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Visual and Haptic Responses as Measures of Word Comprehension and Speed of Processing in Toddlers: Relative Predictive Utility

Erin Smolak[1,6], **Kristi Hendrickson**[2], **Pascal Zesiger**[3], **Diane Poulin-Dubois**[4], **Margaret Friend**[5]

[1]San Diego State University, 5500 Campanile Dr, San Diego, CA 92182; and University of California San Diego, 9500 Gilman Dr, La Jolla, CA 92093

[2]University of Iowa, 19 WJSHC, Iowa City, IA 52242

[3]University of Geneva, Switzerland, 1211, Geneva, rue du Général-Dufour, 24

[4]Concordia University, 1455 Boulevard de Maisonneuve O, Montréal, QC H3G 1M8, Canada

[5]San Diego State University, 5500 Campanile Dr, San Diego, CA 92182

[6]Present Address: Boys Town National Research Hospital, 555 North 30th St., Omaha, NE 68131

Abstract

Early vocabulary knowledge and speed of word processing are important foundational skills for the development of preschool and school age language and cognition. However, the variance in outcomes accounted for by parent-reported receptive or expressive vocabulary is generally modest. Recent research suggests that directly assessed, decontextualized vocabulary predicts developmental outcomes including general language ability and kindergarten readiness, accounting for additional variance above and beyond parent-reported vocabulary. The current research extends this finding by exploring prediction from both decontextualized vocabulary and speed of word processing at two years of age to vocabulary in the preschool period. At age two, children completed a two-alternative forced choice task, which yielded a measure of decontextualized vocabulary (number of correct touch responses) and two measures of speed of processing: latency to fixate the target (visual response latency) and latency to touch (haptic response latency). Results reveal that age-two vocabulary and visual response latency, but not haptic response latency, independently predict vocabulary at three and four years of age. Further, only decontextualized vocabulary remains a significant predictor when controlling for speed of processing, but not vice versa. This suggests that the number of early, stable word-referent associations and the efficiency with which these are processed are important to vocabulary

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Corresponding Author: Erin Smolak, Ph.D., Address: 555 North 30th St., Omaha, NE 68131, Erin.Smolak@boystown.org.

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outcomes. However, it also suggests that decontextualized vocabulary may be a more robust, unique predictor of downstream outcomes.

Keywords

language development; vocabulary; speed of word processing; early childhood development

Toddlers learn many words per month and become increasingly efficient at processing them (DeAnda, Hendrickson, Zesiger, Poulin-Dubois, & Friend, 2018; Fenson et al., 1994; Fernald, Perfors, & Marchman, 2006; Legacy, Zesiger, Friend, & Poulin-Dubois, 2018). Research over the past decade indicates that vocabulary and speed of word processing are related and that each predicts language and cognitive development in later childhood (Duff, Reen, Plunkett, & Nation, 2015; Fernald & Marchman, 2012; Fernald et al., 2006; Friend, Smolak, Liu, Poulin-Dubois, & Zesiger, 2018; Friend, Smolak, Patrucco-Nanchen, Poulin-Dubois, & Zesiger, 2019; Marchman & Fernald, 2008). Describing the co-development of vocabulary and speed of processing is critical to better characterizing the early lexical-semantic system and predicting language and cognitive outcomes. The current study addresses this objective by examining differential prediction across vocabulary and speed of processing.

Vocabulary and Speed of Word Processing

By 6 to 8 months of age, infants comprehend a few commonly encountered words (Bergelson & Swingley, 2012; 2015; Fenson et al., 1994; Tincoff & Jusczyk, 1999, 2012). However, early word comprehension ranges from fragile or context-bound to stable and decontextualized (Bion, Borovsky, & Fernald, 2013; Hendrickson, Mitsven, Poulin-Dubois, Zesiger, & Friend, 2015; Hendrickson, Poulin-Dubois, Zesiger & Friend, 2017). For example, early-acquired words may be restricted to a subset of referents (analogous to underextension errors in production) and subject to interference such that children do not exhibit a reliable understanding of their meanings (Bion et al., 2013; Friedrich & Friederici, 2011; Harris, Yeeles, Chasin, & Oakley, 1995). These word-referent pairs are likely to become stable and decontextualized over time. Decontextualized words are understood and used outside of the context in which they were learned (e.g., Bates, Benigni, Bretherton, Camaioni, & Volterra, 1979). It is likely that infants possess both decontextualized and context-bound words in their repertoires. For instance, Bergelson and Swingley (2012; 2015) report that young infants do have decontextualized representations of some frequently encountered words (see also Tincoff & Jusczyk, 2012). However, they do not show comprehension reliably without additional cues to word identity (Kartushina & Mayor, 2019).

The speed with which children process familiar word meanings also improves over the first two years (Fernald et al., 2006; Fernald, Pinto, & Swingley, 1998; Legacy et al., 2018). At 15 months, children process known words within several hundred milliseconds of presentation (Fernald et al., 2006). By age two, recognition is significantly faster and hearing the initial phoneme of a word is sufficient for children to recognize its referent (Fernald et al., 1998; Fernald, Swingley, & Pinto, 2001).

Vocabulary knowledge and speed of processing are associated over this period such that children who know more words process word meaning more efficiently (DeAnda et al., 2018; Fernald & Marchman, 2012; Fernald et al., 2006; Legacy et al., 2018; Peter et al., 2019; cf. Legacy, Zesiger, Friend, & Poulin-Dubois, 2016). Additionally, speed of processing is facilitated for words in dense, relative to sparse, semantic networks (Borovsky, Ellis, Evans, & Elman, 2016). This suggests that processing efficiency varies with vocabulary size and network structure. However, there is heterogeneity in these results. For example, Fernald and colleagues (2006) assessed speed of processing and parent-reported vocabulary at 15, 18, 21, and 25 months of age. Speed was associated concurrently with vocabulary at 15 and 25 months, but not at the other time points. However, speed at 25 months was significantly associated with point-estimates and growth and acceleration in vocabulary across 12 to 25 months of age. Similarly, Peter and colleagues assessed vocabulary at monthly or bi-monthly intervals between 8 and 37 months of age and speed of processing at 19, 25, and 31 months. Speed at 19 months was associated with vocabulary from 18 to 31 months and at 36 months, but not at other time points. Children with faster speed of processing at 19 months had larger vocabularies on average from 19 to 30 months, and their vocabulary accelerated more quickly from 19 to 25 months, although speed did not predict linear growth over this period. To sum, speed of processing and vocabulary are generally related but there is heterogeneity depending on child age and whether the measure of vocabulary is a point estimate or growth over time.

Additionally, vocabulary and speed of processing are not equivalent: simulations suggest that speed of processing is an emergent property derived from multiple component processes. Specifically, McMurray and colleagues (2012) constructed a dynamic associative model of referent selection in a two-alternative forced choice task. They concluded that processing speed is determined by experience and knowledge but also by parameters such as activation level and rate (higher levels promote processing speed) and competition from other known lexical items (more lexical competition slows processing speed) (McMurray, Horst, & Samuelson, 2012). These parameters correspond roughly to domain-general processing speed and learning rate, and lexical competition in humans.

