford, CA 94305

^bDepartment of Pediatrics, Division of Neonatal and Developmental Medicine, 730 Welch Rd, Stanford University, Palo Alto, CA 94304

Abstract

As rates of prematurity continue to rise, identifying which preterm children are at increased risk for learning disabilities is a public-health imperative. Identifying continuities between early and later skills in this vulnerable population can also illuminate fundamental neuropsychological processes that support learning in all children. At 18 months adjusted age, we used socioeconomic status, medical variables, parent-reported vocabulary, scores on the Bayley Scales of Infant and Toddler Development language composite, and children's lexical processing speed in the looking-while-listening task as predictor variables in a sample of 30 preterm children. Receptive vocabulary as measured by the Peabody Picture Vocabulary Test (4th Edition) at 36 months was the outcome. Receptive vocabulary was correlated with SES, but uncorrelated with degree of prematurity or a composite of medical risk. Importantly, lexical processing speed was the strongest predictor of receptive vocabulary ($r = -.81$), accounting for 30% unique variance. Individual differences in lexical processing efficiency may be able to serve as a marker of information processing skills that are critical for language learning.

Keywords

Language development; Children born preterm; Processing speed; Vocabulary outcomes; Predictive validity

Prematurity is a condition of utmost public health importance. While many children born preterm develop typically, approximately 50% have mild to moderate disabilities that may not be identified until the child enters school (Bhutta, Cleves, Casey, Cradock & Anand, 2002; Marlow, 2004) and 10 to 25% of preterm children have a major disability such as cerebral palsy or intellectual disability (Vohr et al., 2000). Given such variability in developmental trajectories, the early identification of preterm children at risk for delays is imperative in order to increase opportunities for early intervention. Moreover, identifying

¹Correspondence address: Virginia A. Marchman, Department of Psychology, 450 Serra Mall, Stanford University, Stanford, CA 94305, marchman@stanford.edu.

continuities between early skills and later outcomes in this vulnerable population may reveal fundamental neuropsychological processes that support learning in all children. Using a prospective longitudinal design, we explored the predictive validity of early lexical processing efficiency for preschool language knowledge in children born preterm.

Language-based disorders are especially prevalent in children born preterm (Barre, Morgan, Doyle & Anderson, 2011; van Noort-van der Spek, Franken & Weisglas-Kuperus, 2011; Vohr, 2014). Preterm toddlers perform below their full-term peers on standardized tests frequently applied in clinical practice, such as the Bayley Scales of Infant and Toddler Development (BSID-III, Mansson & Stjernqvist, 2014). Moreover, children born preterm also display slower rates of vocabulary growth, as measured by parent report instruments like the MacArthur-Bates Communicative Development Inventory (CDI) (Stolt, Haataja, Lapinleimu & Lehtonen, 2009). By school age, children born preterm demonstrate language functioning below that of full-term age-mates (Guarini et al., 2009; Wolke, Samara, Bracewell & Marlow, 2008), weaknesses that persist into later childhood and adolescence (Lee, Yeatman, Luna & Feldman, 2011). At the same time, at every developmental level, there are striking individual differences in language outcomes in children born preterm, just as there are with full-term children (Sansavini et al., 2014).

Identifying the causes and consequences of these individual differences is clinically and theoretically relevant. For example, while delays in early vocabulary production is a risk factor for poor later outcomes, parent report estimates of vocabulary knowledge taken in isolation tend to have poor predictive validity that limit their clinical utility (Dale, Price, Bishop & Plomin, 2003, US Preventative Services Task Force, 2014; Duff, Reen, Plunkett & Nation, 2015). It is now generally established that early identification of risk for language delays involves examination of multiple factors (Rescorla & Dale, 2013). Moreover, to isolate neuropsychological processes fundamental for learning, and to identify weaknesses that may accumulate over time to cause later disability, experimental measures that assess children's skill in processing spoken language in real time offer a promising alternative approach. Scores on standardized tests like the BSID-III or vocabulary size from the CDI are generally thought to reflect accumulated linguistic knowledge, rather than the information processing skills that are applied in the service of gaining linguistic knowledge (Lee et al., 2011; Taylor, Klein, Minich & Hack, 2000). Experimental studies have shown that a variety of visual information processing skills in preterm infants are linked to increased medical risk, as well as receptive language outcomes (Rose, Feldman, & Jankowski, 2002; 2009). Moreover, studies with children and adolescents born preterm reveal particular deficits in language processing efficiency, such as slower processing speed (Lee et al., 2011; Potharst et al., 2013) and more limited phonological working memory (Sansavini et al., 2007). Identifying valid behavioral indicators of processing efficiency using language-related tasks appropriate for infants could facilitate earlier identification of children at highest risk for delays. Moreover, observing such relations in an at risk sample of children born preterm would provide further evidence that early language processing is critical to learning in children across a broad range of skill levels (Fernald, Perfors & Marchman, 2006; Rose et al., 2009; Shafto, Conway, Field & Houston, 2012).

