Cognitive Psychology 115 (2019) 101238

Contents lists available at ScienceDirect

Cognitive Psychology

journal homepage: www.elsevier.com/locate/cogpsych

Does speed of processing or vocabulary size predict later language growth in toddlers?

Michelle S. Peter[b,*], Samantha Durrant[b], Andrew Jessop[a], Amy Bidgood[c], Julian M. Pine[b], Caroline F. Rowland[a,b,d]

[a] *Language Development Department, Max Planck Institute for Psycholinguistics, the Netherlands*
[b] *ESRC LuCiD Centre, Department of Psychological Sciences, University of Liverpool, UK*
[c] *School of Health and Society, University of Salford, UK*
[d] *Donders Institute for Brain, Cognition and Behaviour, Radboud University, the Netherlands*

ARTICLE INFO

Keywords:
Speed of processing
Lexical processing
Vocabulary development
Syntactic development

ABSTRACT

It is becoming increasingly clear that the way that children acquire cognitive representations depends critically on how their processing system is developing. In particular, recent studies suggest that individual differences in language processing speed play an important role in explaining the speed with which children acquire language. Inconsistencies across studies, however, mean that it is not clear whether this relationship is causal or correlational, whether it is present right across development, or whether it extends beyond word learning to affect other aspects of language learning, like syntax acquisition. To address these issues, the current study used the looking-while-listening paradigm devised by Fernald, Swingley, and Pinto (2001) to test the speed with which a large longitudinal cohort of children (the Language 0–5 Project) processed language at 19, 25, and 31 months of age, and took multiple measures of vocabulary (UK-CDI, Lincoln CDI, CDI-III) and syntax (Lincoln CDI) between 8 and 37 months of age. Processing speed correlated with vocabulary size - though this relationship changed over time, and was observed only when there was variation in how well the items used in the looking-while-listening task were known. Fast processing speed was a positive predictor of subsequent vocabulary growth, but only for children with smaller vocabularies. Faster processing speed did, however, predict faster syntactic growth across the whole sample, even when controlling for concurrent vocabulary. The results indicate a relatively direct relationship between processing speed and syntactic development, but point to a more complex interaction between processing speed, vocabulary size and subsequent vocabulary growth.

1. Introduction

Increasingly, we are coming to realise that the way that children acquire cognitive representations depends critically on the way their processing system is developing. For example, the input from which children acquire their knowledge of the world often comes in rapid and transient signals (e.g., actions, speech), which must be processed quickly, in the moment, in order to be utilised by the child's learning mechanisms. Constraints on how much of the signal can be processed in the moment will affect how the child acquires knowledge from the environment. Thus, understanding the processing constraints under which children operate, and

---

* Corresponding author.
E-mail address: michelle.peter@liverpool.ac.uk (M.S. Peter).

https://doi.org/10.1016/j.cogpsych.2019.101238
Received 11 April 2019; Received in revised form 24 August 2019; Accepted 25 August 2019

explaining how individual differences and dynamic developmental changes in the processing system affect what can be acquired, are crucial for theory development.

In language acquisition, recent research has isolated one processing constraint that seems to play a key role in driving development: the speed with which children process familiar words seems to explain a significant proportion of the variance in the speed of children's vocabulary growth. This observation is based on a large number of studies showing that young children who react faster to questions like "Where's the dog?" in a looking-while-listening paradigm have larger vocabularies (e.g., Fernald, Perfors, & Marchman, 2006; Marchman, Adams, Loi, Fernald, & Feldman, 2015). The proposed mechanism behind this finding is rarely spelled out, but some have suggested that faster processing of familiar words frees up resources that can then be dedicated to the learning of new words (Fernald & Marchman, 2012), that having more experience hearing and using speech results in a larger lexical network, which then improves lexical processing speed across the board, for both new and old words (Fernald et al., 2006), or that the extent and diversity of lexical and sub-lexical information stored in the lexicon drives both the speed of processing of familiar chunks, and the speed of vocabulary acquisition (Jones & Rowland, 2017).

It is apparent that there is some kind of relationship between processing speed and vocabulary development. However, a closer look at the literature reveals that the precise nature of this relationship is far from clear. One problem is that most studies report only a correlational relationship, so the extent to which processing speed plays a role in driving new vocabulary learning is not yet robustly established; It may simply be that children with large vocabularies are faster to process familiar words, with no implications for the later learning of new words. In addition, the age at which such relationships are found seems to be inconsistent across studies. Thus, we do not yet know whether the relationship between speed of processing and word learning remains consistent across development or is restricted to a specific developmental period (in the same way that joint engagement exerts its influence most strongly early in development; Carpenter, Nagell, & Tomasello, 1998). Finally, nearly all studies have focussed only on the relationship with early vocabulary. Thus, we do not know whether processing speed plays a role in the acquisition of other properties of language, such as syntax.

These issues have important theoretical implications. If the speed with which children process familiar words is a robust, long-term predictor of the speed with which they grow their vocabulary, we will need to build processing speed parameters into our models of vocabulary acquisition. If, however, it is simply the case that children with large vocabularies are better able to access the representations of familiar words in long-term memory, with no implications for later language learning, speed of processing will play a more minor, or no, role in our theories of vocabulary acquisition. Similarly, if speed of processing differences are found only at one developmental time point (e.g., at 19 months but not 31 months), or affect vocabulary learning but not syntax learning, then we will need to build more dynamic developmental models of language learning, in which some predictors come into play at particular developmental time points, and affect only a subset of language learning tasks. We may also have to conclude that speed of processing has a much more limited role in explaining individual trajectories of language acquisition than has previously been assumed.

The goal of the present study was to pinpoint the role that processing speed plays in language acquisition across the second and third year of life by analysing data from a large longitudinal sample (the Language 0–5 Project), with multiple measures across early development. We had three objectives. Our first was to determine whether children with faster processing speed grow their vocabularies faster, since this has substantial implications for how we characterise the role of processing speed in language learning. Our second objective was to determine whether the relationship between speed of processing and vocabulary learning is consistent across development or is specific to a particular time point or to a particular vocabulary size. Our third objective was to determine whether the relationship between speed of processing and language extends to syntax, or is restricted to vocabulary acquisition. The findings have substantial implications for how we characterise the role of processing speed in language acquisition.

1.1. The role of linguistic processing speed in language acquisition

Fernald, Swingley, and Pinto (2001) first demonstrated the relationship between infants' speed of language processing and vocabulary size using the looking-while-listening paradigm (Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998) to assess spoken word recognition in 18- and 21-month olds. Typically, in looking-while-listening tasks, children see a pair of images on a screen (e.g., a ball on the left side of the screen and a shoe on the right) whilst simultaneously listening to speech that refers to one of these images (e.g., "Where's the ball?"). During this time, their eye movements are monitored and are then coded offline. Because individuals tend to fixate on a referent when it is labelled (Thomas, Campos, Shucard, Ramsay, & Shucard, 1981), and since these fixations are closely time-locked to the words that are heard, the latency to shift away from the distracter image (in this case, the shoe) towards the target image (the ball) is used as a way of measuring the speed with which children are able to link a word to its referent (i.e. to process a word).

Performance on these tasks provides an online reaction time measure of speed of language processing (also called lexical processing efficiency (Lany, 2018) and speed of lexical access (Law & Edwards, 2015)), which allows us to examine individual differences across children. Fernald et al. (2001) found that children aged 18 and 21 months with faster mean reaction times (i.e., faster latency to shift from distracter to target image) had larger vocabularies than those with slower reaction times. A similar pattern of results has been reported in a number of studies since (Fernald & Marchman, 2012; Fernald et al., 2006; Fernald, Marchman, & Weisleder, 2013; Hurtado, Grüter, Marchman, & Fernald, 2014; Hurtado, Marchman, & Fernald, 2007, 2008; Loi, Marchman, Fernald, & Feldman, 2017; Marchman & Fernald, 2008; Marchman et al., 2015; Weisleder & Fernald, 2013).[1]

---

[1] For other work showing a relationship between language processing ability and vocabulary size (albeit not using reaction time measures) see Swingley (2003; 2009), and Law, Mahr, Schneeberg, and Edwards (2017).

A large body of evidence, thus, reports a relationship between the speed with which children process linguistic input and vocabulary size in early childhood. However, this is not the same as showing that processing speed is a robust predictor of language acquisition. A closer look at the literature shows that the conclusion that processing speed differences explain a significant proportion of the variance in children's vocabulary growth throughout early childhood is not yet warranted.

First, it is not clear whether children with large vocabularies are simply better at processing familiar words, or whether this advantage at processing familiar words also leads to faster vocabulary growth. There is a (sometimes unspoken) assumption in the speed of processing literature that we see a relationship between processing and vocabulary size because faster processing of known words facilitates the learning of new words. For example, Law and Edwards (2015: 19) have speculated that children who are more efficient at lexical processing might more quickly and reliably recognize a novel word as a "new" word … [and thus] more rapidly add new words to their vocabulary". Similarly, Fernald and Marchman (2012) have suggested that faster processing of familiar words frees up resources that can then be dedicated to the learning of new words.

However, an equally likely hypothesis, stemming from the adult literature on language processing, is that the direction of the relationship is the other way round; that having a larger lexicon facilitates the processing of familiar words (see Lany, 2018, for a similar point). Adults with larger vocabularies show accurate and faster processing of familiar words in a variety of tasks (Mainz, Shao, Brysbaert, & Meyer, 2017), including spoken word recognition (Janse & Jesse, 2014), the use of predictive information in a spoken context (Federmeier, McLennan, De Ochoa, & Kutas, 2002), speech recognition in non-optimal conditions (Bent, Baese-Berk, Borrie, & McKee, 2016), and word recognition in lexical decision and speeded pronunciation tasks (Yap, Balota, Sibley, & Ratcliff, 2012). The explanation is that adults with larger vocabularies have not only been exposed to more words, but have also been exposed to each word more frequently (Kuperman & Van Dyke, 2013). Since word knowledge develops gradually, rather than in a single fast-mapping context (Smith & Yu, 2008), more frequent exposure leads to stronger, more robust and more distinct lexical representations, which are then accessed faster and more efficiently during online language processing tasks. Specific evidence to support this model comes from studies showing that adults with larger vocabularies show smaller word frequency effects in processing tasks than adults with smaller vocabularies, which is explained by positing that, for adults with large vocabularies, more of the words in their lexicon have strong, fully entrenched lexical representations (Diependaele, Lemhöfer, & Brysbaert, 2013; Yap, Tse, & Balota, 2009).