Although only a handful of approaches assess lexical-semantics prior to 30 months of age, each taps the structure of this system somewhat differently (DeAnda et al., 2018; Fernald et al., 2006; Fernald et al., 1998; Friend & Keplinger, 2003; 2008; Friend, Schmitt & Simpson, 2012; Hendrickson et al., 2015; Legacy et al., 2016). For example, vocabulary can be measured via parent report or direct assessment, and evidence suggests direct assessment: 1) provides an estimate of decontextualized vocabulary because responses to items are made without supportive context, and 2) is a stronger predictor of downstream outcomes than is parent report (Friend et al., 2018). Speed of processing can be measured via direct assessment using either visual (i.e., fixation) or haptic (i.e., touch) responses to images. We use the term haptic to refer to an overt, reaching response that culminates in a point or touch (as opposed to haptic perception). These different assessments entail varying demand characteristics and may therefore tap distinct processes in the lexical-semantic system. We review evidence in support of this idea below.

In a two-alternative forced choice task, Hendrickson and colleagues (2015; 2017) assessed online speed of word processing (latency of gaze shifts from the distractor to the target referent) and receptive vocabulary (the number of words correctly selected by haptic response) concurrently at 16 and 22 months of age. The authors found evidence that early word knowledge is graded and that visual response times may index comprehension of word meanings that vary in strength of representation. This was illustrated by behavioral dissociations across visual and haptic modalities, which are thought to reveal graded or weak knowledge (Munakata, 2001). Specifically, these modalities converged when children touched the target referent (with a quick visual fixation to the target) and when they did not touch either referent (with a slow or absent visual fixation to the target). In the first case, a correct haptic response is taken as indicative of word comprehension and quick visual fixation as indicative of efficient processing of its meaning. In the second case, an absent haptic response provides no evidence of word comprehension and slow or no visual fixation suggests its meaning was not processed efficiently (if at all). Importantly, responses diverged when children touched the distractor – they were as quick to fixate the target as when they touched the target referent even though, in this case, the haptic response was incorrect. Quick visual fixations occurred for both strong (correct touch) and weak (distractor touch) word knowledge, suggesting that visual response latency assesses efficiency of processing for word meanings across a continuum of associative strength, from fragile to stable, between words and referents.

Relatedly, variable demand characteristics across processing speed measures may lead to differential prediction of later outcomes; results on the early co-development of vocabulary and speed of processing likely reflect the types of skills implicit in their measurement. For example, infants readily integrate auditory and visual information resulting in automatic visual search (Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987). In contrast, a haptic response requires offline decision-making, and executing a controlled motoric response involves executive function abilities (Gottwald, Achermann, Marciszko, Lindskog, & Gredebäck, 2016). Haptic responses can therefore be considered relatively computationally expensive compared to visual responses. Different measures of processing speed can vary in the complex associations they have with working memory and inhibition, which can influence developmental prediction (Cepeda, Blackwell, & Munakata, 2013). Therefore, a reconsideration of the relative influence of processing speed and vocabulary taking into account multiple approaches to assessment is warranted.

The Current Study

Much of the evidence for an early relation between vocabulary, processing speed, and later outcomes comes from studies using an online, visual response measure of speed and (often) an indirect measure of receptive or expressive vocabulary. However, it is not clear how well this relation generalizes across measures. No prior work has compared prediction from processing speed and vocabulary using a direct measure of vocabulary with multiple measures of processing speed. Three findings inform the present research: 1) visual and haptic response measures tap different aspects of vocabulary comprehension and processing speed (Hendrickson et al., 2015; 2017; Munakata, 2001); 2) directly-assessed, decontextualized vocabulary at age two is a stronger predictor of some early outcomes than parent-reported vocabulary (Friend et al., 2018; 2019); and 3) online word processing differs in timescale from word learning and from the timescale of offline decision-making (McMurray et al., 2012).

The goal of the current research is to clarify the relative roles of vocabulary comprehension and two measures of processing speed (visual and haptic response latency) in the second year for predicting vocabulary in the third and fourth years. At age two, using a two-alternative forced choice task, we simultaneously estimate vocabulary (number of correct haptic responses to the target image) and processing speed using visual (latency of gaze shifts from distractor to target) and haptic (latency to touch the target) measures.

We argue that latency of visual responses estimates the efficiency of online processing of word-referent associations along a continuum of strength (Hendrickson et al., 2015; 2017). On the other hand, the latency of haptic responses estimates the speed with which relatively strong word-referent associations are processed and depends on motor control and executive attention/function (Gottwald et al., 2016). Finally, correct haptic responses yield an estimate of decontextualized vocabulary comprehension. Differences in task demands across measures are expected to influence prediction to developmental outcomes. Based on prior research and modeling evidence, we have three hypotheses.

> 1a. Consistent with Friend et al. (2018), measured vocabulary at age two will display the strongest independent prediction to downstream vocabulary at ages three and four. However, consistent with Fernald et al. (2006; Marchman and Fernald, 2008), vocabulary and processing speed combined should more strongly predict the trajectory of vocabulary acquisition.
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> 1b. It is also predicted that processing speed will significantly predict downstream vocabulary but account for less variance than early vocabulary.
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> 2. We contrast prediction from two measures of processing speed to evaluate how demand characteristics contribute to differential long-term prediction. On the one hand, visual response latency may account for additional variance beyond early vocabulary by indexing how efficiently children shift attention to lexical targets. On the other hand, haptic response latency may account for unique variance by indexing how efficiently children choose a referent in a two-alternative task. There are three possibilities: visual and haptic latency will yield similar patterns of prediction, visual latency will be superior to haptic latency, or haptic latency will be superior to visual latency in predicting downstream development. Of these, we expect that haptic latency will have greater predictive power since it is a more conservative measure of speed to process decontextualized word comprehension.
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> 3. Finally, vocabulary and speed of processing are related but dissociable: the variance that they account for in developmental prediction does not fully overlap. Although children with large vocabularies are likely to process word meanings more efficiently and vice versa, it may be the case that some children have larger vocabularies but relatively inefficient language processing, or efficient processing but relatively smaller vocabularies. If vocabulary acquisition in the preschool period requires strength both in early vocabulary and processing, both should predict later

vocabulary. If, on the other hand, strength in one skill can compensate for weakness in the other, vocabulary and processing speed at age two may exercise compensatory effects on acquisition at ages three and four. This is an exploratory, tertiary goal of the present study.

Methods

Participants

Forty-one English-speaking monolingual toddlers were tested as part of a larger, multi-institutional project. Participants were recruited via birth records, WIC centers, and parent expos in a large metropolitan city to match as closely as possible the demographics of the county. See Table 1 for demographic results on the full sample. Children were typically developing with normal hearing and vision. There were five waves of data collection of which three are reported here: at roughly two (*M* = 22;28 months, *range* = 21;6 to 25;12), three (*M* = 37;23 months, *range* = 35;6 to 41;24), and four years of age (*M* = 50;0 months, *range* = 47;15 to 53;3). We conducted an a priori power analysis using G*Power (Faul, Erdfelder, Buchner, & Lang, 2009) for a linear multiple regression fixed model, estimating effect sizes (increase in R^2) based on Marchman and Fernald (2008). Data from Marchman and Fernald (2008) suggest an increase in R^2 for the regression model predicting age-eight expressive language of .17 and .16 for vocabulary and speed of processing, respectively. The present sample was sufficient to achieve power greater than .80 for detecting the effect of one predictor, and greater than .70 for detecting the effect of two predictors in combination.