Experimental studies with full-term infants using the looking-while-listening (LWL) task show that early efficiency in language processing predicts vocabulary growth and cognitive outcomes (Fernald et al., 2006; Marchman & Fernald, 2008). In the LWL task, infants look at pictures of familiar objects while listening to speech naming one of the objects (“Where’s the doggy?”). Their gaze patterns as they encode the auditory signal and identify the referent are assessed with precision in relation to relevant points in the speech signal, yielding reliable measures of reaction time (RT) and accuracy. Children who were more efficient in spoken word recognition at the age of 18 months, as measured by faster RTs, showed more rapid vocabulary growth, higher IQ scores, and stronger working memory skills at 8 years (Fernald et al., 2006; Marchman & Fernald, 2008). Efficient language processing also predicted “catch up” in vocabulary in late-talking infants at risk for language delays (Fernald & Marchman, 2012). Thus, how quickly and reliably young children interpret familiar spoken words in real time is thought to reflect efficiency in language processing that is critical for learning new vocabulary words and that shapes longer-term trajectories of cognitive and language development.

Do individual differences in lexical processing efficiency by preterm infants at 18 months predict their later receptive vocabulary knowledge at 3 years? Finding such relations would provide further evidence that early efficiency in language processing supports later learning, and that these critical information processing skills are vulnerable in populations with neurodevelopmental risk. In order to control for global immaturity associated with premature birth, we assessed the infants when they were 18 months old, correcting for degree of prematurity (18 mos AA). Outcomes were assessed at or around the child’s 3rd birthday (36 mos). Two standard scores were computed, one based on unadjusted (chronological) age, and the other based on age after adjusting for degree of prematurity.

Evaluating our hypothesis required comparing the role of early language processing efficiency to other factors that have been linked to adverse outcomes in preterm populations. Many studies find that gestational age (GA) and birth weight (BW) are negatively linked to neurodevelopmental functioning (Allen, 2008). For example, GA at birth, particularly at the limits of viability, has been associated with mortality as well as morbidity, including the probability of disability (Allen, 2008) and associated neural markers of adverse outcomes, such as reduced gray matter volume and increased cerebrospinal fluid volume (Inder, Warfield, Wang, Hüppi & Volpe, 2005). However, poor outcomes after preterm birth has been linked to the number of medical complications, such as seizure disorder, respiratory distress syndrome and retinopathy that generally are also associated with gestational age and birth weight (Stoll et al., 2010; Feldman et al., 2002). Neurological conditions, such as decreased brain volume, microstructure abnormalities, and alterations in neural connectivity linked to shorter gestational periods tend to persist to school age and are associated with learning challenges (Kidokoro, Anderson, Doyle, Woodward, Neil & Inder, 2014). Importantly, recent studies have shown that presence of neural injuries, particularly those involving white matter assessed through magnetic resonance imaging (MRI), predict increased risk for poor outcomes in older children and adolescents using tasks that specifically assess processing speed (Feldman et al., 2012; Soria-Pastor et al., 2008). Of particular interest in the current study was whether a global index of the degree of prematurity, such as GA and BW, or cumulative risk of medical complications of preterm

birth would be associated with early measures of processing speed in preterm toddlers as well as later language outcomes in preschool. To our knowledge, no standardized composite measure is routinely used to assess degree of medical risk. Therefore, we created a composite score that catalogued the presence of 11 conditions, capturing medical risk that extends beyond global health variables such as GA and BW

Socioeconomic status (SES) has also been associated with children's language outcomes in preterm as well as full-term children (Johnson, Beitchman & Brownlie, 2010; Ramey & Ramey, 2004). The higher incidence of preterm birth in lower SES populations has remained stable over four decades (Glinianaia et al., 2013), with rates of preterm birth in disadvantaged families nearly twice that of affluent families (Smith, Draper, Manktelow, Dorling & Field, 2006). Taken together, children born preterm may experience cumulative risks for language delays due to a variety of medical and social factors.