There is no reason to think that this differs for children. Children with larger vocabularies are also likely to have more robust lexical knowledge of familiar words, relative to children with smaller vocabularies, even when we consider only words familiar to both groups of children. On this model, although faster processing of familiar words may also lead to faster vocabulary growth, this is not a given. For example, it may be that a third factor (e.g., richer input, brain maturation) causes some children to start the process of vocabulary learning earlier in life. These children will have larger vocabularies at a particular developmental time point (e.g., 19 months), will have more robust lexical representations for familiar words, and will process these familiar words more efficiently. They may not, however, grow their vocabularies more quickly.

To support the idea that faster familiar word processors also grow their vocabularies faster, we have to show that processing speed predicts the rate of future vocabulary growth not just that it correlates with concurrent vocabulary size. There is currently little evidence that shows this directly, because most work has looked only at concurrent relationships (e.g., Fernald et al., 2006; Hurtado et al., 2014; Hurtado et al., 2007, 2008; Loi et al., 2017) or relationships between speed of processing and earlier vocabulary size (Fernald & Marchman, 2012; Fernald et al., 2006, 2013; Hurtado, Marchman, & Fernald, 2008). Of the work that does look at predictive relationships over time, much does not control for concurrent vocabulary, which means that we cannot tell whether it is simply the case that children with larger vocabularies at the time at which speed of processing was measured also have larger vocabularies at later time points (Fernald et al., 2013; Hurtado et al., 2014; Weisleder & Fernald, 2013).

Only three studies (Fernald & Marchman, 2012; Fernald et al., 2006; Marchman et al., 2015) have shown that speed of processing predicts later vocabulary growth while controlling for concurrent vocabulary size. However, for two of these studies, the relationships are not clear-cut. Marchman et al. (2015) reported that speed of processing at 18 months explained unique variance in PPVT-4 scores at 36 months, but this was in a sample of preterm infants, not typically developing children, and the effect held only when speed of processing was measured in reaction time to respond after noun onset, not in terms of accuracy (mean proportion of time spent looking at the target image). Fernald and Marchman (2012) report an effect of speed of processing at 18 months (again measured by reaction time) on vocabulary growth between 18 and 30 months, but here the effect was present only in the late talkers in their sample. Amongst the typically developing children, growth in the vocabulary of the faster processors actually decelerated over time.

One study establishes a direct link between language processing and performance on novel word learning tasks at 17 months of age, over and above vocabulary size (Lany, 2018). However, again the results are not clear-cut; the 30 month olds only showed the effect when the word-learning task was made more challenging (experiment 2), and even in the experiments where speed of processing did correlate with novel word learning, it did not also correlate with concurrent vocabulary size (17 months in experiment 1, 30 months in experiment 2). Thus, the relationship between familiar word processing speed, familiar word vocabulary size and new vocabulary growth may not be as robust or consistent as previously assumed.

The first aim of the present study was to determine whether speed of processing explains later vocabulary growth, over and above concurrent vocabulary size. In order to do so, we tested two alternative hypotheses: (1) that children with faster processing speed grow their vocabularies faster, and (2) that children with large vocabularies are faster to process familiar words, but this has no implications for later vocabulary growth.

A second problem is that it is not clear whether the relationship between speed of processing and vocabulary remains consistent across development or is restricted to a specific developmental range. The age at which such relationships are found seems to be inconsistent across studies. For instance, although Fernald et al. (2006) tested speed of processing at 15, 18, 21 and 25 months, they only found robust concurrent relationships with language at 21 and 25 months. Similarly, both Hurtado et al. (2008) and Fernald et al. (2013) found significant correlations between vocabulary and speed of processing only at 24 months, but not at 18 months. Contrariwise, Loi et al. (2017), Fernald and Marchman (2012) and Marchman et al. (2015) all report correlations between 18 month processing speed and concurrent or later language.

These inconsistencies mean that we do not have a clear picture of how speed of processing relates to vocabulary development as children grow older. If we find that speed of processing effects on language learning are found only at one particular age (e.g., at 25 months but not 15 months), then we will need to build more dynamic, developmental models of vocabulary acquisition, in which some predictors only come into play at particular time points. For example, it may be that processing speed is only important later in development. Perhaps younger children know so few words that the gains they make from processing these words quickly has very little effect on overall cognitive efficiency, or perhaps linguistic processing is so effortful for younger children that even fast processors gain little advantage. Alternatively, it may be that processing speed is only important early in life. Older children may be so good at processing familiar words quickly that processing speed ceases to be a predictive factor in subsequent vocabulary growth, with other skills, such as the ability to do syntactic bootstrapping, playing an increasingly important role in acquisition (see Hollich et al., 2000, for the proposal that children differentially weight different cues to word learning throughout development). The second aim of the present study, therefore, was to determine whether the relationship between speed of processing and vocabulary learning is consistent across development or is specific to a particular time point or a particular vocabulary size.

The third aim was to look beyond vocabulary acquisition to test the effect of processing speed on syntax growth. There are two ways in which processing speed could affect syntax acquisition. The first is indirectly, via effects on prior vocabulary learning. Vocabulary size has been shown to be a strong predictor of later syntactic achievements (Bates, Bretherton, & Snyder, 1988) and the onset of verb morphology (Marchman & Bates, 1994). Thus, a prominent idea is that syntax emerges from, and is crucially dependent on, lexical knowledge (Bannard, Lieven, & Tomasello, 2009; Bates & Goodman, 1999; Bates et al., 1994; Braginsky, Yurovsky, Marchman, & Frank, 2015). For instance, Marchman and Bates (1994) have proposed that the mechanisms involved in acquiring the lexicon are such that, as the lexicon grows, the quality of the emergent grammar changes. On this view, domain-general learning mechanisms underlie the development of both word and grammar learning (e.g., Elman, Bates, Johnson, & Karmiloff-Smith, 1996); “the native speaker learns to map phrasal configurations onto propositions, using the same learning principles and representational mechanisms needed to map single words onto their meanings” (Bates & MacWhinney, 1987: 163). Similarly, usage-based theorists suggest that syntactic representations will initially be item-specific and gradually become abstract over the course of acquiring a sophisticated and dense lexicon (Pine & Lieven, 1997; Tomasello, 2000). On this model, speed of processing might be expected to act on syntax indirectly via vocabulary learning. Thus, though we might expect to see a relationship between speed of processing and syntactic knowledge, this relationship would disappear once we control for vocabulary.

Another model is that speed of processing acts directly on the acquisition of syntax. For example, more efficient processing of familiar words might help in the tracking of the relations and co-occurrences between words, which is a necessary skill for syntactic development (Marchman & Fernald, 2008). On this view, just as it may facilitate the learning of new words, faster processing speed may also directly benefit syntax acquisition. If this were the case, we would expect faster speed of processing to predict faster syntactic growth even after concurrent vocabulary knowledge is taken into account.

Only one study provides evidence that the effects of processing speed go beyond vocabulary growth in the language domain. Fernald et al. (2006) reported significant concurrent relations between speed of processing at 25 months and two syntactic measures taken from the MacArthur-Bates CDI Words and Sentences (Fenson et al., 2007): grammatical complexity and M3L (mean length of the child’s three longest utterances). However, this study establishes only that processing speed relates to concurrent syntactic knowledge, not that it is a significant predictor of syntax growth. Thus, our third objective was to determine whether the relation between speed of processing and language extends to syntax, and, if so, whether this reflects direct or indirect effects.

In summary, we used the looking-while-listening paradigm devised by Fernald et al. (2001) to test the speed with which a large longitudinal cohort of children (the Language 0–5 Project) processed language at 19, 25, and 31 months of age, and took multiple measures of vocabulary and syntax between 19 and 37 months of age. We tested the predictions that: (a) processing speed will correlate with vocabulary size at each age tested, (b) processing speed will predict growth of vocabulary size after controlling for concurrent vocabulary, and (c) processing speed will predict later syntax acquisition, after controlling for concurrent vocabulary size.

2. Method

2.1. Participants

This study forms part of a larger longitudinal project in the North West of England, the Language 0–5 Project (http://www.lucid.ac.uk/what-we-do/research/language-0-5-project/). A total of 95 families were recruited to take part, an initial sample of 89 families at the outset of the project (at six months of age) and an additional six families at the 15-month measurement point to replace families that were no longer able to participate. A screening instrument (Family Questionnaire; Alcock et al., 2019) was used to gather family background, health, and demographic information. Of the full sample of 95 recruited families, one was excluded due to the reporting of a persistent ear infection that might affect hearing, and four decided not to continue after the initial visit, thus contributing no data to the project. By the end of data collection for this study, a further 13 had dropped out of the project. At the time of recruitment, all infants were born full-term, none were low birth weight, and all were typically-developing. Out of the final sample of 90 families that contributed data for at least one measurement point, nine had a family history of language delay or dyslexia and nine had a relative with a history of colour blindness. Around half of the final cohort of 90 were male ($n = 44$) and a similar proportion were first born ($n = 50$), with the remainder having one or more older siblings (1 older sibling: $n = 25$; 2 or more older siblings: $n = 15$). Further details of the sample characteristics including maternal education and household income can be found in Appendix A.