Thirty-eight additional children were tested but excluded due to fussiness (*N*=3), missing data on one or more predictor variables due to poor video quality (*N* = 3), missing the age-two visit (*N*=8), becoming bilingual (*N*=1), or attrition at later waves (*N*=23). Attrition over the two-year period for the current study was 29 percent. Much of this attrition is due to the fact the study was conducted in an area in which it is common for young families to move out of state after a year or two. This level of attrition is within the range (13–35%) reported for other longitudinal studies of children in a similar age range (Ghassabian et al., 2014; Lee, 2011; Peter et al., 2019). A series of independent t-tests revealed no significant differences in demographic variables (maternal education, age at first visit) or performance on predictor variables for children who remained in the study compared to children who did not (all *p*s > .10).

Measures

Language Exposure Assessment Tool (LEAT).—Relative exposure to English was assessed via the Language Exposure Assessment Tool (DeAnda, Bosch, Poulin-Dubois, Zesiger, & Friend, 2016). The LEAT is an intensive interview with caregivers that gathers information on each individual who regularly interacts with the child (i.e., at least once per week), the languages they speak, and the number of hours the child is exposed to each language per day. This yields an estimate of relative exposure to each language. LEAT percent relative exposure significantly predicts relative receptive vocabulary in bilingual toddlers, indicating high criterion validity. The criterion for inclusion in the English monolingual sample was relative exposure to English at 80% or greater.

Computerized Comprehension Task.—The Computerized Comprehension Task (CCT; Friend & Keplinger, 2003; 2008; downloaded from https://childes.talkbank.org/) is an experimenter-controlled, two-alternative forced choice assessment of early, decontextualized receptive vocabulary administered on a touch-sensitive screen. Administration followed the published protocol (Friend et al., 2012). Toddlers were seated on their caregiver's lap centered at approximately 30 cm from the monitor. Parents wore blackout glasses and noise-cancelling headphones to reduce the potential for parental interference during the task. The experimenter was seated to the side of the dyad and administered verbal prompts to the toddler to instantiate joint attention within trials. Finally, a camera positioned above the monitor (directed toward the child's face) recorded the child's visual responses and another camera positioned above the setup recorded touch responses. See Appendix A (Figure A1) for an illustration of this setup. On each trial, two images (e.g., a dog and a bird) appeared simultaneously to the right and left of center screen and the experimenter prompted the toddler to touch the target referent (e.g., "Where's the dog? Touch dog!"). The side on which the target appeared was pseudo-randomized across trials: targets could not appear on the same side on more than two consecutive trials and were presented with equal frequency at left- and right-screen. A target touch (i.e., to the dog) yielded congruous auditory feedback (e.g., the sound of a dog barking) whereas a distractor touch (i.e., to the bird) yielded no feedback. The CCT consists of 4 training trials, 41 test trials, and 13 reliability trials. Words included in the CCT were obtained from the MacArthur-Bates Communicative Development Inventories (MCDI; Fenson, Marchman, Thal, Dale, Reznick, & Bates, 2007). In the test trials there were an approximately equal number of easy (comprehension = >66%), moderately difficult (comprehension = 33–66%), and difficult words (comprehension < 33%) based on normative data at 16 months of age from the original report of the MCDI (Frank, Braginsky, Yurovsky, & Marchman, 2016). In Appendix A (Table A1), we provide CCT item pairs with their difficulty level according to the original MCDI norms (Dale & Fenson, 1996) and current Wordbank norms (Frank et al., 2016).

During training, participants viewed four noun pairs known by at least 80% of 16-montholds (Frank et al., 2016) and were prompted to touch the target. If a participant failed to touch during training, the training trials were repeated once. All children completed training.

Each testing trial began with a plain blue screen. When the toddler's gaze was directed toward the touchscreen, the experimenter delivered the prompt in infant-directed speech (e.g., "Where is the dog? Touch dog.") and simultaneously began the trial. Target word onset occurred just prior to the image onset. The images were not present on the screen for inspection prior to the prompt, in contrast to some previous studies using visual response measures (e.g., Fernald, Zangl, Portillo, & Marchman, 2008). This procedural adjustment was implemented due to the constraints of including a touch response and a touchscreen: during pilot testing it was found that children would spontaneously touch the screen if there was a silent inspection period. Each test trial lasted until the toddler touched the screen or seven seconds elapsed. Those participants who remained quiet and alert for the full 41 test trials ($N = 40$), participated in a reliability phase in which 13 of the test trial image pairs were re-presented in opposite left-right orientation.

The CCT has moderate test-retest reliability and short-term stability across a 4-month interval (Friend & Keplinger, 2008) and strong internal consistency (Form A α =.86; Form B α =.93), converges with parent report of receptive vocabulary, and predicts subsequent language production (Friend et al., 2012). Finally, responses on the CCT are nonrandom (Friend & Keplinger, 2008; Hendrickson, et al., 2015). This finding has been replicated across languages (Friend & Zesiger, 2011). Sample-specific immediate test-retest reliability was $r(39) = .59$, $p < .001$. From this task we coded haptic responses as an estimate of vocabulary, latency of gaze shifts as a measure of visual processing speed, and touch latency as a measure of haptic processing speed. Test, but not training, trials were coded.

Coding.

Haptic Responses.: The initial haptic response was coded as correct if toddlers touched the target image (i.e., within the image boundary) and incorrect if they touched the distractor, failed to respond, or made an ambiguous touch to an area outside of the image boundary. If a toddler did not touch the screen, but pointed toward the target image, this response was coded as correct. One coder viewed video recordings of the child’s haptic responses offline using the criteria above. A second coder viewed twenty percent of the videos independently. Inter-rater agreement was 95 percent.

Processing Speed.

Visual response latency (VRL).: To code VRL, a waveform of the experimenter’s prompts was extracted from the eye-tracking video using Audacity® (http://audacity.sourceforge.net/). The waveform, eye gaze video, and touch video were synchronized using Eudico Linguistics Annotator (ELAN) (<http://tla.mpi.nl/tools/tla-tools/elan/>, Max Planck Institute for Psycholinguistics, The Language Archive, Nijmegen, The Netherlands; Lausberg & Sloetjes, 2009).

Coder one annotated the onset and offset of the target word spoken by the experimenter (e.g., in the phrase *“Where is the DOG?”)* using the waveform from the audio file and annotated the frame during which the target and distractor images appeared, the target word, and the side on which the target image appeared. Coder two, blind to target word onsets and offsets and the relative position of the target and distractor, annotated gaze fixations using the eye gaze video with no sound. Coding began at image onset (~238 ms after target word onset and prior to target word offset in the first sentence prompt). Coder two advanced the video frame by frame (40 ms) and coded each change in looking behavior using three event codes: right look, left look, and away look.

Twenty-five percent of the eye gaze videos were coded for inter-rater agreement (latencies that both coders identified within a one or two frame window were coded as agreements and these were divided by total latencies [agreements plus disagreements]), considering only frames in which a shift in fixation occurred. This score is more stringent than including all possible coding frames because agreement during sustained fixations is likely to be higher relative to gaze shifts (Fernald et al., 1998). Coders were within one frame (40 ms) for 82% of these fixation shifts and within two frames on 91% of shifts.