In this study, we evaluated several predictors of 3-year receptive vocabulary outcomes in a sample of very preterm children. We first examined first-order correlations between SES, global measures of prematurity (BW and GA), and a composite of medical risk. We next explored the predictive validity of traditional estimates of early language knowledge using parent report and standardized tests. We then explored the contributions of an experimental measure of early language processing efficiency. We hypothesized that processing efficiency, as indexed by accuracy and processing speed (RT) in the LWL task, would predict receptive vocabulary outcomes in preterm children, based on associations seen previously in children born full term (Fernald et al., 2006) and on findings of compromised processing in older preterm children (Lee et al., 2011; Soria-Pastor et al., 2008). We address the following questions:

- How much variance in 3-year receptive language is accounted for by family SES and medical/birth variables?
- Do children's vocabulary size and performance on a standardized developmental assessment at 18 months AA predict later receptive language?
- Do experimental measures of real-time language processing in infancy account for additional variance in later receptive vocabulary beyond SES and standardized language assessments typically used to assess outcomes in children born preterm?

Method

Participants

Participants were 30 children (15 males, 15 females), all born preterm, with gestational age (GA) ≥ 32 weeks and birth weight (BW) < 1800 grams. Most families were recruited from the neonatal intensive care unit and the High-Risk Infant Follow-up Clinic of the local children's hospital. Other families were recruited through a research registry and an online newsletter from a local mothers' group. Exclusionary criteria were medical conditions that would prevent participants from understanding and actively participating in the study's tasks, such as a history of meningitis, a seizure disorder requiring medication, a ventriculoperitoneal shunt, a genetic disorder, and visual or hearing impairments. All

children were primarily English speaking and heard less than 25% of another language at home. The research protocol was approved by a university IRB and parents gave signed consent at each visit.

Children were tested at 18 months adjusted age (AA), following the routine clinical practice of adjusting the age of assessment for preterm children younger than 2 years of age. Date of test was determined by adding number of days premature to each participant's 18-month birthday. In 80% of the cases, children were tested within 30 days of this target date. Mean AA at test was 18.6 months (range = 18.0–20.3; chronological age: $M = 21.1$, range = 20.3–22.8 months). Follow-up language measures were administered when the children were 36 months unadjusted age (chronological age: $M = 36.5$, range = 35.4–38.3 months).

Table 1 shows the sociodemographic background of the sample. Most mothers had completed a college degree and the mean years of maternal education was >16 years. SES was also classified using the Hollingshead Four-Factor Index (HI, Hollingshead, 1975), a composite based on both parents' education and occupation (possible range = 8–66). The mean Hollingshead Index score of 57 reflects that participants were primarily from mid- to high-SES backgrounds.

Birth History and Medical Risk

Information about birth history is also presented in Table 1. Mean birth weight was approximately 1200 grams and mean gestational age was 29 weeks. Half of the children were part of a multiple birth, as is typical in this population (Goldenberg, Culhane, Iams & Romero, 2008). In two cases, only one twin in the pair is included based on inclusion criteria.

Several medical conditions were targeted as being particularly vulnerable in this population. The presence/absence of each condition was catalogued by trained research assistants in consultation with the last author based on information in the daily progress notes and discharge summaries from the NICU. Table 1 shows the proportion of children with each condition. For each child, the presence or absence of each condition was coded and summed to yield a medical risk score (max = 11). The mean per child was just over 3 (range = 0–7). In this relatively healthy group of children born preterm, none of the children had a hearing or visual impairment that precluded participation in the study. Based on either an MRI or a head ultrasound conducted during hospitalization, only two children were identified as having white matter injury associated with periventricular leukomalacia. Only five children were identified as having an intraventricular hemorrhage (Volpe, 2001), most of which were mild grades.

Measures

Vocabulary size—Expressive vocabulary was assessed at 18 months AA with the MacArthur-Bates CDI: Words and Gestures (CDI: W&G), a reliable and valid parent report instrument appropriate for children 8 to 18 months (Fenson et al., 2007). Parents marked words that their child “understands and says” and a total vocabulary score was derived (396 max). Percentile scores were computed based on adjusted age and gender.

Receptive and expressive language—When the children were 18 months AA, a trained examiner administered the Bayley Scales of Infant and Toddler Development, 3rd Edition (BSID-III, Bayley, 2005), a standardized developmental assessment for children aged 16 days to 42 months. Testing typically occurred over the course of two visits, conducted approximately 1 week apart. We chose to use the language composite in our analyses because this measure is commonly applied in clinical protocols and it offers a comprehensive evaluation of a broad range of children's language skills. Children point to a named picture, follow simple and complex commands, and produce words. Scaled scores were summed and converted to a standard full-scale score, based on the child's adjusted age.