Children were tested in the laboratory at the University of Liverpool at, on average, 19;3 months (range = 19;1–20;1), 25;15 months (range = 24;25–26;4), and 31;16 months (range = 30;20–32;15), respectively. At the 19-month measurement point, 80 children (42 females) were tested. At the 25-month measurement point, 76 children (39 females) were tested, and at the 31-month measurement point, 75 children (39 females) were tested. Data for some children were not included because they included fewer than 25% good trials (19 months: $n = 4$; 25 months: $n = 7$; 31 months: $n = 2$). This refers specifically to the calculation of accuracy (proportion of time spent looking to the target image); a trial was considered good if the child looked to either the target or distracter image during the analysis window of 300–1800 ms after noun onset, and bad if the child looked at neither image during this time. Correlations and growth curve analyses were computed only on data in which children had both a processing speed and a language score. At the time of testing, all of the children appeared to be typically-developing, all were monolingual English learners, and none had any reported problems with vision or hearing.

2.2. Measuring vocabulary size

Throughout the Language 0–5 Project, measures of vocabulary size were taken at regular intervals. At 8, 9, 11, 12, 15, 16, and 18 months, caregivers were asked to complete the UK-CDI Words and Gestures (UK-CDI; Alcock et al., 2019) – a checklist on which they indicate the items that their child “understands” (receptive vocabulary) and the items that their child “understands and says” (expressive vocabulary; total possible score for both receptive and expressive vocabulary = 396). The UK-CDI has been standardised for the UK population, and has good validity and reliability (see Alcock et al., 2019). Since the UK-CDI is suitable for use only up until 18 months, caregivers completed the Lincoln CDI Words and Sentences (Meints, Fletcher, & Just, 2017) at 19, 21, 24, 25, 27, and 30 months (total possible vocabulary score = 689). The Lincoln CDI is the UK version of the MacArthur-Bates CDI Words and Sentences (Fenson et al., 2007). It has not yet been validated but is expected to have good validity and reliability due to its similarity to the MacArthur-Bates instrument. Finally, the CDI-III (Dale, 2007) was completed by caregivers at the 31-, 34-, 36-, and 37-month measurement points and provides a measure of expressive vocabulary. The CDI-III is a brief upward extension of the CDI for children between 30 and 37 months (total possible vocabulary score = 100). Further information about construction, validity and reliability can be found in Fenson et al. (2007). We asked that checklists be completed in the week prior to coming in to the lab, either on paper, or online via a link sent in an email. Those caregivers who did not complete the checklist before attending the testing session filled in a paper version during the session. For all CDIs, scores were calculated according to the instructions in the manuals referenced above. We calculated only expressive vocabulary scores, in line with the speed of processing literature.

2.3. Measuring productive syntax

We used the Lincoln CDI Words and Sentences at the 19-, 21-, 24-, 25-, 27- and 30-month measurement points to measure children’s syntactic productivity in terms of mean length of three longest utterances (M3L) and syntactic complexity. To measure M3L, caregivers reported the three longest utterances that they had heard their child produce, from which the mean number of morphemes in these utterances was calculated. To measure syntactic complexity, parents indicated which of two sentences (total of 37 sentence pairs) sounded most like the way their child talks (e.g., *baby blanket* vs. *baby’s blanket*). Scores were calculated in accordance with the instructions in Fenson et al. (2007).

2.4. Measuring speed of processing using the looking-while-listening paradigm

The task was designed to replicate as closely as possible the task used at the Center for Infant Studies at Stanford University (e.g., Fernald et al., 2006). Some changes were made, but these are made explicit below. A detailed description of the Language 0–5 speed of processing method can be found on the Language05 OSF site at https://osf.io/z2ukm/.

2.4.1. Speech stimuli

In line with Fernald et al. (2006), to avoid ceiling effects and boredom during the task, we varied the speech stimuli so that the children were exposed to increasingly challenging words across the three ages at which they were tested. We included only familiar nouns at 19 months, but added adjective-noun combinations at the 25- and 31-month time points.

All sentences for all three time points were pre-recorded by the same female speaker, who was a native speaker of English and had an accent that was local to the area. All sentences were normalised for pitch and volume. Each sentence included a familiar two-part question and the target word (e.g., “*Where’s the* ***baby****? Can you find it?*”). The questions varied to keep the child engaged. Sentences were presented in two blocks (A and B) so that target words in block A, were distracter words in block B. All children were presented with both blocks, but block order was counterbalanced across children so that half were presented with block A first and the other half with block B first. Assignment to a counterbalance group (“A then B” or “B then A”) was random. At 19 months, children were presented with 64 test trials across two blocks: eight different nouns (e.g., *baby*) were each presented eight times as a target noun across these 64 trials. Each block also included three filler sentences (e.g., “*Well done! Do you like the pictures*?”), purely to prevent the child’s attention from wandering due to the repetitive nature of the task. At 25 months, children were presented with 60 test trials across two blocks (plus an additional two filler sentences in each block): eight different nouns were each presented six times as a target, and four different colour adjective-noun combinations (e.g., ***red*** *shoe*) were each presented three times as a target across two blocks. At 31 months, children were presented with 64 test trials across two blocks (plus an additional two filler sentences in each block): six different nouns were each presented six times as a target. There were also 14 different adjective-noun combinations: six describing the colour of the noun (e.g., ***red** shoe*) and eight describing the size of the noun (e.g., ***little** spoon*). All 14 adjective-noun combinations appeared twice across each block as a target. All adjective trials were informative because they provided a pre-nominal cue as to where to look (e.g., *red shoe* was always paired with *blue ball*). Within the task at each time point, nouns and adjective-noun combinations were always paired in the same way (e.g., at 25 months, *juice* always appeared with *car*, and at 31 months, *juice* always appeared with *book*; for a full list of the target words used, see Appendix B).

2.4.2. Visual stimuli

The visual stimuli were pictures of objects that matched the chosen target words. They were shared by the Center for Infant Studies at Stanford University, who have run a number of experiments using these images. Therefore, as in Fernald et al. (2006), all images were matched in terms of size and brightness and presented on a grey background.

2.5. Procedure

Unlike previous studies, which have coded eye movements offline from video recordings (e.g., Fernald et al., 2006; Marchman et al., 2015), the current study used eye-tracking technology, allowing for the tracking and coding of eye movements online. Not only does this method provide highly precise fixation data (the high sampling rate of the equipment used (EyeLink 1000 Plus; SR Research: Ottawa, Ontario, Canada) means that up to 2000 samples of the eye position are taken every second with an average accuracy of 5°), but it is also time-saving; fixation data is relayed back to the system within 3 ms, removing the need for manual frame-by-frame coding – a process that can be arduous and is subject to human error.

2.5.1. The task at 19 months

On entering the lab, the experimenter asked the caregiver to sit their child in a car seat (or in a high-chair or on their lap, if the child was unwilling to sit in the car seat) in front of a 17″ LCD monitor mounted on a hydraulic arm.

The experimenter first played a short cartoon animation in order to familiarise the child with the set-up and to orient the child's eyes to the screen. Then the eye-tracker was calibrated using a 5-point calibration in which the child saw a looming high-contrast circular shape accompanied by a twinkly sound. After successful calibration, the experimenter launched the experiment. The experiment began with the presentation of a central smiley face (location 352, 224)[2] on the screen. The smiley face acted as an attention getter and was programmed to be gaze-contingent such that the next trial would not begin until the child had fixated on the face for 800 ms. We chose to include a central attention getter in between each trial for two reasons: (1) to ensure that trials would not begin until the child was attending to the screen, thus minimising trial loss, and (2) to remove potential positional side bias by ensuring that the pupil was centrally-located at trial onset (note that Delle Luche, Durrant, Poltrock, and Floccia (2015) reported reduced trial loss when a central attention getter was included in between trials). Once the child had fixated on the attention getter for the maximum threshold, the image disappeared, and the test trial began.

For every test trial, the child first saw two images - the target and the distracter - presented on the left side (location: 0, 262) and right side (location: 704, 262) of the screen. These images were presented in 2000 ms of silence before the onset of the familiar two-part question and target word (e.g., "*Where's the baby? Can you see it?*"). Both images remained on the screen for the entirety of the trial, which, for all trials (including filler trials), was 7000 ms.

Caregivers were instructed not to speak to the child during the task except to comfort them if necessary, and to refrain from naming the images. If it was deemed necessary by the caregiver, the child was allowed a dummy/pacifier or snack during the task. The experimenter noted on a trial-by-trial basis those trials where there was audible disruption (e.g., talking or crying) over the critical target item. Before leaving, caregivers were asked to indicate which words their child understood on a checklist that included all of the target words presented in the task.

2.5.2. The task at 25 and 31 months

The procedure for the task at 25 and 31 months was identical to that at 19 months, apart from the following: (1) The maximum threshold for the attention getter at 31 months was reduced to 400 ms, (2) at 31 months, some children were seated in front of the monitor on a chair on their own (and not in a car seat or their caregiver's lap).

2.6. Analysis of fixation data

Fixation data were recorded using an SR Research EyeLink 1000 plus eye-tracker. Interest areas were set to be identical to the dimensions of the target and distracter images, allowing for the creation of reports that provide information about fixations within these regions. Speed of processing, which is a reaction time (RT) measure, was defined as in the literature: the initiation of a shift from the distracter image to the target image that occurs at least 300 ms after and up to 1800 ms post target word onset; a time window that maximises the possibility of capturing individual differences in the early decision making of eye movements (Swingley, 2011). Trials were also excluded if: (a) there was audible disruption (e.g., crying, talking) at target word onset, (b) the target word

---

[2] The X coordinate (e.g., 352) corresponds to the number of pixels along the horizontal axis of the display screen with 0 being the extreme left of the screen. The Y coordinate (e.g., 224) corresponds to the number of pixels along the vertical axis of the screen with 0 being the top of the screen.

was not “understood” by the child, as reported by the caregiver, (c) the child did not fixate towards both the distracter and target during the baseline period (the first 2000 ms of the trial during which there was no speech). In addition, since reaction times rely on a shift from the distracter to the target image, (d) RT was only calculated on trials on which the child was looking at the distracter image at the onset of the target word (distractor-initial trials). For the calculation of a mean RT score per child, we applied the following criterion: a child’s data were excluded if that child had fewer than two trials that fit all of the above criteria (resulting in three exclusions at 25 months and one at 31 months[3]; mean number of trials per child = 10.98, *SD* = 5.10, range = 2–27).