To assess VRL, consistent with Fernald and colleagues (1998; 2006) we included only distractor-initial trials—trials for which toddlers first fixated the distractor image. Gaze shifts from distractor to target that occurred less than 400 ms after image onset were excluded from the analyses because short latencies likely reflect eye movements planned prior to target word onset and therefore not driven by the target word (Fernald et al., 2008). The choice of cutoff point varies across eye-tracking studies (from 200 – 400 ms) depending on the age of the participants and the type of analysis to be conducted (see Fernald et al., 2008). Longer cutoffs are typically used for younger children. Thus, consistent with this work and with prior studies using these data (Hendrickson et al., 2015; 2017), we chose 400 ms as the lower cutoff. We note that Swingley & Aslin (2000) report no difference in results for cutoffs anywhere from 200 to 400 ms. Similarly, because responses further from stimulus onset are less likely to be driven by stimulus parameters (Aslin, 2007; Fernald et al., 2006; Swingley & Fernald, 2002), gaze shifts were coded only during the first 2000 ms of each trial. This upper cutoff restricts our analysis to the period prior to the decision to touch and avoids a dependency between looking and touching: only 4 children (out of 41) had a mean haptic response latency that was less than 2000 ms. The dependent variable of interest is processing speed operationalized as the latency of a gaze shift from distractor to target for those trials on which a toddler first fixated the distractor image. We included all trials in the analysis regardless of whether the haptic response was correct or whether parents reported the child knew the word. We did this for two reasons: 1) it reduces the amount of data that is excluded per child, decreasing variability, and 2) it is consistent with our interest in obtaining a measure of processing efficiency for word-referent pairings along a continuum of strength (regardless of the correctness of the haptic response). In the current study, latency for words reported as known was very similar to latency for the entire set of words (M = 747.32, SD = 96.29 and M = 718.4, SD = 162.10, respectively).

Haptic response latency (HRL).: Similar to the coding for VRL, a waveform of the experimenter’s prompts was extracted and synchronized to the video of children’s haptic responses using ELAN. We coded target word onset, the target and distractor image onset, and the frame in which a touch was executed (touch onset). Only touches (not points) to the target were included. Because trials with short latencies likely reflect the execution of a response planned prior to the onset of the target word, trial latencies less than 400 ms were excluded from analyses consistent with cutoffs typically used in eye-tracking studies (Fernald, et al., 2008; DeAnda et al., 2018). Additionally, each child’s distribution of RT latencies was examined for outliers, as removal of outliers is common in RT studies to reduce the effect of uncharacteristically quick or slow responses (e.g., Kail, 1991; Montgomery 2008). For each child, trials with a latency +/− 3 SD from that child’s mean latency were excluded as outliers. This resulted in the removal of a total of 15 trials, or 1.3 percent. Results were equivalent whether we used the original latency variable or the variable with outliers excluded; we report results from the modified latency variable.

Coding for HRL began at image onset. Touch onset was coded as the frame in which the child’s finger touched the screen (when forward mobility ceased and the finger contacted the screen). Inter-rater agreement was established for 20% of the data for target word onset and offset and touch onset. Agreement was calculated as percent of latencies coded within a three frame window across two coders, corrected for latencies that fell outside of this window and was at least .90 for each measure (DeAnda et al., 2018).

Peabody Picture Vocabulary Test-III (PPVT-III).—At three and four years of age, we administered the PPVT (Dunn & Dunn, 1997), a measure of decontextualized receptive vocabulary for individuals 30 months of age through adulthood. The PPVT consists of four-alternative forced choice trials. The child is prompted to touch the picture corresponding to the target word. The PPVT is adaptive, such that children are tested until they miss 8 or more of 12 words in a given set. Internal consistency of the PPVT ranges from α=.92 to α=.98 over 25 standardization groups at differing ages and test-retest reliability coefficients are high (above .90).

Procedure

Before each visit, caregivers completed an interview using the LEAT (DeAnda et al., 2016) to estimate language exposure across waves. All participants were exposed to English at least 89 percent of the time from birth and were functionally monolingual. Caregivers provided informed consent at each visit. Each visit began with a detailed demographic questionnaire. At 22 months, children completed the CCT. At three and four years, children completed the PPVT as part of a battery of language and cognitive measures. At the end of each visit, families were compensated with a 25 dollar gift card to a retail store and children received an age appropriate gift.

Results

Descriptive Statistics and Zero-Order Correlations

All data and code for analyses will be shared on the open science framework (OSF; https://osf.io) under the title of this manuscript following publication of two manuscripts currently in review. See Table 2 for descriptive statistics and zero-order correlations for all variables of interest as well as 95% confidence intervals for correlation coefficients and t-test coefficients. All variables were approximately normally distributed. The mean and range for VRL and HRL are comparable to previous reports at this age (DeAnda et al., 2018; Fernald et al., 2006; Hendrickson et al., 2017; Marchman & Fernald, 2008).

We first evaluated zero-order correlations between variables of interest to characterize the significance of these relations prior to constructing our models. We corrected for multiple comparisons using the Benjamini and Hochberg approach, which controls the false discovery rate (Benjamini & Hochberg, 1995). We first evaluated the effect of potential control variables (age at each wave, maternal education, and biological sex). Age was not significantly correlated with any variable at any wave. Maternal education was significantly correlated with CCT vocabulary ($r(39) = .34$, $p = .03$) though not after correcting for multiple comparisons and was not associated with any other variable. There was a significant effect of sex on HRL ($t(23.05)=-2.31$, $p = .03$) that was not significant after controlling for multiple comparisons, indicating that boys responded more slowly than girls. It was not associated with any other variable. We nevertheless included sex and maternal education as controls to ensure that we captured demographic variance in our variables of interest as both have been shown to be significant predictors of language measures in larger studies (e.g., Reilly et al., 2010).

We next investigated correlations between predictors of interest and outcomes. We expected negative correlations between VRL/HRL and CCT Vocabulary/PPVT Vocabulary. A negative correlation would indicate that children with larger vocabularies respond more quickly relative to children with smaller vocabularies. CCT vocabulary was significantly correlated concurrently with VRL but not with HRL, although this correlation was in the expected direction. VRL and HRL were not significantly correlated after correcting for multiple comparisons. Both CCT vocabulary and VRL, but not HRL, were significantly correlated with PPVT vocabulary at ages three and four (although the association between VRL and PPVT vocabulary at age four was not significant after correcting for multiple comparisons). See Appendix B for data visualizations of the distributions and correlations of the predictor and outcome variables of interest.