Real-time language comprehension—Children's efficiency in comprehending words in real time was assessed at 18 months AA using the Looking-While-Listening (LWL) procedure (Fernald, Zangl, Portillo & Marchman, 2008), conducted in two visits approximately one week apart. The child sat on the caregiver's lap while pairs of pictures of familiar objects appeared on a screen and a prerecorded voice named one of the pictures. Looking patterns were videorecorded and later coded offline. The caregiver wore opaque sunglasses or closed their eyes to block their view of the images. Each session lasted approximately 5 min.

Visual stimuli were color pictures of familiar objects, presented in fixed pairs matched for visual salience and animacy. Trials were presented in two pseudo-random orders, such that each image served equally often as target and distracter; target order and picture position were counterbalanced across participants and across sessions. Pictures were displayed for 2 s prior to speech onset and remained onscreen for 1 s after sound offset. Auditory stimuli presented the target noun in sentence-final position followed by an attention-getter (e.g., *Where's the doggy? Do you like it?*). Target nouns were selected to be familiar to children of this age range, presented in yoked pairs: *baby-doggy*, *birdie-kitty*, *ball-shoe*, and *book-car*. Mean length of target noun was 639 ms (range = 565–769). Target nouns were presented four times each as target and distracter, interspersed between four filler trials, yielding 64 experimental trials. Trials on which the parent reported that the child did not understand the target word were excluded on a child-by-child basis. All children were reported to know at least five of the target words, and about two-thirds were reported to know all eight words.

All LWL sessions were later prescreened and coded offline by trained research assistants blind to target side. Trials where the participant was identified as inattentive or where there was parent interference ($M=6.9$ trials; range = 0–17) were not coded. On codable trials, eye gaze was identified for each 33-ms interval as either fixed on one of the images (*left* or *right*), or shifting between pictures or away (*off*). Trials were later designated as target-initial (T-initial) or distracter-initial (D-initial) based on the child's fixation at target noun onset.

Two measures of language processing efficiency were derived. *Accuracy* was the mean proportion looking to the target image divided by the total looking time to either image from 300–1800 ms after noun onset on all trials ($M=39.7$ trials; range = 17–58). *Reaction time (RT)* was the mean latency (in ms) of shifts from the distracter to the target image after target noun onset on D-initial trials ($M=15.2$ trials; range = 2–29). Shifts were excluded if they occurred before 300 ms or after 1800 ms from target noun onset. 25% of the sessions

were randomly selected and re-coded for reliability. Inter-coder agreement was 96% for proportion of frames within 300–1800 ms from noun onset identified as target vs. distracter. Proportion of trials on which first-shift latency agreed within one 33-ms frame was 100%.

Receptive vocabulary at 36 months—Children’s receptive vocabulary outcomes were assessed using the Peabody Picture Vocabulary Test, 4th Edition (PPVT-4) (Dunn & Dunn, 2007). Children are shown colored drawings and are asked to select the appropriate picture (of four choices) in response to the examiner’s prompt. Standard scores were used in all analyses.

Results

Overview

We first present descriptive statistics for all variables at 18 months AA and 36 months. To establish which predictors are relevant to our outcome measure, we next document first-order correlations between all predictors and the outcome variable of interest. A series of multiple regression models then examine the shared and unique contributions of each significant predictor to receptive vocabulary outcomes on the PPVT-4, focusing on the shared and unique contributions of language processing efficiency.

Performance at 18 months AA (Age adjusted for degree of prematurity)

As shown in Table 2, mean vocabulary size was 61 words. This placed the group at the 29th percentile (Fenson et al., 2007), on average, yet both raw scores and percentiles spanned the possible range. Children performed near the normative mean on the BSID-III, as a group, with only three children falling < 85 standard score. Again, scores reflected a broad range of performance. On the LWL task, children could identify the named picture with about 60% accuracy, on average, reliably looking to the target picture at above-chance levels, $t(29) = 5.4$, $p < .001$, [CI: .58 – .66]. Children initiated a shift within about 800 ms of target word onset, on average, yet some children had mean RTs less than 600 ms and others were nearly twice as slow.

Prediction to PPVT-4 at 36 months

At 36 months, PPVT-4 performance reflected a broad range of receptive vocabulary skills (Table 2), indicated in both the raw and standard scores. Looking first at unadjusted standard scores, the mean was 105, with a few children (5 of 30, 16.7%) scoring < 85, and others (3 of 30, 10.0%) performing >2 SDs above the normative mean. When scores were adjusted for degree of prematurity, the mean was slightly higher overall ($M = 109$), however, the same number of children fell < 1 SD and > 2 SDs above the mean. Since adjusting for degree of prematurity only impacts absolute values and not the relative ordering of the children, the two standard scores were highly correlated ($r = .99$) and yielded identical results in all subsequent analyses. For ease of exposition, we only report results using unadjusted standard scores for the 36-month outcome measure.