3. Results

Below we report two preliminary analyses that were performed to test whether our results replicated the main effects in the literature, before presenting the analyses that test our hypotheses. Since girls tend to be faster than boys at this age, we first ran models where Gender was included as a fixed effect but retained it in the main model only if it interacted with one of the predictors of interest. Since Gender did not interact with any of our predictors, we report these models only in the supplementary materials, which are available at https://osf.io/z2ukm/.

3.1. Preliminary analysis: How does speed of language processing change over development?

Previous work has demonstrated that infants become quicker at recognising familiar words in spoken speech over the second year of life (Fernald et al., 1998), and that this effect holds when comparing the same children’s performance across development (Fernald et al., 2006). We therefore performed preliminary analyses on children’s speed of language processing at three measurement points (19, 25 and 31 months) to examine whether, as a group, children in the current study became faster at processing familiar words as they got older (see Table 1 and Fig. 1). If they did, then we would expect to see a significant decrease in reaction time (RT) across development. A mixed effects model was fitted to examine our data (Baayen, Davidson, & Bates, 2008; Jaeger, 2008) using the *lmer* function of the *lme4* package (version 1.1.20; Bates, Mächler, Bolker, & Walker, 2015) in *R* 3.5.2 (R Core Team, 2018).

The outcome variable was RT, the fixed effect was Measurement point in months (19 months/25 months/31 months) and the model contained Measurement point as a random slope for Participant. Measurement point in months was centred to reduce multicollinearity (Neter, Wasserman, & Kutner, 1985), and model comparison using a log-likelihood ratio test was used to compute chi-square and p-values. The results revealed a main effect of Measurement point ($\beta = -8.32$, $\chi^2(1) = 49.71$, $p < .001$), indicating that children got faster at recognising familiar words in speech with age.

We next examined whether individual differences in speed of language processing remain stable across development. In other words, did the children who were fast to process speech early on remain fast at the subsequent measurement points? To do this, we calculated a mean RT score for each child at each measurement point and then correlated mean RT scores between 19 and 31 months. There was a significant correlation in mean RTs between 19 and 25 months ($r(68) = 0.23$, $p = .029$), and between 19 and 31 months ($r(69) = 0.28$, $p = .009$), indicating that fast processors at 19 months continued to be fast processors six months later at 25 months, and 12 months later at 31 months. There was no correlation between mean RT at 25 months and 31 months ($r(68) = -0.05$, $p = .658$), a point we return to in the discussion. However, overall the results suggest that individual differences in speed of language processing remained broadly stable between 19 and 31 months. (Note that we also used an accuracy measure, which is sometimes used as well as reaction time in some studies but we do not report these data here since accuracy is not a measure of processing speed. The code and data for these analyses can be found in the supplementary materials at https://osf.io/z2ukm/).

3.2. Analysis 1: Does speed of language processing correlate with expressive vocabulary at each measurement point tested?

Our first main aim was to test whether processing speed correlated with vocabulary size at each measurement point (or only at certain measurement points). To do this, we correlated the mean RT for each child at each measurement point (19 months/25 months/31 months) with each child’s expressive vocabulary score between 8 and 37 months (see Table 2).[4] All *p*-values were adjusted for multiple comparisons using Holm correction based on the number of comparisons within each measurement point.

There were significant correlations between Mean RT at 19 months and all expressive vocabulary measures between 18 and 31 months, and at 36 months, indicating that individual differences in speed of processing at 19 months were associated with earlier, concurrent, and later vocabulary. Surprisingly, however, there was no evidence of such an association between speed of processing at either 25 or 31 months and vocabulary at any of the three measurement points. We return to this point in Analysis 4 below.

---

[3] In response to a comment by a reviewer, we redid the analyses with a more stringent exclusion criteria (children with fewer than four trials). This did not make a difference to the overall pattern of results – though the consequent loss of power meant that the effect of Mean RT on the quadratic term for the GCA model between 19 and 25 months was only marginally significant. We have reported these analyses only in the supplementary materials (https://osf.io/z2ukm/).

[4] The inclusion of RTs only where children make the correct choice (because the initiation of a shift to the wrong picture is likely noise) has the potential to weaken our correlations (because it reduces variance). Thus, we ran some additional analyses to assess whether children with lower vocabularies contributed fewer RT trials. We correlated the number of RT trials per child at 19M with Expressive Vocabulary at 19M, but found no correlation between the two ($r(76) = 0.04$, $p = .365$).

Table 1

Descriptive statistics for speed to recognise familiar words at 19, 25, and 31 months.

	Measurement point	*N*	Mean *(SD)*	SE
RT[a]	19 months	80	729.94 (348.18)	11.26
	25 months	73	675.73 (337.66)	12.22
	31 months	74	639.14 (335.73)	12.04

Note.

[a] RT = reaction time (in msec) to shift eye gaze from distractor to target in time window 300–1800 ms after onset of target word.

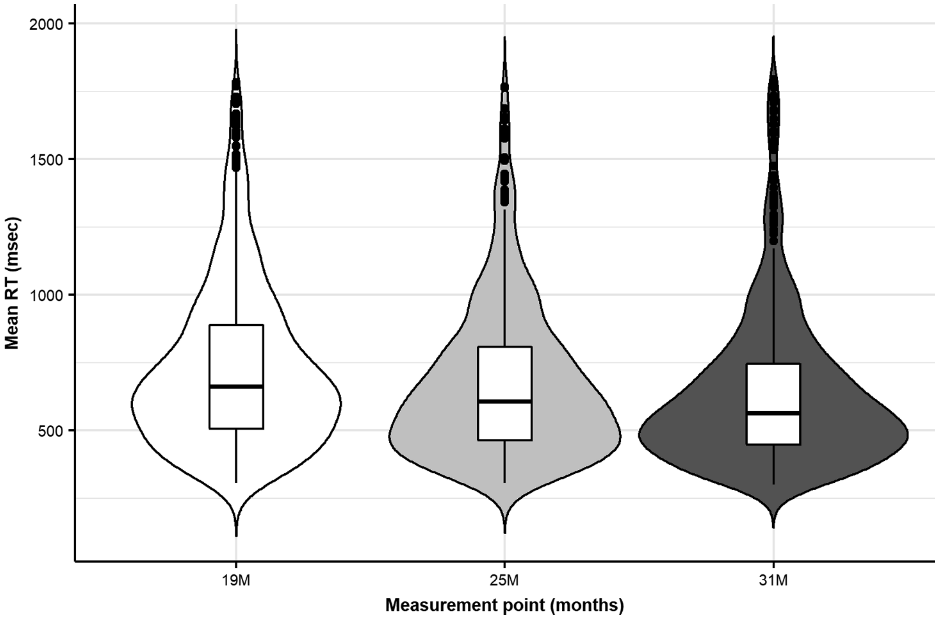


Fig. 1. Mean reaction time (msec) at 19, 25 and 31 months (occurring at least 300 ms after and up to 1800 ms post target word onset).

3.3. Analysis 2: Does processing speed predict later vocabulary growth, while controlling for concurrent vocabulary size?

Our second aim was to test whether individual differences in processing speed predict later growth in vocabulary, while controlling for concurrent vocabulary. In order to do this, we used growth curve analyses to plot the effect of reaction time on vocabulary growth between 19 and 30 months of age. Since there was no evidence from Section 3.2 above of any relationship between any vocabulary measure and processing speed at either 25 or 31 months, we assessed the relationship between vocabulary growth[5] and speed of processing at 19 months only.

Growth curve analyses (GCA; Mirman, 2014) were performed using the *lme4* package. Model comparisons were used to identify the appropriate polynomial order for each GCA model. In cases where the comparison revealed vocabulary over time (Measurement point in months) to be best explained in terms of linear growth, a first-order polynomial was used. Where model comparisons revealed vocabulary growth over time to be curvilinear, second-order orthogonal polynomials were used. All models were fitted with the maximal random effects structure that would converge supported by the data (Barr, Levy, Scheepers, & Tily, 2013). The outcome variable was Expressive vocabulary score. The fixed effect of Mean RT at 19 months (centred to reduce multi-collinearity, Neter et al., 1985) was added individually and its effects on model fit were evaluated using −2 times the change in log-likelihood. Confirmatory tests were performed using log likelihood-ratios via the sequential decomposition of the model (Bates et al., 2015) with bootstrapped simulations ($R = 1000$) to obtain 95% confidence intervals (CIs) and p-values for the model estimates (Luke, 2017). The marginal and conditional pseudo-R^2s are also reported for the growth curve model, which represent the proportion of the variance in the data explained by both the fixed effects alone and the entire model structure respectively (Johnson, 2014; Nakagawa & Schielzeth, 2013; Nakagawa, Johnson, & Schielzeth, 2017).

To investigate whether individual differences in processing speed at 19 months predicted expressive vocabulary growth between 19 and 30 months (see Fig. 2), we first identified the polynomial order that best fit the observed data.

---

[5] Vocabulary growth was initially assessed across two CDIs: the Lincoln CDI measured vocabulary between 19 and 30 months, and the CDI-III measured vocabulary between 31 and 37 months. We report only results from the Lincoln CDI since effects related to the CDI III are confounded by a ceiling effect. Code and data for the analyses using scores from the CDI-III are available in the supplementary materials (https://osf.io/z2ukm/).