Planned Analyses: Prediction to Vocabulary Outcomes

We performed a series of linear regressions using R (R Core Team, 2020) in RStudio (RStudio Team, 2016) using the lm() function in the base stats package to examine relations between vocabulary comprehension and processing speed at age two and vocabulary comprehension at ages three and four. For transparency, the R session information output is included in Appendix C. At each age, a full model was constructed with maternal education and sex as controls and CCT vocabulary, HRL, and VRL as predictors. Several reduced models were also constructed: an intercept only model, a model with control variables only, and models with predictors of interest added alone and in combination. This approach was taken in order to evaluate the effect of each predictor on its own and when controlling for the effects of the other predictors. First, we compared these models in order to determine the best fitting, most parsimonious model of prediction to PPVT vocabulary at ages three and four. We used Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), estimates of model fit that penalize for the addition of parameters: lower values indicate better fit. Given our sample size, a conservative estimate that a model is a better fit is when AIC and BIC values are 10 less than the competing model (Hilbe, 2011). Nested models were also compared using chi-squared Likelihood Ratio (LR) tests. In the case of disagreement between AIC, BIC, and LR test results we interpret best model fit on the basis of the LR test. Second, we present standardized parameter estimates along with standard errors for models with best fit to characterize effect size. Standardized regression coefficients were calculated using the lm.beta package (Behrendt, 2014).

In the models predicting PPVT vocabulary at age three, child sex and maternal education did not result in better fit than the base model ($F(2, 38) = .78$, $p = .47$, ΔAIC = 2.35, ΔBIC = 5.78) but were nevertheless retained as control variables in subsequent models. The addition of CCT vocabulary to the control variables improved fit according to all three metrics (AIC, BIC, and the LR test). The addition of VRL to the control variables improved fit according to the LR test but not AIC/BIC values. In contrast to our hypothesis, the addition of HRL to the control variables did not improve fit by any metric. See Table 3 for model comparisons including LR and AIC/BIC values. We did not further consider the effect of HRL. We turn next to models with combinations of the predictors that independently resulted in better model fit. First, adding CCT vocabulary to the model with VRL and control variables improved fit according to the LR test but not according to AIC/BIC values. In contrast, adding VRL to the model with CCT vocabulary and control variables did not improve fit by any metric. See Table 3.

From the model comparisons, we concluded that three models provided good fit for prediction to PPVT vocabulary at age three: control variables + CCT vocabulary; control variables + VRL; and control variables + CCT vocabulary + VRL. Standardized parameters for these models are presented in Table 4. Observed power was .96 for the CCT vocabulary model and .87 for the VRL model. Table 4 provides estimates of effect size for CCT vocabulary and VRL and confirms the results of the model comparisons: although both age-two vocabulary and visual processing speed independently predicted vocabulary at age three, only early vocabulary accounted for significant unique variance. Please see Figure B5 in Appendix B for visualizations of the unique effects of CCT vocabulary and VRL on PPVT vocabulary at age 3 using estimates from the control variables + CCT vocabulary + VRL model.

In the models predicting PPVT vocabulary at age four, child sex and maternal education did not result in better fit than the base model ($F(1, 38) = 1.34$, $p = .27$, $\Delta\text{AIC} = 1.19$, $\Delta\text{BIC} = 4.62$) but were nevertheless retained as control variables in subsequent analyses. The addition of CCT vocabulary to the model with control variables improved model fit according to the LR test only (recall that, in the case of a conflict, we interpret findings in terms of the LR test). The same pattern of results was obtained for the addition of VRL to the model with control variables. In contrast, the addition of HRL to the model with control variables did not improve fit by any metric. See Table 5. The effect of HRL was not considered further. Models with combinations of the predictors of interest revealed that adding CCT vocabulary to the model with control variables and VRL improved fit according to the LR test but not according to AIC/BIC values. In contrast, adding VRL to the model with control variables and CCT vocabulary did not improve fit by any metric. See Table 5.

We concluded that three models provided a good fit for prediction to PPVT vocabulary at age four: control variables + CCT vocabulary; control variables + VRL; and control variables + CCT vocabulary + VRL. The standardized parameters for these models are presented in Table 6. Results confirm the findings from the model comparisons: similar to the results at age three, although both age-two CCT vocabulary and visual processing speed independently predicted vocabulary at age four, only early vocabulary accounted for significant unique variance. Observed power was .96 for the CCT vocabulary model and .87 for the VRL model. Please see Figure B5 in Appendix B for visualizations of the unique effects of CCT vocabulary and VRL on PPVT vocabulary at age 4 using estimates from the control variables + CCT vocabulary + VRL model.

Exploratory Analyses: Median Splits

Following Marchman and Fernald (2008), we were interested in whether children who fall in the lower end of the distribution of CCT vocabulary and processing speed at age two show slower vocabulary growth compared to children with a larger vocabulary and more efficient processing. We were also interested in children who fall in intermediate categories: those who have a larger vocabulary and less efficient processing at two years or vice versa. Linear regression analyses suggest that children with larger vocabularies who process word meanings more quickly at age two have larger vocabularies at ages three and four, with CCT vocabulary predicting unique variance above and beyond processing speed. However, vocabulary and processing speed do not completely overlap. It is possible that strength in *either* receptive vocabulary or processing speed bolsters performance relative to children who are weak in *both*. Because VRL, but not HRL, significantly predicted later vocabulary, we assess median split results only for early vocabulary and VRL.

Children were placed into four groups: Low Vocabulary, Slow VRL ($N = 14$); Low Vocabulary, Fast VRL ($N = 10$); High Vocabulary, Slow VRL ($N = 7$); and High Vocabulary, Fast VRL ($N = 10$). See Figure 1 for univariate scatterplots of non-independent data (following templates from Weissgerber, Milic, Winham, & Garovic, 2015) of PPVT vocabulary by group. Given the small sample in each category, planned comparisons were conducted using non-parametric Mann-Whitney U tests. Non-parametric tests do not make distributional assumptions and are therefore preferred for analyses using small samples. We supplemented the Mann-Whitney U tests with Bayesian independent sample Mann-Whitney t-tests using Jeffreys's Amazing Statistics Program (JASP Team, 2020) with 1,000 samples. In the Bayesian analyses, we compared the alternative (Group 1 ≠ Group 2) to the null hypothesis (Group 1 = Group 2). We report results in terms of the Bayes factor (B_{10}), the Bayes effect size (δ, population version of Cohen's d), and the 95% confidence interval of the effect size. For the Bayes factor, values greater than 1 indicate support for the alternative hypothesis, with values between 1 and 3 indicating anecdotal support, and values between 3 and 10 indicating moderate support (Jeffreys, 1961). Bayes factor values less than 1 provide support for the null, with values between .33 and 1 indicating anecdotal support, and values between .10 and .33 indicating moderate support. In contrast, values around 1 indicate similar amount of evidence for the alternative and the null.