Table 3 presents first order correlations between the 18 months AA variables and PPVT-4 at 36 months. Children from higher-SES backgrounds scored higher than children from lower-

SES backgrounds and therefore, subsequent analyses controlled for SES. Note, however, that although the global risk factors of GA, BW, and the Medical Risk Composite Score were intercorrelated ($r_s = -.50$ to $-.63$), none were significantly related to PPVT-4 scores (all $r < .28$). In contrast, CDI vocabulary and BSID-III scores were significantly correlated with PPVT-4, accounting for 20–44% of the variance. In addition, both accuracy and RT in the LWL task were significantly correlated with PPVT-4, with RT showing a particularly strong link. Speed of language processing accounted for more than 65% of the variance (Figure 1).

We next explored patterns of relations among the predictors and PPVT-4 in a series of multiple regression models, focusing on those correlates that had significant first-order relations (SES, vocabulary size, BSID-III, accuracy, RT). In all models, SES was entered first. In Table 4, the baseline model with only SES accounted for 27% of the variance in PPVT-4. Model 1 indicated that vocabulary size adds an additional 17% after controlling for SES, and together these factors accounted for nearly 45% of the variance. In Model 2, the additional contribution of the BSID-III was slightly greater than that of vocabulary, just over 20%, and SES was no longer significant. Model 3 examined the additional contribution of these two predictors taken together. Here, the model accounted for more than 50% of the variance in later receptive language; however, none of the predictors contributed significant unique variance.

The models in Table 5 assessed the predictive strength of the two processing measures from the LWL task. Due to their high collinearity and similarity of the constructs measured, accuracy and RT were evaluated as predictors in separate models. Model 4 showed that accuracy accounted for nearly 16% additional variance beyond SES and these factors together accounted for about 43% of the variance. Model 5 confirmed that RT strongly correlated with later PPVT-4, contributing close to 50% additional variance beyond SES. Together, RT and SES accounted for almost 75% of the variance in 3-year PPVT-4. Note that both SES, RT and accuracy each contributed significant unique variance.

Our final models, Models 6 and 7, explored the contributions of accuracy and RT over and above vocabulary and BSID-III, controlling for SES. In Model 6, the four predictors together accounted for nearly 60% of variance in PPVT-4 scores, although none accounted for significant unique variance. In Model 7, mean RT, the measure of online processing that reflects how efficiently children processed words in real time, accounted for over 30% additional variance beyond SES, CDI and BSID-III. Including all four factors accounted for more than 80% of the variance in 3-year receptive language skill, with RT and SES remaining the only significant predictors.

Follow-up analyses indicated that including overall general health and degree of prematurity as control variables in addition to SES did not change the general pattern of results reported in Tables 4 and 5. Most notably, adding GA, BW and the medical risk composite to Model 7 did not increase the overall model fit (Total $R^2 = 81.8\%$). In addition, RT remained a significant predictor of PPVT-4, contributing about 26.6% unique variance ($p < .001$). Interestingly, including these additional variables in the model reduced the contribution of SES such that its unique contribution was no longer statistically significant ($p = .08$). Thus, a task of real-time spoken language comprehension captured meaningful individual

differences in toddler's processing speed that were uniquely related to later receptive vocabulary, above and beyond degree of prematurity and medical risk, as well as SES, vocabulary size and overall language knowledge.

We can also note that our results were not influenced by the fact that our population contained a large number of multiple births. Follow-up analyses were conducted on two sub-samples of children, each including all of the singletons and one randomly selected twin pair. In both sub-samples, the results were strikingly similar to those from the overall analyses, with RT making a substantial unique contribution to the prediction of 3-year PPVT-4: sub-sample 1: unique $r^2 = 19.4$, $B = -.07$ (.01), $p < .0001$; sub-sample 2: unique $r^2 = 26.3\%$, $B = -.08$ (.01), $p < .001$.

Finally, we can illustrate the strong relation between speed of real-time language processing and receptive vocabulary outcomes in Figure 2. This graph plots the time course of the mean proportion looking to the target picture on distracter-initial trials at 18 months AA for children sub-grouped by PPVT-4 scores (median = 107.5). Children with higher PPVT-4 scores increased their mean proportion looking to the target picture sooner in the sentence and reached a higher mean proportion looking than children with lower PPVT-4 scores. This advantage is also reflected in mean RT. Children with higher PPVT scores were significantly faster to shift from the distracter to the target image on average ($M = 699$ ms; $SD = 99$, [CI: 649 – 745]) than those with lower PPVT-4 scores ($M = 909$; $SD = 163$ [CI: 828 – 988]), $t(28) = 4.3$, $p < .001$, $\eta_p^2 = .39$.