Table 2

Correlations between RT at 19, 25, and 31 months and expressive vocabulary measures between 8 and 37 months.

	Measurement point	RT		
		19 months	25 months	31 months
Words produced: CDI W & G[a]	8 months	−0.03	−0.02	0.07
	9 months	−0.02	−0.08	0.18
	11 months	−0.11	0.06	−0.04
	12 months	−0.15	0.09	0.08
	15 months	−0.29	−0.11	0.00
	16 months	−0.25	−0.11	−0.03
	18 months	−0.36**	−0.13	−0.12
Words produced: L-CDI[b]	19 months	−0.40***	−0.11	−0.16
	21 months	−0.45***	−0.14	−0.14
	24 months	−0.45***	−0.11	−0.25
	25 months	−0.38**	−0.03	−0.10
	27 months	−0.40**	−0.02	−0.07
	30 months	−0.34**	−0.08	0.00
Words produced: CDI-III[c]	31 months	−0.34*	−0.02	−0.10
	34 months	−0.15	0.06	−0.07
	36 months	−0.37*	−0.22	−0.21
	37 months	−0.31	−0.23	−0.15

Note. RT = reaction time (msec).

[a] UK-CDI Words and Gestures.

[b] Lincoln CDI Words and Sentences.

[c] CDI-III.

*** $p < .001$.

** $p < .01$.

* $p < .05$.

Compared to a model with only a first order (linear) term for Measurement point (AIC = 5293; BIC = 5318), the model containing a second order (quadratic) Measurement point parameter (AIC = 5247; BIC = 5280) was shown to be more likely according to a number of different model fit metrics ($\chi^2(2) = 50.45$, $p < .001$).

Overall, the model's fixed effects accounted for 62.92% of the variance in the data, which increased to 95.12% with the inclusion of the maximal random effects ($R_m^2 = 0.63$; $R_c^2 = 0.95$). The maximal model that converged contained quadratic Measurement point as a random slope for Participant. Adding Mean RT significantly improved the model fit for the intercept term ($\beta = -0.39$ [-0.56,

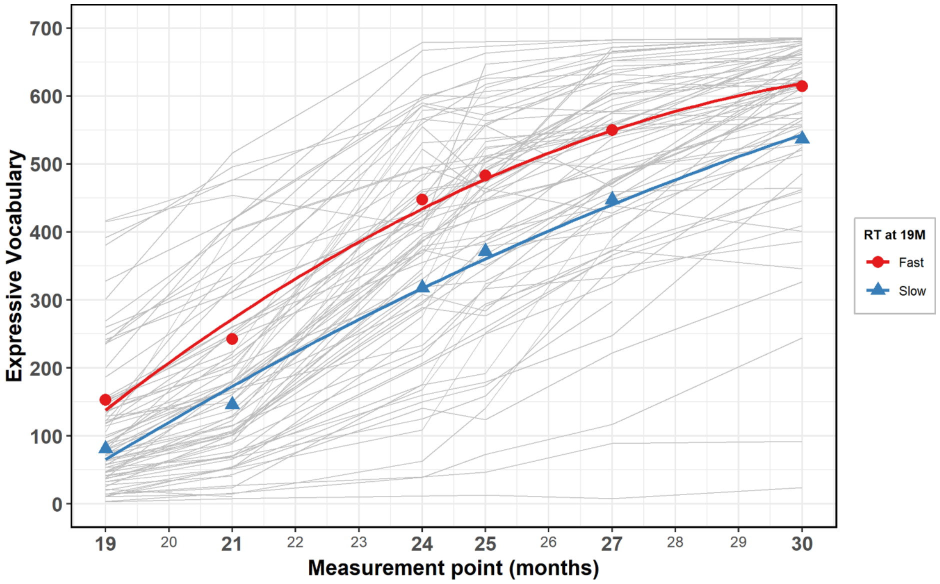


Fig. 2. Vocabulary growth between 19 and 30 months. Grey lines indicate fitted growth trajectories of individual children, as outputted by the model. For the purposes of the graph, we have superimposed a fast (red) and slow (blue) processors line over the individual measurement points, which was determined by a median split; points show average Expressive Vocabulary at that measurement point and the line plots the fit of the best fitting model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

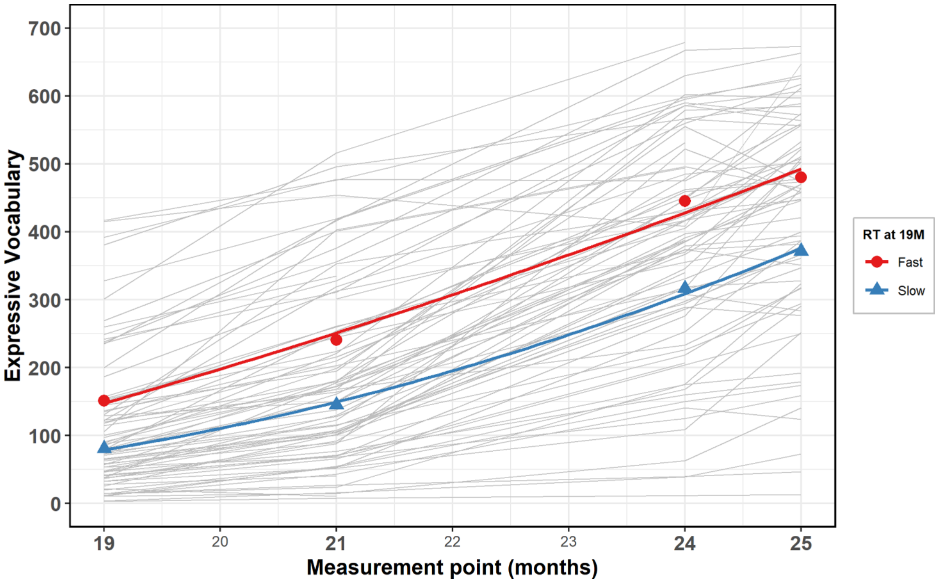


Fig. 3. Vocabulary growth between 19 and 25 months. Grey lines indicate fitted growth trajectories of individual children, as outputted by the model. For the purposes of the graph, we have superimposed a fast (red) and slow (blue) processors line over the individual measurement points, which was determined by a median split; points show average Expressive Vocabulary at that measurement point and the line plots the fit of the best fitting model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

−0.21], SE = 0.09, $\chi^2(1) = 11.97$, $p = .001$). There was also an interaction between Mean RT and the quadratic term ($\beta = 0.16$ [0.02, 0.30], SE = 0.07, $\chi^2(1) = 5.00$, $p = .026$). No interaction, however, was observed between Mean RT and the linear term ($\beta = 0.02$ [−0.161 0.21], SE = 0.09, $\chi^2(1) = 0.40$, $p = .583$). Since the model included orthogonal polynomials, an effect on the intercept term indicates that children who were faster at lexical processing at 19 months had larger vocabularies, on average, across the age range (19–30 months).

The fact that there was no effect on the linear term suggests that, contrary to the prediction, children's speed of processing at 19 months did not significantly influence their growth in vocabulary between 19 and 30 months. However, the effect on the quadratic term indicates an effect of processing speed on the shape of vocabulary growth. Visual inspection of Fig. 3[6] indicates that the shape of the growth curve differed according to the children's processing speed; slow processors tended to show consistent (linear) growth over time, although the slowest children showed slow initial growth which sped up between 25 and 30 months of age. In comparison, fast processors grew their vocabularies more quickly up until 25 months at which point the rate of growth slowed. This may be due to the fact that fast processors were nearing ceiling on the Lincoln CDI by the time they reached 25 months (i.e., leaving little room for further growth; total possible score = 689). Thus, we re-ran the model, but this time using only expressive vocabulary scores between 19 and 25 months (i.e. from the measurement points that occurred before the fastest processors reached ceiling; see Fig. 3).

Once again, model comparisons indicate that a second order polynomial was a better fit to the observed data than a first order polynomial ($\chi^2(2) = 7.29$, $p < .04$). Overall, this model's fixed effects accounted for 52.59% of the variance in the data, which increased to 94.66% with the inclusion of the maximal random effects ($R^2_m = 0.53$; $R^2_c = 0.95$). The maximal model that converged included linear Measurement point as a random slope for Participant.

As before, adding Mean RT to the model significantly improved model fit for both the intercept term ($\beta = -0.41$ [−0.59, −0.21], SE = 0.10, $\chi^2(1) = 15.51$, $p < .001$) and the quadratic term ($\beta = 0.08$ [0.01, 0.16], SE = 0.04, $\chi^2(1) = 4.83$, $p = .031$), but not the linear term ($\beta = -0.10$ [−0.27, 0.07], SE = 0.08, $\chi^2(1) = 1.53$, $p = 0.229$). Thus, in terms of linear growth, faster processors did not show significantly greater vocabulary gains between 19 and 25 months of age than slower processors. They did, however, show a different pattern of growth compared to slow processors. As Fig. 3 shows, fast processors, who tended to start with larger vocabularies at 19 months, grew their vocabulary at a relatively steady pace across the age range. Slow processors, who started with smaller vocabularies at 19 months, showed a quadratic shape of vocabulary growth, beginning slowly but speeding up after 21 months.

To explore these differences further, we assessed whether the effect of processing speed on vocabulary growth differed according to expressive vocabulary level at 19 months. This decision was motivated by the findings of Fernald and Marchman (2012), who reported effects of processing speed on vocabulary growth of late talkers, not typically developing children. We asked: does Mean RT affect vocabulary growth for children with low vocabularies differently from children with high vocabularies, and can this explain the

---

[6] Fig. 2 displays summary lines as well as individual lines per child, which were created using a median split to group children into fast and slow processors. However, note that the median split was performed for graphical purposes only. For all GCA models, individual children's mean RTs were entered into the model.