Of interest was whether strength in *either* CCT vocabulary or VRL boosted later vocabulary performance. We compared the lower vocabulary/slower VRL group to all other groups. As expected, the High Vocabulary/Fast VRL group outperformed the Low Vocabulary/Slow VRL group at age three ($U = 17.5$, $p = .001$; $B_{10} = 5.25$; $\delta = -.93$ [−1.84, −.11]) and age four ($U = 24$, $p = .004$; $B_{10} = 4.01$; $\delta = -.85$ [−1.74, −.04]). Further, children with lower vocabulary but faster VRL outperformed children with lower vocabulary and slower VRL in vocabulary at age three, although the 95% confidence interval of the effect size did include 0 ($U = 39.5$, $p = .03$; $B_{10} = 1.23$; $\delta = -.57$ [−1.39, .17]). This was not the case at age four ($U = 48$, $p = .07$; $B_{10} = .92$; $\delta = -.50$ [−1.33, .20]). Additionally, both Bayes factor values were close to 1, which does not indicate support for group differences. Finally, children with slower VRL but higher vocabulary outperformed children with slower VRL and lower vocabulary at age three ($U = 23$, $p = .04$; $B_{10} = 1.04$; $\delta = -.55$ [−1.53, .22]) and four and ($U = 18$, $p = .01$; $B_{10} = 1.79$; $\delta = -.70$ [−1.70, .10]). Again, the 95% confidence intervals of the effect size included 0 and the Bayes factor value for age three was close to 1. The results of the Mann-Whitney U t-tests and the Bayesian analyses largely agreed, suggesting that either larger vocabulary or faster VRL at age two predicts age three vocabulary but vocabulary is the stronger predictor by age four. However, although the Bayes factors were above 1, the evidence in support of this conclusion is rather weak and requires replication with larger sample sizes.

Discussion

The current work follows from two lines of evidence. First, early, decontextualized vocabulary is a relatively stronger predictor of outcomes than is parent reported vocabulary (Friend et al., 2018; 2019). Second, early processing efficiency predicts language and cognitive development up to age eight above and beyond parent reported vocabulary alone (Fernald et al., 2006; Marchman & Fernald, 2008). The present study extends these findings by contrasting a direct measure of early vocabulary with two measures of processing speed as predictors of vocabulary at ages three and four. Across the analyses reported, decontextualized vocabulary at age two accounted for unique variance in vocabulary at ages three and four beyond that accounted for by either visual or haptic processing speed.

Predicting Downstream Vocabulary

Both vocabulary and visual processing speed at age two independently predicted vocabulary at age three. However, haptic processing speed was not significant in any model. When vocabulary and visual processing speed were considered in combination, only vocabulary accounted for additional unique variance relative to visual processing speed. These results replicated in prediction to vocabulary at age four. In summary, consistent with predictions 1a and 1b, *vocabulary* was a relatively more robust predictor of subsequent vocabulary than *processing speed,* remaining significant even when controlling for the effects of other predictors.

That vocabulary was found to be a more robust predictor than processing speed is inconsistent with prior research (Marchman & Fernald, 2008), in which visual processing efficiency predicted significant unique variance above that accounted for by parent reported vocabulary. The difference in these two sets of findings may lie, in part, in the use of different measures of vocabulary. In recent studies, decontextualized vocabulary as assessed on the CCT emerged as a stronger predictor of language development than parent report (Friend, et al., 2018; 2019). The present findings suggest that processing speed no longer significantly predicts later vocabulary when controlling for concurrent decontextualized vocabulary. This is also consistent with the heterogeneity observed in results of the association between processing speed and vocabulary development. For example, Peter and colleagues (2019) concluded that processing speed predicts variance up to a critical mass of vocabulary but subsequently becomes a less reliable predictor relative to other skills.

Further differences lie in the approach to assessing visual processing speed. First, Marchman and Fernald assessed processing speed only for trials on which children were reported to know the meaning of the target word. In contrast, the current study utilized all trials regardless of reported word knowledge. For comparibility, we restricted analysis to words reported to be known by the child, but this measure was not correlated with vocabulary at any age (all *p*s > .06). However, this is likely because we used parent report of *production* rather than *comprehension* as in Marchman and Fernald (2008). Since production lags behind comprehension, this might account for the non-significance of the VRL measure for words reported as known. Indeed, in an earlier study, Fernald, Perfors, and Marchman (2006), found parallel results for visual speed of processing measured for “known” words and for both “known” and “unknown” words combined. Second, Fernald and colleagues do not include a haptic response component. It is possible that adding a haptic response changes task demands. Third, in the typical LWL paradigm, images are on screen for silent inspection for one or two seconds before speech onset whereas we did not include a silent inspection period. Nevertheless, mean and standard deviation of visual response latency in this study were similar to that observed in the typical LWL task. Additionally, the time course of looks to semantic competitors and the timing and magnitude of target activation in the visual world paradigm is similar regardless of the presence of an inspection period (Hendrickson & McMurray, 2018; Huettig & McQueen, 2007). Although these studies were conducted with adults, and it is unknown whether the omission of a silent viewing period may change the task for children, the similarily of the distribution of responses suggests any differences are minimal. Overall, these methodological differences are unlikely to have led to the current findings. Rather the change in the vocabulary measure at age two more likely accounts for the change in the relative pattern of prediction from vocabulary and processing speed.

It is also important to note that, whereas in the current study we predicted vocabulary at ages three and four, Marchman and Fernald utilized a more comprehensive language outcome measure. It is possible that vocabulary more strongly predicts later vocabulary but that processing speed adds unique prediction to other language skills. Importantly, CCT vocabulary and PPVT vocabulary are similar measures: both are forced choice haptic response assessments of receptive vocabulary. Therefore, it is important to compare prediction to other language outcomes; for example, prediction to an assessment of global language skills as in Marchman and Fernald (2008). We return to this point in directions for future research.

The absence of significant longitudinal prediction from haptic processing speed was unexpected given that it is concurrently associated with vocabulary in both monolingual and bilingual children (DeAnda et al., 2018; Legacy et al., 2018). Notably, haptic processing speed at 16 months of age significantly predicts vocabulary at 22 months in French-English bilingual children but not in monolingual French-speaking children (Legacy et al., 2018). It is possible that observed concurrent relations between vocabulary and haptic processing speed do not hold longitudinally. In the current study, zero-order correlations between haptic processing speed and vocabulary outcomes were positive but non-significant and confidence intervals were large. We attribute this lack of significant longitudinal relation (and positive directionality) to demand characteristics inherent in an offline measure of processing speed. This measure likely involves not only word processing but also executive control (Gottwald et al., 2016) and levels of decision confidence: some children may delay responses until a high level of decision confidence is reached, and such children may exhibit increased executive control and faster vocabulary development. Additionally, processing speed, controlled attention, and self-regulation (skills implicit in controlling a touch response) are important early indicators of later executive function (Hendry, Jones, & Charman, 2016).

Variability in these skills is a potential contributor to variability in touch latencies unrelated to vocabulary comprehension. We return to this idea in directions for future research.

Our findings suggest that assessments with varying demand characteristics tap distinct processes in the lexical-semantic system. Specifically, visual processing speed reflects the efficiency of the initial recognition of word meanings across a range of word-referent associative strengths (Hendrickson et al., 2015; Hendrickson et al., 2017; Munakata, 2001). In contrast, haptic processing speed reflects more deliberate referent selection following recognition. Whereas both measures are indicative of the efficiency of the lexical-semantic system, only the speed of initial recognition predicts how many words children will acquire downstream. However, it is the size of the decontextualized lexicon, itself an indicator of the maturity of the lexical-semantic system, that best predicts later vocabulary development. Finally, visual processing speed and decontextualized vocabulary accounted for 31 percent of the variance in vocabulary at age three and 22 percent of the variance in vocabulary at age four. This is a substantial portion of variance; however, as much as 78 percent of the variance remains unaccounted for. Other abilities that may contribute to vocabulary development include language input, family characteristics, preschool attendance, and the timing of other early language milestones including word combinations (e.g., Reilly et al., 2010). Examination of other predictors is a continuing direction for future research.