Discussion

In this prospective longitudinal study, we examined the predictive validity of early language processing efficiency in relation to preschool receptive vocabulary in preterm infants. Language processing efficiency at 18 months AA not only strongly predicted receptive vocabulary at 3 years when considered in isolation, but also captured variation beyond that attributable to SES, vocabulary size, the BSID-III language scale, and medical factors. Those infants who were faster and more accurate in real-time language processing were those who also scored higher in receptive vocabulary at 3 years, with RT adding more than 30% additional variance over knowledge-based assessments. When processing speed, BSID-III, and vocabulary size were all considered together, in addition to SES, the full model accounted for nearly 80% of the variance in later scores and processing speed and SES remained the only significant predictor. This finding indicates that processing speed not only accounts for, but also adds to, the continuities between traditional tests of vocabulary knowledge and later outcomes in this population.

These results support our hypothesis that experimental measures of early neuropsychological processes known to support learning in full-term children are also strongly predictive of later receptive vocabulary outcomes in children born preterm. Measures of early neuropsychological processing tap into aspects of language proficiency critical to building a functioning linguistic system, such as processing speed, attention, and working memory. Our results showed that those preterm children who can more quickly orient to the correct referent in response to familiar words are those who are more efficient at linking information

in the speech signal to the appropriate picture. Such effects support earlier findings that processing speed is a particularly vulnerable aspect of information processing in preterm adolescents (Lee et al., 2011). Such results also parallel continuities between early information processing and later outcomes using different experimental measures (Rose et al., 2009; Shafto et al., 2012). These results are also consistent with studies of full-term children showing that speed of information processing is a foundational skill that has cascading effects on language and cognitive outcomes (Fernald et al., 2006; Marchman & Fernald, 2008). As in studies with at-risk full-term children (Fernald & Marchman, 2012), the early identification of continuities between early processing skill and later receptive vocabulary outcomes in this preterm population suggests that variation in early processing speed may be a marker of continued risk beyond global health and early knowledge-based measures.

Why are some preterm children more efficient at online language processing than others? One possibility is that processing speed is related to degree of prematurity and relatedly, may be at risk in children who experience more medical complications. In this study, health factors such as BW and GA, as well as a composite score of medical risk, were not related to later receptive vocabulary. Relations were nevertheless in the expected direction, so it is possible that continuities would be significant in a larger or more medically at risk sample of preterm children. A more likely explanation is that early processing efficiency is linked to features of children's developing brain structure and functioning. An increasing body of literature has found that the white matter of the brain is vulnerable to complications of preterm birth (Back & Miller, 2014). White matter injury and dysmaturity are not well visualized on clinical MRI studies and therefore may not necessarily have been detected on the MRI scans obtained near the time of hospital discharge. White matter injury is best detected with diffusion MRI, which these children unfortunately did not have as part of their clinical protocol.

Another possible explanation for the variability in outcomes is that some children born preterm experience a more supportive language learning environment than others. Substantial individual differences in caregivers' speech to children born preterm are evident early in life (Caskey, Stephens, Tucker & Vohr, 2011). As in full-term children, those children born preterm who experience more child-directed speech would have more opportunities to tune up early processing skills that are critical for later learning (Weisleder & Fernald, 2013). The fact that SES was strongly associated with outcomes further suggests that environmental factors play a role in shaping learning in this population. These findings are consistent with other studies showing that features of children's daily experiences linked to family background are important determinants of vocabulary and other language outcomes (Dollaghan et al., 1999). Identifying which features of early language environments function to strengthen processing skills and thus support outcomes in preterm children is a topic of ongoing investigations.

While early processing efficiency was clearly the strongest predictor of later receptive vocabulary, children with better outcomes also had larger vocabulary sizes on the CDI and scored higher on the language composite of the BSID-III at 18 months CA. Each of these conventional assessments explained unique variance beyond SES, accounting altogether for

over 50% of the variance in children's later receptive language abilities. But given that measures of processing efficiency at 18 months AA significantly improved prediction over these traditional measures, it would be beneficial to explore ways to incorporate processing-based tasks into early clinical protocols (Feldman et al., 2012).