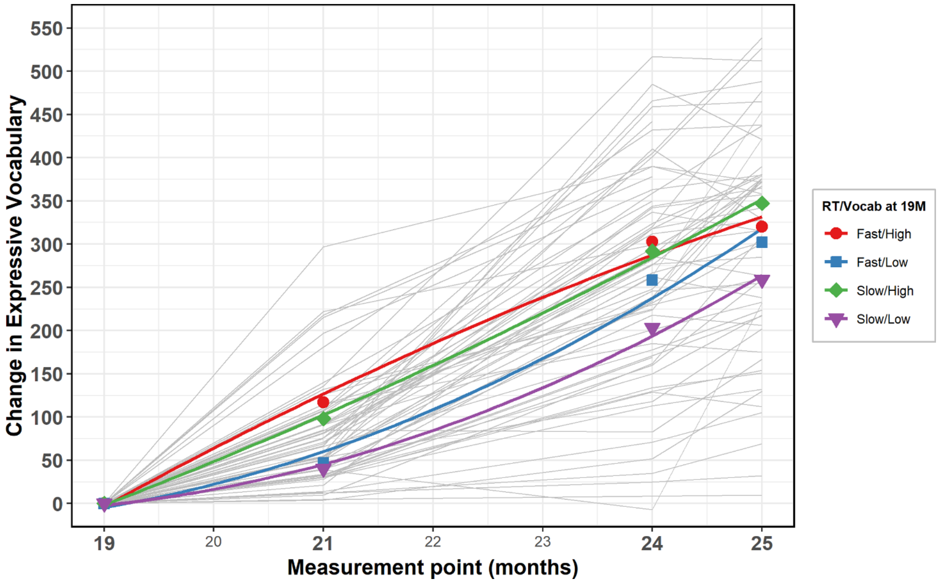


Fig. 4. Change in expressive vocabulary between 19 and 25 months. Grey lines indicate fitted growth trajectories of individual children, as outputted by the model. For the purposes of the graph, the children have been divided via a median split into fast and slow language processors and a median split into those with high and low vocabularies; points show average change in Expressive Vocabulary at that measurement point and the line plots the fit of the best fitting model.

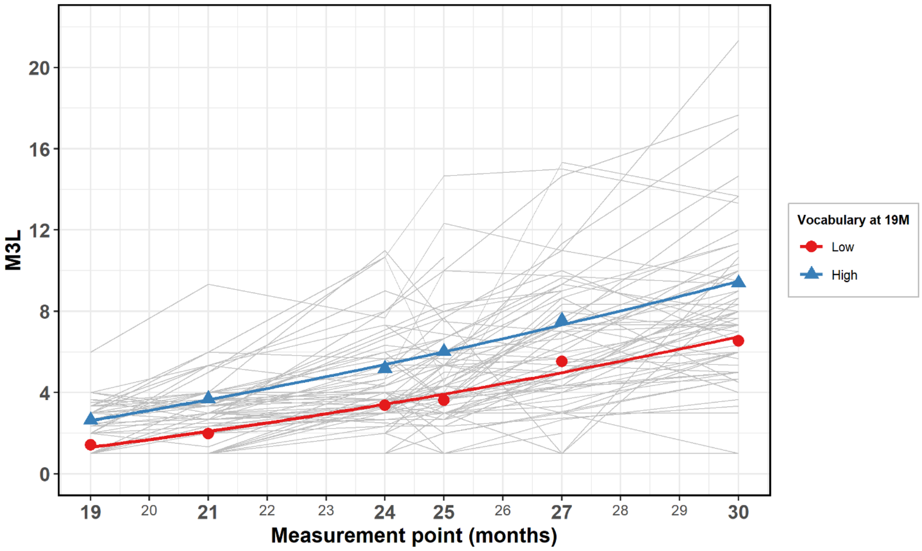


Fig. 5. Growth in M3L between 19 and 30 months with Expressive Vocabulary at 19 months as a predictor. Grey lines indicate fitted growth trajectories of individual children, as outputted by the model. For the purposes of the graph, we have superimposed a low (red) and high (blue) vocabulary line over the individual measurement points, which was determined by a median split; points show average M3L at that measurement point and the line plots the fit of the best fitting model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different shapes of growth we find in the analyses above? Using a median split, we first divided children by vocabulary level (high or low) according to their expressive vocabulary score at 19 months. We then calculated each child's change (difference) in expressive vocabulary score between 19 and 25 months. This was done so that each child's score at 19 months was zero. Thus, in this model, the outcome variable was Change (in expressive vocabulary), and the fixed effects that were fitted to a second-order polynomial were Mean RT and Vocabulary Level at 19 months (high/low).

Overall, this model's fixed effects accounted for 70.45% of the variance in the data, which increased to 80.48% with the inclusion of the maximal random effects ($R_m^2 = 0.70$; $R_c^2 = 0.80$). The maximal model that converged included Measurement point on the intercept term as a random slope for Participant. No interaction between Mean RT and Vocabulary Level was observed on the intercept ($\beta = 0.13$ $[-0.10,\ 0.36]$, SE = 0.12, $\chi^2(1) = 1.07$, $p = 0.323$) or on the quadratic term ($\beta = 0.15$ $[-0.12,\ 0.41]$,

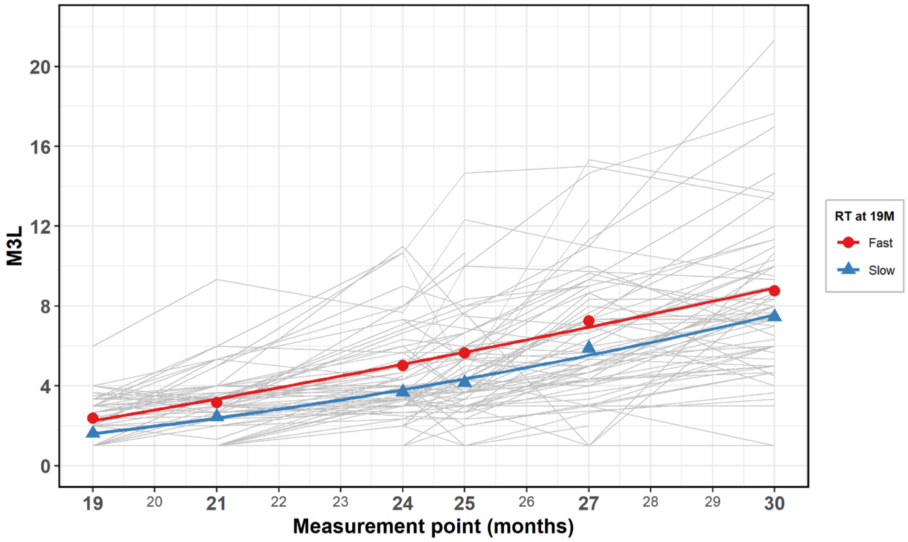


Fig. 6. Growth in M3L between 19 and 30 months with Expressive Vocabulary and Mean RT at 19 months as predictors. Grey lines indicate fitted growth trajectories of individual children, as outputted by the model. For the purposes of the graph, we have superimposed a fast (red) and slow (blue) processors line over the individual measurement points, which was determined by a median split; points show average M3L at that measurement point and the line plots the fit of the best fitting model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

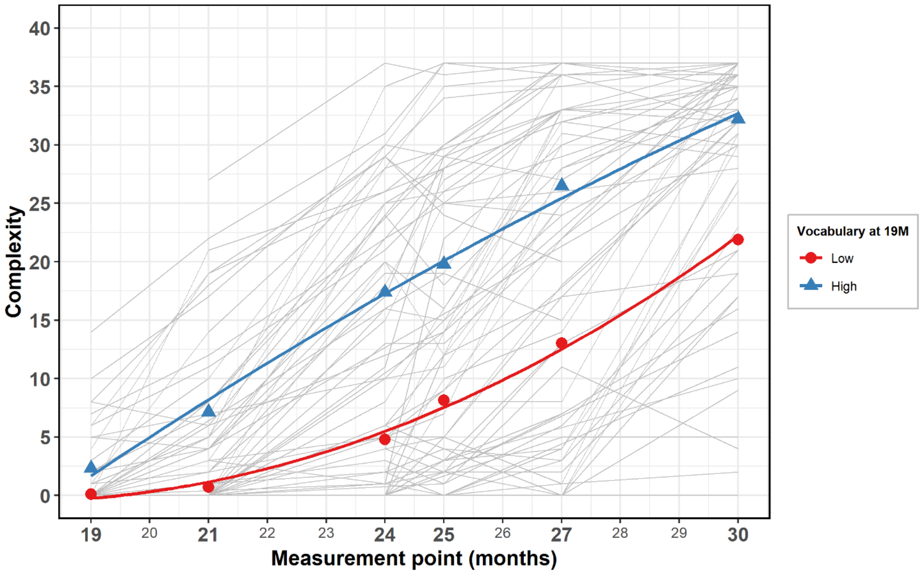


Fig. 7. Growth in syntactic complexity between 19 and 30 months with Expressive Vocabulary at 19 months as a predictor. Grey lines indicate fitted growth trajectories of individual children, as outputted by the model. For the purposes of the graph, we have superimposed a low (red) and high (blue) vocabulary line over the individual measurement points, which was determined by a median split; points show average syntactic complexity at that measurement point and the line plots the fit of the best fitting model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

SE = 0.14, $\chi^2(1) = 1.12$, $p = 0.283$). An interaction between Mean RT and Vocabulary Level, however, did significantly improve the model fit for the linear term ($\beta = 0.30$ [0.03, 0.57], SE = 0.14, $\chi^2(1) = 1.53$, $p = 0.038$), indicating that the effect of processing speed on linear vocabulary growth was different for children with high versus low vocabularies.