Group Differences

A third, exploratory goal was to examine group differences for children above or below the median on vocabulary and processing speed. This analysis was prompted by results from Marchman & Fernald (2008) and from modeling evidence that processing efficiency is a by-product not only of the structure of the word knowledge but also other endogenous factors (McMurray et al., 2012). Based on this evidence, we explored whether dissociations exist across these constructs, with processing and vocabulary exerting compensatory effects on development. Not surprisingly, children with larger early vocabularies evince strong vocabulary development. However, children without many stable word-referent associations at age two, who nevertheless process words efficiently, are in a better situation developmentally by age three than children who score low on both measures. That visual processing speed provides a compensatory effect appears to contradict the regression results, which revealed that CCT vocabulary provides unique prediction to downstream vocabulary development above and beyond visual speed of processing, but not vice versa. Together however, these results suggest that although CCT vocabulary is the best predictor of downstream outcomes, children who perform below the median on CCT scores at age two are in a slightly better developmentally position if they are also above the median in processing speed. Efficient processing may free up resources that can be devoted to learning unknown word meanings or strengthening associations between already acquired words and their referents, however children may not accelerate in vocabulary acquisition to the same extent as peers with larger vocabularies at age two.

Limitations and Directions for Future Research

The sample size of the present study was small though adequate for our statistical approach according to a priori power analyses and comparable to other laboratory-based studies of children in the toddler/preschool period (e.g., Friend et al., 2018; Marchman & Fernald, 2008; Weisleder & Fernald, 2013). It is nevertheless important to replicate these findings with larger samples. Relatedly, the sample was slightly skewed toward higher SES families. These results should be replicated with children from diverse backgrounds to assess generalizability.

We note two areas for future research brought to light by our findings. First, for both latency measures, we used the absolute time to fixate or touch the target. However, there may be variability in the extent to which children attempt to “guess” the target response. This may be most problematic for the haptic response measure, leading to correct responses that hover around chance. Of interest would be to utilize “purer” measures of latency that take into account this potential confound of processing speed with guessing. We are currently working on a project to tease out guessing from true latency to respond to a target. Relatedly, whereas we operationalized vocabulary as number of correct touches, it is also possible to estimate vocabulary from item-level accuracy of gaze responses. Given a potential influence of the haptic component on looking behavior, it would be worthwhile to investigate gaze data before and after onset of the haptic response.

Second, the current study examined prediction to a single outcome measure (i.e., receptive vocabulary). However, similarities between the predictor and outcome may have contributed to higher shared variance between these measures than between processing speed and vocabulary. Indeed, Marchman and Fernald (2008) found that both early vocabulary and speed of processing predicted unique variance in later language as assessed using a global language assessment and general cognition. Therefore, processing speed may more strongly predict other language and cognitive outcomes than vocabulary. Of particular interest given the disparate findings for prediction from haptic and visual response latencies is the relation of processing speed to cognitive control. If, as we have suggested, haptic processing speed reflects decision processes rather than word processing alone, we might expect to see this reflected in performance on executive function tasks. That is, perhaps the decision process indexed by the haptic response predicts children’s facility with executive decisions more generally. In future research, we plan to extend these analyses to additional outcome measures.

In sum, we found that vocabulary and processing efficiency significantly predicted vocabulary at ages three and four but that vocabulary was the only unique predictor when controlling for the effects of efficiency. In contrast, processing efficiency did not predict unique variance above and beyond vocabulary. Further, at age three, children who were strong in *either* vocabulary or speed of processing at age two outperformed children who were weak in both, suggesting a potential compensatory mechanism that supports learning up to age three, with the best outcomes for children strong in both skills. The present research extends extant work by evaluating the relative predictive utility of decontextualized vocabulary and processing efficiency. Results contribute to our understanding of the early lexical-semantic system.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- Toddlers’ vocabulary size and speed of word processing predict later vocabulary
- This pattern holds for visual but not haptic speed of processing
- Vocabulary remains significant when controlling for speed but not vice versa
- Vocabulary and speed of processing vary in their relative predictive strength

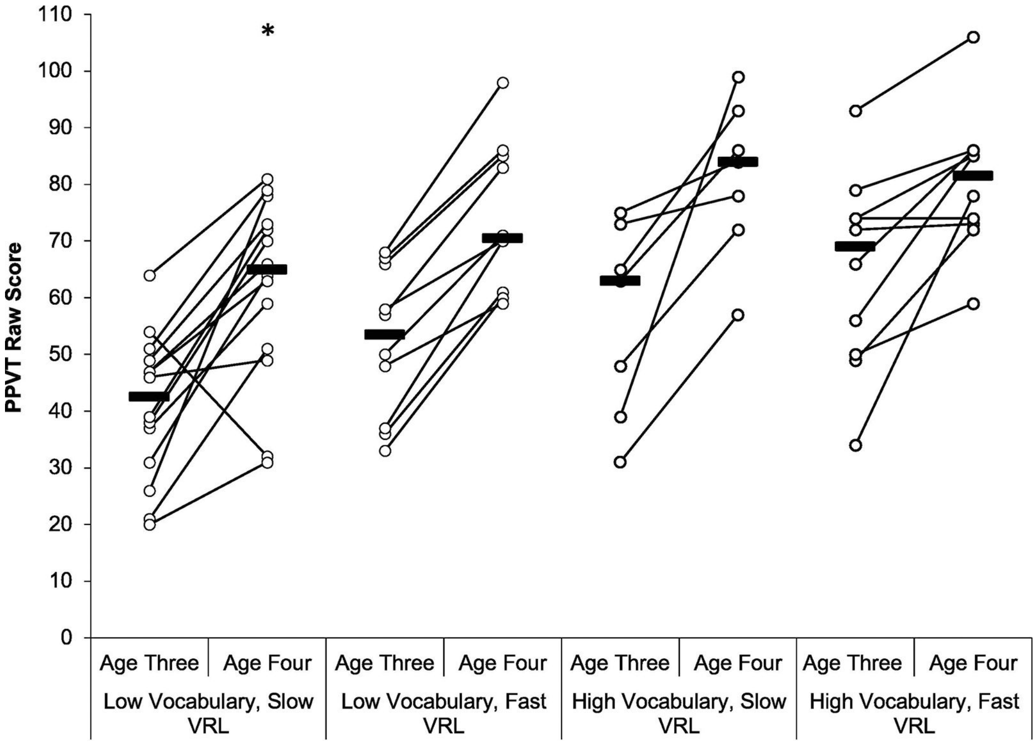

Fig. 1.

Peabody Picture Vocabulary Test (PPVT) vocabulary scores at 3 and 4 years of age in the median split analysis. Black dashes indicate median performance for each group at each age. *Significant difference ($p < .05$) in Mann–Whitney U test. VRL, visual response latency.

Table 1.

Distribution of Selected Demographic Characteristics of Participants.