The study is not without limitations. First, the current study involved a relatively small sample of children born preterm. While the results here were quite robust and paralleled those reported in earlier studies with children born full term, ongoing data collection will allow us to directly compare these relations in preterm children to those in matched full term controls. A second limitation is that this sample included a large number of children who were twins, however, analyses indicated that our results were not different when only one of each twin pair is included in the analyses. A final limitation is that our outcome measure was limited to receptive vocabulary at 3 years. In our continuing studies, we plan to explore longer-term links between early processing speed and later outcomes utilizing comprehensive language and IQ-related assessments just prior to when the children are entering school.

In conclusion, speed of early lexical processing at 18 months is highly predictive of receptive vocabulary outcomes at age 3. Thus, differences among infants in their efficiency in interpreting language in real time are linked to differences in skills critical for building linguistic knowledge, in children born preterm as well as in full-term children. Future research that explores the neuropsychological and environmental correlates of early language processing deficits in typically developing and at-risk populations will deepen our understanding of neuropsychological mechanisms that support receptive language learning.

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Figure 1.

Scatterplot of first-order correlation between speed of lexical processing (RT) on the LWL task at 18 months AA and receptive language (PPVT-4) at 36 months ($n = 30$).

Figure 2.

Time course of spoken language comprehension at 18 months AA in preterm children with higher and lower PPVT scores at 36 months. Error bars represent 95% CI.

Table 1Descriptive statistics for sociodemographic, birth history, and medical risk ($n = 30$).

Family Demographics		<i>M (SD)</i>	range
Maternal Education (years)		16.5 (1.7)	12 – 18
HI: SES ^a		57.3 (7.7)	35 – 66
Birth History			
Birth weight (g)		1231.5 (263.8)	710 – 1660
Gestational age (weeks)		29.4 (1.8)	26.3 – 32.7
		% (n)	
Twin		53.3 (16)	
Medical Risk Composite ^b (11 max.)		% (n)	
1. Hearing Loss		0.0 (0)	
2. Seizure Disorder		0.0 (0)	
3. Small for gestational age: Birth weight < 10 th percentile		6.7 (2)	
4. Periventricular Leukomalacia: Injury to the white matter around the ventricles in the brain		6.7 (2)	
5. Necrotizing Enterocolitis: Injury to intestines		13.3 (4)	
6. Intraventricular Hemorrhage		16.7 (5)	
<i>Grade I-II</i>		80.0 (4)	
<i>Grade III-IV</i>		20.0 (1)	
7. Bronchopulmonary Dysplasia: Oxygen requirement at 28 days of life		36.7 (11)	
8. Patent Ductus Arteriosus: Persistent abnormal circulation through heart and major blood vessels		36.7 (11)	
9. Retinopathy of Prematurity: Injury to the retina of the eye		43.3 (13)	
10. Respiratory Distress Syndrome: Breathing problems due to immature lung development		76.7 (23)	
11. Hyperbilirubinemia: Jaundice:		86.7 (26)	
		<i>M (SD)</i>	range ^b
		3.2 (1.8)	0 – 7

^aHollingshead Four Factor Index of Socioeconomic Status (HI, Hollingshead, 1975; range = 8–66).^bComposite score based on presence/absence of 11 conditions derived from inspection of discharge notes.

Table 2Descriptives (*M*, *SD*, range) for measures at 18 months AA and 36 months (*n* = 30)

18 months CA	M (SD)	range
CDI: Vocabulary Size ^a		
Raw	61.2 (71.9)	0 – 330
Percentile	28.6 (28.7)	0 – 97
LWL: Online Language Processing		
Accuracy ^b	0.61 (.12)	0.29 – 0.81
Reaction Time (ms) ^c	804.0 (170.4)	531 – 1159
BSID-III: Language composite ^d	98.6 (12.5)	68 – 127
36 months		
PPVT-4: Receptive Vocabulary ^e		
Raw score	49.6 (23.3)	5 – 111
Standard Score (Unadjusted)	104.9 (20.5)	61 – 154
Standard Score (Adjusted)	109.1 (20.7)	65 – 158

^aReported number of words produced on the MacArthur-Bates CDI: Words & Gestures;^bMean proportion looking to target on all distracter- and target-initial trials, computed from 300 to 1800 ms from target noun onset;^cMean latency to shift to target picture on distracter-initial trials, including only shifts that occurred between 300 to 1800 ms from target noun onset;^dStandard scores on a composite of the Expressive and Receptive subscales of the BSID-III (Bayley, 2005);^eRaw scores on the Peabody Picture Vocabulary Test (PPVT-4) (Dunn & Dunn, 2007) at 36 months, and standard scores both unadjusted and adjusted for degree of prematurity.

Table 3

First order correlations among all variables.