Visual inspection of Fig. 4 suggests that processing speed has a positive effect on vocabulary growth for children with lower vocabularies - more so than children with high vocabularies. In other words, in the high vocabulary group, differences in processing speed did not have an effect on the rate of vocabulary growth. However, in the low vocabulary group, those with faster processing

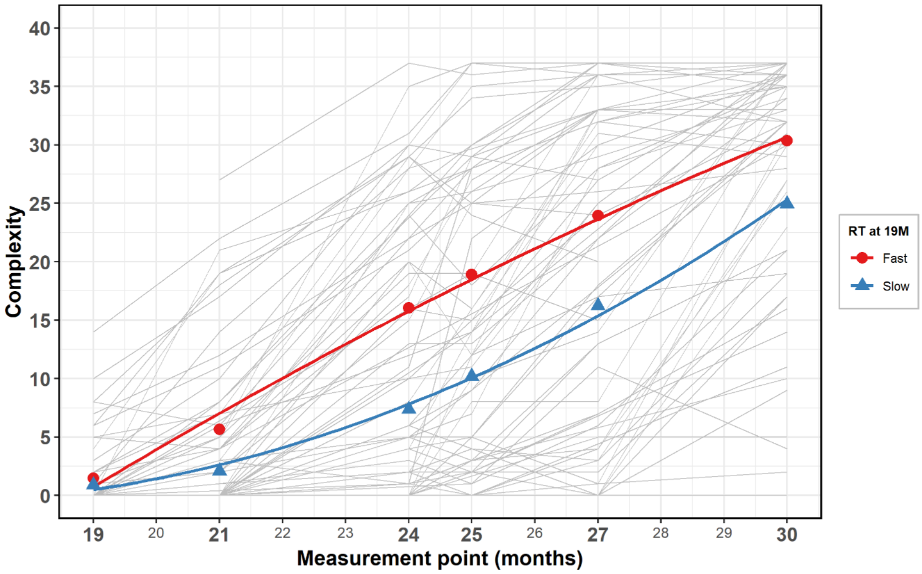


Fig. 8. Growth in syntactic complexity between 19 and 30 months with Expressive Vocabulary and Mean RT at 19 months as predictors. For graphical purposes only, the children have been divided via a median split into fast (red) and slow (blue) processors; points show average complexity score at that measurement point and the line plots the fit of the best fitting model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

speeds showed greater acceleration in their vocabulary growth over the next six months.

3.4. Analysis 3: Does processing speed predict later syntactic growth, while controlling for concurrent vocabulary size?

We next used growth curve analysis to assess whether speed of processing at 19 months facilitates syntactic growth between 19 and 30 months over and above vocabulary size, using the M3L score of the Lincoln CDI as a measure of syntactic ability (Fig. 5). Model comparisons revealed a first-order polynomial was a better fit to the observed data than a second-order polynomial ($\chi^2(2) = 3.86, p = .15$), and so fixed effects were fitted to a model that included only a linear term for Measurement point. Since this analysis controlled for children's vocabulary at the point at which processing speed was measured, we first built a growth curve model with only Expressive Vocabulary at 19 months as the fixed factor.

This model's fixed effects accounted for 56.11% of the variance in the data, which increased to 71.43% with the inclusion of the maximal random effects ($R^2_m = 0.56$; $R^2_c = 0.71$). The maximal model that converged included Measurement point on an intercept term as a random slope for Participant. There was a significant effect of Expressive Vocabulary size on both the intercept ($\beta = 0.01$ [0.01, 0.02], SE = 0.002, $\chi^2(1) = 42.72$, $p < .001$) and linear terms ($\beta = 0.008$ [0.004, 0.01], SE = 2.07e−03, $\chi^2(1) = 13.03$, $p < .001$). Thus, the speed of growth in syntax between 19 and 30 months is strongly predicted by vocabulary size at 19 months.

To test whether speed of processing determines syntactic growth over and above vocabulary size, we added Mean RT at 19 months as an additional fixed factor to the vocabulary model and ran model comparisons between the full linear models with and without Mean RT (Fig. 6). This model's fixed effects explained only an additional 0.79% unique variance in the data (without Mean RT: $R^2_m = 0.56$; $R^2_c = 0.71$; with Mean RT: $R^2_m = 0.57$; $R^2_c = 0.71$). The maximal model that converged included Measurement point on an intercept term as a random slope for Participant. Contrary to the prediction, the addition of Mean RT did not improve model fit for either the intercept ($\beta = 1.912e-05$ [−5.14e−06, 4.36e−05], SE = 1.24e−05, $p = .142$) or linear terms ($\beta = 9.37e-06$ [−2.11e−05, 3.84e−05], SE = 1.52e−05, $p = .559$; comparison of full linear models with and without Mean RT: $\chi^2(4) = 3.119$, $p = .54$). Thus, speed of processing ability does not explain additional significant variance in syntactic growth (in terms of M3L) over and above vocabulary size.

We also used growth curve analysis to assess whether speed of processing at 19 months predicts syntactic growth between 19 and 30 months over and above vocabulary size, using the syntactic complexity score of the Lincoln CDI as a measure of syntactic ability[7]. Model comparisons revealed a second-order polynomial to be a better fit to the observed data than a first-order polynomial ($\chi^2(2) = 49.64$, $p < .001$), and so fixed effects were fitted to a model that included a quadratic Measurement point parameter. As before, this analysis controlled for children's vocabulary at the point at which processing speed was measured, and so we first built a growth curve model with only Expressive Vocabulary at 19 months as the fixed factor. This model's fixed effects accounted for 67.4% of the variance in the data, which increased to 80.33% with the inclusion of the maximal random effects ($R^2_m = 0.67$; $R^2_c = 0.80$). The

---

[7] Again, here we report only results from the Lincoln CDI and not the CDI-III. Code and data for the analyses using scores from the CDI-III are available in the supplementary materials (https://osf.io/z2ukm/).

maximal model that converged included Measurement point on an intercept term as a random slope for Participant. We observed a significant effect of Expressive Vocabulary on the intercept term ($\beta = 0.06$ [0.05, 0.07], SE = 6.13e−03, $\chi^2(1) = 57.61$, $p = \ < 0.001$), the linear term ($\beta = 0.03$ [0.02, 0.05], SE = 7.01e−03, $\chi^2(1) = 20.26$, $p = \ < 0.001$), and the quadratic term ($\beta = -0.05$ [−0.01, −0.03], SE = −6.98e−03, $\chi^2(1) = 44.78$, $p = \ < 0.001$).

Visual inspection of Fig. 7 indicates that this is because children with bigger vocabularies at 19 months have better syntactic knowledge over the age range, and grow their syntactic knowledge at a steady fast pace, whereas syntactic growth for children with smaller vocabularies at 19 months begins slowly, but accelerates once children reach 24 months.

To test whether speed of processing determines syntactic growth over and above vocabulary size, we added Mean RT at 19 months as an additional fixed factor to the vocabulary model and ran model comparisons between the full quadratic models with and without Mean RT (Fig. 8). This model's fixed effects accounted for 69.01% of the variance in the data which increased to 81.25% with the inclusion of maximal random effects ($R_m^2 = 0.69$; $R_c^2 = 0.81$). The maximal model that converged included Measurement point on an intercept term as a random slope for Participant. The addition of Mean RT at 19 M did not improve model fit for the intercept ($\beta = -7.65\text{e}-05$ [−1.07e−05, 2e−04], SE = 4.46e−05, $p = .091$; comparison of full models with and without RT: $\chi^2(1) = 2.65$, $p = 0.091$) nor the quadratic terms ($\beta = -4.45\text{e}-05$ [−5.49e−05, 1e−04], SE = 5.13e−05, $p = .391$; comparison of full models with and without RT: $\chi^2(6) = 0.78$, p = 0.391). It did, however, improve model fit for the linear term (β = −1.74e−04 [7.84e−05, 3e−04], SE = 4.91e−05, p < .001; comparison of full models with and without Mean RT: $\chi^2(4) = 11.93$, $p < .001$). Thus, children who were fast processors got better at producing more syntactically complex sentences more quickly than children who were slow processors, even after controlling for vocabulary size at 19 months.

3.5. Analysis 4: Post-hoc investigation of the relationship between speed of processing and vocabulary – analysis by trial type

In analysis 2 above we reported that only processing speed at 19 months, not at 25 or 31 months, correlated with vocabulary size. Given that other work has shown a relationship between processing speed and vocabulary beyond 19 months (Fernald et al., 2006), we explored the data for a potential explanation.

First, we looked for errors in data entry or analysis scripts, but did not find any. Second, we considered whether the tasks at 25 and 31 months were unreliable and simply capturing noise. However, we dismissed this explanation because there were significant correlations between performance at 19 months and both the 25- and 31-month measurement points, suggesting that the task was measuring meaningful, reliable, variation at the later measurement points. Third, we considered whether the results were due to the items we used in the task. The success of the speed of processing task in measuring individual differences depends on the age appropriateness of the items used in the test; these items must yield scores that meaningfully differentiate between fast and slow processors. However, both children and adults process familiar high frequency words faster than unfamiliar low frequency words. Thus, we hypothesised that perhaps many of the words we used were so familiar and high frequency in the children's input that even slow processors were able to process them quickly at 25 and 31 months of age. This would reduce the variance associated with meaningful individual differences at these measurement points, increase the variance associated with other factors (e.g., noise, visual attention differences), and thus reduce the likelihood of finding meaningful correlations with vocabulary size.