	Number (%) of participants		
	Female	**Male**	**Total**
Maternal education			
High School or Less	2 (4.9)	4 (9.8)	6 (14.6)
Some College	8 (19.5)	1 (2.4)	9 (22.0)
College Graduate	6 (14.6)	5 (12.2)	11 (26.8)
Post-Baccalaureate	10 (24.4)	5 (12.2)	15 (36.6)
Approximate Income			
18,000–40,000	4 (9.8)	2 (4.9)	6 (14.6)
41,000–60,000	1 (2.4)	3 (7.3)	4 (9.8)
61,000–80,000	2 (4.9)	0 (0.0)	2 (4.9)
81,000–100,000	12 (29.3)	5 (12.2)	17 (41.5)
>100,000	7 (17.1)	5 (12.2)	12 (29.3)
Maternal Ethnicity			
Asian	0 (0.0)	1 (2.4)	1 (2.4)
Black/not Hispanic	1 (2.4)	0 (0.0)	1 (2.4)
Hispanic	7 (17.1)	0 (0.0)	7 (17.1)
White/not Hispanic	14 (34.1)	12 (29.3)	26 (63.4)
Mixed Race	4 (9.8)	2 (4.9)	6 (14.6)

Note. Some values may not sum to 100 due to rounding error.

Table 2.

Descriptive statistics and zero-order correlations (with 95% confidence intervals) for study variables.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. CCT Vocabulary Age 2	1									
2. VRL Age 2	−.47* (−.68, −.19)	1								
3. HRL Age 2	−.18 (−.46, .14)	.33 (.03, .58)	1							
4. PPVT Vocabulary Age 3	.55* (.29, .73)	−.46* (−.68, −.18)	.18 (−.13, .46)	1						
5. PPVT Vocabulary Age 4	.42* (.12, .64)	−.35 (−.59, −.05)	.11 (−.20, .41)	.63* (.39, .78)	1					
6. Age (2)	.22 (−.10, .49)	−.19 (−.47, .13)	−.18 (−.46, .13)	.08 (−.23, .38)	.01 (−.30, .32)	1				
7. Age (3)	.03 (−.28, .33)	−.19 (−.47, .12)	−.13 (−.42, .18)	−.02 (−.32, .29)	.02 (−.29, .32)	.67* (.46, .81)	1			
8. Age (4)	.05 (−.26, .35)	−.16 (−.44, .16)	−.06 (−.36, .25)	.04 (−.27, .34)	.03 (−.28, .33)	.60* (.36, .77)	.91* (.83, .95)	1		
9. Maternal Education	.34 (.03, .58)	−.05 (−.35, .26)	−.06 (−.36, .25)	.19 (−.13, .47)	.11 (−.21, .40)	.03 (−.28, .33)	.003 (−.30, .31)	.06 (−.25, .36)	1	
10. Biological Sex ǂ	.99 (−2.45, 6.93)	−.68 (−90.06, 45.26)	−2.31 (−870.91, −48.14)	−.25 (−13.90, 10.88)	−1.54 (−16.84, 2.27)	.33 (−.46, .64)	−.53 (−1.32, .78)	−.89 (−1.40, .55)	.54 (−1.14, 1.96)	1
Means	28.49	747.30	2573	51.98	72.78	22.94	37.73	50.04	15.66	F M
SDs	6.51	96.29	602.66	17.14	15.98	.86	1.52	1.40	2.11	26 15
Range	10–39	570.9– 1009.2	1264– 3812	20–93	31–106	21.1–25.4	35.2–41.8	47.5–53.1	12–18	

ǂ Numbers for sex are reported as t-tests rather than correlations, with a 95% confidence interval of the true difference in means.

Note.

* indicates significance after controlling for the false discovery rate using the Benjamini-Hochberg procedure.

Table 3.

Model comparison ANOVA results and change in AIC/BIC values for each parameter addition predicting PPVT vocabulary at age three. Negative change in AIC/BIC values indicates better model fit.

Model Year 2 Predictors	**ANOVA Results**	***p* value**	**AIC**	**ΔAIC**	**BIC**	**ΔBIC**
Child Sex and Maternal Education			354.68		361.54	
+ CCT vocabulary	F(1,37) = 15.21	<.001 **	342.56	−12.12	351.13	−10.41
+ VRL	F(1,37) = 10.66	.002 **	346.30	−8.38	354.87	−6.67
+ HRL	F(1,37) = 1.36	.25	355.20	.52	363.77	2.23
Controls + CCT vocabulary			342.56		351.13	
+ VRL	F(1,36) = 3.32	.08	340.94	−1.61	351.23	.10
Controls + VRL			346.30		354.87	
+ CCT vocabulary	F(1,36) = 7.08	.01 *	340.94	−5.36	351.23	−3.64

Note.

[*] $p < .05$

[**] $p < .01$. Negative change in AIC/BIC values indicates better model fit.

Table 4.

Hierarchical regression parameters for models predicting PPVT vocabulary at age three.

	R^2	β	SE	P
Vocabulary Only Model	.26			.002 **
Sex		.14	4.84	.32
Maternal education		.01	1.15	.94
CCT vocabulary		.57	.38	<.001 **
Processing Speed (Visual) Only Model	.19			.01 *
Sex		.11	5.04	.44
Maternal education		.18	1.14	.22
VRL		−.47	.02	.002 **
Vocabulary and Processing Speed Model	.31			.002 **
Sex		.15	4.70	.27
Maternal education		.04	1.12	.75
CCT vocabulary		.43	.42	.01 *
VRL		−.27	.03	.08

Note.

* $p < .05$

** $p < .01$. R^2 values are adjusted.

Table 5.

Model comparison ANOVA results and change in AIC/BIC values for each parameter addition predicting PPVT vocabulary at age four.

Model	**ANOVA Results**	***p* value**	**AIC**	**ΔAIC**	**BIC**	**ΔBIC**
Child Sex and Maternal Education			347.80		354.66	
+ CCT vocabulary	F(1,37) = 9.73	.003[**]	340.23	−7.57	348.80	−5.86
+ VRL	F(1,37) = 6.61	.01[*]	343.07	−4.74	351.63	−3.02
+ HRL	*F*(1, 37) = .05	.82	349.75	1.95	358.31	3.65
Controls + CCT vocabulary			340.23		348.80	
+ VRL	F(1,36) = 1.81	.19	340.22	−.01	350.50	1.70
Controls + VRL			343.07		351.63	
+ CCT vocabulary	F(1,36) = 4.52	.04[*]	340.22	−2.23	350.50	−1.13

Note.

[*] $p < .05$

[**] $p < .01$. Negative change in AIC/BIC values indicates better model fit.

Table 6.

Hierarchical regression parameters for models predicting PPVT vocabulary at age four.

	R^2	β	SE	P
Vocabulary Only Model	.20			.01 *
Sex		.30	4.70	.04 *
Maternal education		−.02	1.12	.88
CCT vocabulary		.47	.37	.003 **
Processing Speed (Visual) Only Model	.14			.03 *
Sex		.28	4.85	.07
Maternal education		.11	1.09	.44
VRL		−.38	.02	.01 **
Vocabulary and Processing Speed Model	.22			.01 **
Sex		.31	4.66	.04 *
Maternal education		.004	1.11	.98
CCT vocabulary		.36	.42	.04 *
VRL		−.22	.03	.19

Note.

[*] $p < .05$

[**] $p < .01$. R^2 values are adjusted.