	1.	2.	3.	4.	5.	6.	7.	8.
1. PPVT-4: Receptive Vocabulary ^a	-							
2. HI: SES ^b	0.52**	-						
3. Gestational Age (weeks)	0.25	0.36	-					
4. Birth Weight (g)	0.08	0.22	0.85***	-				
5. Medical Risk Composite ^c	-0.28	-0.19	-0.63***	-0.50**	-			
6. CDI: Vocabulary Size ^d	0.44*	0.04	0.16	0.08	0.06	-		
7. BSID-III: Language Composite ^e	0.67***	0.56**	0.32	0.11	-0.22	0.57**	-	
8. LWL: Accuracy ^f	0.57**	0.39*	0.17	0.08	-0.30	0.15	0.55**	-
9. LWL: Reaction Time (RT) ^g	-0.81***	-0.31	-0.08	0.01	0.31	-0.23	-0.46*	0.71***

* $p < .05$,** $p < .01$,*** $p < .001$ ^aStandard score on the Peabody Picture Vocabulary Test (PPVT-4) at 36 mos (Dunn & Dunn, 2007).^bHollingshead Four-Factor Index of Socioeconomic Status (HI, Hollingshead, 1975).^cComposite of 11 medical risk factors listed in Table 2.^dReported number of words produced on the MacArthur-Bates CDI at 18 months AA.^eStandard scores on the Expressive and Receptive composite of the BSID-III (Bayley, 2005) at 18 months AA.^fMean proportion looking to the correct target picture in the LWL task (accuracy), computed from 300 to 1800 ms from target noun onset, averaged across all distracter- and target-initial trials, at 18 months AA.^gMean latency to shift (RT in ms) from distracter to target picture on the LWL task, including only shifts that occurred between 300 to 1800 ms from target noun onset at 18 months AA.

Table 4

Multiple regression models predicting receptive vocabulary (PPVT-4) at 36 months from 18 months AA demographic and language measures. Unstandardized B (SE).

	Baseline	Model 1	Model 2	Model 3
HI: SES ^a	1.37 (0.42) **	1.32 (0.38) **	0.56 (0.44)	0.77 (0.48)
CDI: Vocabulary Size ^b	-	0.12 (0.04) **	-	0.06 (0.05)
BSID-III: Language Composite ^c	-	-	0.90 (0.27) **	0.64 (0.36)
r^2 -change		17.4% **	20.9% **	23.2% **
Total R^2	27.0% **	44.4% ***	48.0% ***	50.3% ***

Note:

**
 $p < .01$,

 $p < .001$;

r^2 change for Models 1–3 in reference to Baseline.

^aHollingshead Four-Factor Index of Socioeconomic Status (HI, Hollingshead, 1975);

^bReported words produced on the MacArthur-Bates CDI: Words & Gestures at 18 months AA;

^cStandard scores on the language composite (Expressive and Receptive subscales) of the BSID-III (Bayley, 2005).

Table 5

Multiple regression models predicting receptive vocabulary (PPVT) at 36 months from

	Model 4	Model 5	Model 6	Model 7
HI: SES ^a	0.92 (0.42) *	0.78 (0.27) **	0.75 (0.46)	0.66 (0.30) *
CDI: Vocabulary Size ^b	-	-	0.08 (0.05)	0.06 (0.03)
BSID-III: Language Composite ^c	-	-	0.29 (0.39)	0.19 (0.24)
LWL: Accuracy ^d	74.40 (27.13) *	-	54.80 (27.73)	-
LWL: RT ^e	-	-0.09 (0.01) ***	-	-0.08 (0.01) ***
r^2 change	15.9% *	46.7% ***	6.7%	31.1% ***
Total R^2	42.9% **	73.7% ***	57.0% ***	81.4% ***

Note:

* $p < .05$,** $p < .01$,*** $p < .001$; r^2 change for Models 4 and 5 are in reference to Baseline model (Table 4); r^2 -change for Models 7 and 8 are in reference to Model 3 (Table 4).^a Hollingshead Four-factor Index of Socioeconomic Status (HI, Hollingshead, 1975).^b Reported number of words produced on the MacArthur-Bates CDI: Words & Gestures.^c Standard scores on the Expressive and Receptive subscales of the BSID-III (Bayley, 2005). 18 months AA demographic, language and processing measures. Unstandardized B (SE).^d Mean proportion looking to target in the looking-while-listening (LWL) task, computed from 300 to 1800 ms from target noun onset and averaged across all distracter- and target-initial trials.^e Mean latency to shift (RT) from distracter to target picture on the LWL task, including only shifts that occurred between 300 to 1800 ms from target noun onset.