To determine the plausibility of this hypothesis, we ran additional analyses that exploited the fact that we tested both single word targets and adjective-noun combinations (e.g., *red* shoe) at the 25- and 31-month measurement points. Adjectives present a challenge to young children: they appear later than nouns in comprehension and production (Ramscar, Thorpe, & Denny, 2007; Waxman & Booth, 2001), children find it difficult to map novel adjectives onto object properties unless provided with rich referential information (Mintz & Gleitman, 2002), and despite spontaneously producing colour adjectives like red and blue in their own speech, 30-month olds still show a delay in their real-time processing of adjective-noun combinations (e.g., blue car; Fernald, Thorpe, & Marchman, 2010). In short, early proficiency with adjectives is poor compared to other grammatical classes. This late emergence has been attributed, in part, to the relatively low frequency of adjectives in the input (e.g., see Sandhofer, Smith, & Luo, 2000, who reported the relative frequency of adjective tokens to be substantially lower in mothers' speech to their children than noun or verb tokens: 938 adjectives compared to 4747 nouns and 4595 verbs). Given this, we predicted that adjective-noun combinations would be more likely to yield meaningful individual differences in processing speed, and thus more likely to yield correlations with vocabulary size. The descriptive data showing mean RTs separately for noun trials and for adjective-noun trials can be found in Table 3, and the correlations between these mean RTs and vocabulary can be found in Table 4.

The children's processing speed was slower for adjective-noun trials than for noun-only trials, and the variance (SD) was substantially higher. In addition, critically, and as predicted, the correlations with vocabulary were also substantially higher on

Table 3

Descriptive statistics for speed to recognise familiar words at 25 and 31 months split by trial type.

	Measurement point	Noun-only		Adjective + Noun	
		Mean (*SD*)	SE	Mean (*SD*)	SE
RT[a]	25 months	647.86 (299.66)	12.11	788.71 (377.36)	30.71
	31 months	607.41 (298.96)	14.71	675.14 (334.32)	17.52

Note.

[a] Reaction time (msec).

Table 4
Correlations between Mean RT at 25 and 31 months (split by noun and adjective-noun trials) and vocabulary measures.

	Measurement point	Mean RT 25 months Noun-only	Adjective + Noun	31 months Noun-only	Adjective + Noun
Words understood: CDI W & G[a]	16 months	−0.03	−0.28	−0.02	−0.23
	18 months	−0.03	−0.28	−0.10	−0.29
Words understood: L-CDI[b]	19 months	−0.08	−0.22	−0.11	−0.25
	21 months	−0.09	−0.28	−0.06	−0.22
	24 months	−0.14	−0.21	−0.07	−0.29
	25 months	−0.07	−0.20	−0.03	−0.25
	27 months	−0.03	−0.23	−0.08	−0.22
	30 months	−0.10	−0.19	−0.10	−0.15
Words produced: CDI W & G[a]	16 months	−0.02	−0.32	0.11	−0.17
	18 months	−0.01	−0.40	0.03	−0.22
Words produced: L-CDI[b]	19 months	−0.01	−0.33	−0.01	−0.27
	21 months	−0.08	−0.33	−0.02	−0.27
	24 months	−0.14	−0.20	−0.14	−0.25
	25 months	−0.06	−0.19	−0.06	−0.23
	27 months	−0.04	−0.19	−0.08	−0.23
	30 months	−0.10	−0.19	−0.01	−0.20

Note. RT = reaction time (msec).
[a] UK-CDI Words and Gestures.
[b] Lincoln CDI Words and Sentences.

adjective-noun trials than on noun-only trials. Since this was a post-hoc analysis, we did not conduct inferential statistics, but it is clear from Table 4 that there were much larger (small- to medium-sized) correlations between mean RTs at 25 and 31 months and vocabulary at a number of measurement points for adjective-noun trials than for noun-only trials. In sum, as expected, once reaction times for adjective-noun trials were calculated separately, the relationships between vocabulary and speed of processing at 25 and 31 months emerged.

4. Discussion

The aim of the current work was to use data from a large longitudinal sample of children to determine the relationship between language processing speed and language acquisition. To do this, we tested (a) whether processing speed correlates with vocabulary size at each age tested, (b) whether processing speed predicts later vocabulary growth and (c) whether processing speed predicts later syntax acquisition, controlling for concurrent vocabulary size.

In our preliminary analysis, we replicated the effects of age and consistency across time that have been found in the literature, so are satisfied that our task is measuring meaningful, reliable variation in processing speed. Children got faster at recognising familiar words in spoken speech between 19 and 31 months, and individual differences in language processing remained broadly stable across development – those children who were fast at processing at 19 months were those same children who were fast at processing 12 months later.

With respect to our first main analysis, we found that speed of processing at 19 months correlated with vocabulary size between 18 and 36 months of age, as predicted. We did not find a correlation between 25- and 31-month processing speed and vocabulary size, but we believe that that this was because the items chosen for the task were so familiar and highly frequent that even our slow processors could process them quickly at 25 and 31 months. This reduced the variance associated with meaningful individual differences in language processing speed, increased the variance associated with other factors (either noise, or other intrinsic differences, e.g., in visual processing ability), and thus reduced the likelihood of finding meaningful correlations with vocabulary size. This conclusion is consistent with our exploratory Analysis 4, which showed that processing speed of the less frequent adjective-noun targets did correlate with vocabulary size. Thus, we contend that our data strongly support the hypothesis that children with larger vocabularies are able to process familiar words more efficiently at 19 months, and provide tentative support that this relationship may hold more generally across early childhood; or at least across the 2nd and 3rd years of life.

Our second analysis tested whether speed of processing predicted the rate of later vocabulary growth. Although we could not meaningfully interpret vocabulary growth after 25 months because of ceiling effects in our vocabulary measure, we found that processing speed predicted quadratic growth between 19 and 25 months of age. That is, the shape of vocabulary growth differed depending on how quick children were to process familiar words. Faster processors maintained their initial advantage in vocabulary size, growing their vocabularies at a steady pace between 19 and 25 months. In contrast, vocabulary growth in slow processors began slowly, but accelerated after 21 months. Follow-up analyses suggested that these results could be explained by the fact that processing speed had different effects on children with large and small vocabularies. For the children with large vocabularies, faster processing of familiar words **did not** lead to accelerated new word learning in the subsequent six months. However, amongst the group of children with small vocabularies, faster processing of familiar words **did** lead to faster vocabulary growth in the subsequent six months. Thus, our findings suggest that processing speed predicts vocabulary growth, but only for children with smaller vocabularies.

One fairly simplistic interpretation of this finding is that processing speed is advantageous, but only for slow processors (who also tend to have small vocabularies). We are reluctant to draw this conclusion, however, because there is at least some evidence in the literature for a more widespread predictive relationship between being fast at processing language and vocabulary growth, even after controlling for concurrent vocabulary size (Fernald et al., 2006; note that our children were slightly, though not substantially, more advanced in their vocabulary size (at 25 months: mean = 418.6 (*SD* = 157.0)) than those tested by Fernald et al. (at 25 months: mean = 391.7 (*SD* = 176.8)), but we cannot draw robust conclusions from this comparison because the measurement methods may not be comparable (no cross-linguistic analysis has been done to compare the MB-CDI used in the United States and the Lincoln-CDI used in the United Kingdom), and our children were on average one month older (19 vs. 18 months)). We suggest instead that children who are faster at processing have an advantage early in the lexicon-building process, but that once vocabulary reaches a critical mass, speed of processing becomes less reliable as a predictor of variance in vocabulary learning (though there may be another methodological explanation concerning task difficulty – see below). In other words, our high vocabulary children may already be so good at processing familiar words quickly that processing speed ceases to be a predictive factor in their subsequent vocabulary growth, with other skills, such as the ability to do syntactic bootstrapping, playing an increasingly important role (see Hollich et al., 2000).

This hypothesis is also compatible with the findings of three of the four studies that have previously reported similar predictive relationships, which also found that the effect of processing speed on vocabulary was stronger (or only present) in children with low or below average language; in preterm 18 month olds (Marchman et al., 2015), in late talking 18 month olds (Fernald & Marchman, 2012) and in children with low levels of language (Lany, 2018). Relatedly, Lany also found stronger effects in more difficult word learning situations, which provides converging evidence that familiar word processing speed might play a bigger role in new word learning when the word learning task is challenging. Our hypothesis, thus, also makes a unique prediction that can be tested in subsequent research; that whether or not speed of processing predicts the speed of vocabulary growth will depend on how difficult it is for the child to learn new words.

Our third analysis tested whether processing speed contributes to individual differences in syntax acquisition. Although one previous study has explored this relationship, it assessed only concurrent relationships (Fernald et al., 2006). To go beyond this, we investigated the direct relationship between processing speed and later syntax growth, controlling for concurrent vocabulary. We found that, while speed of processing did not predict the growth of syntax as measured by M3L, it did predict syntactic growth using the CDI syntactic complexity measure. Children who were fast at processing familiar words at 19 months had accelerated syntactic growth compared with children who were slow processors, even when we controlled for vocabulary size at 19 months.

Note that, in our study, syntactic growth was also predicted by expressive vocabulary at 19 months. That is, children who produced more words got better at producing syntactically complex sentences more quickly. Thus, our findings add to the large body of work that has argued for a strong association between vocabulary and syntactic development during early acquisition (e.g., Bannard et al., 2009; Bates & Goodman, 1999; Braginsky et al., 2015). In our study, however, vocabulary size alone did not drive the acquisition of syntactic complexity - an additional contributing factor was the speed with which a child was able to process the language that they hear. We therefore conclude that speed of processing directly influences the rate of syntactic complexity growth.

There are two questions that remain to be addressed. The first is: why did we observe speed of processing effects for syntactic growth when using a measure of syntactic complexity, but not when using the M3L measure? We think a likely explanation is that the complexity measure is more reliable at capturing individual differences in syntactic knowledge because it does not rely exclusively on parental recall. Variation across M3L scores are likely to reflect parental recall ability, as well as child's syntactic ability, since the parent has to recall the child's three longest utterances without prompts. Unlike the M3L measure, the complexity measure is a recognition measure; it provides explicit examples from which parents choose, which makes the task less demanding. In addition, M3L is often a more noisy measure because parents' examples of an utterance are not always compatible with what constitutes an utterance according to the M3L scoring guidelines, and because it depends somewhat on how spontaneously productive a child is (which is likely to be a function of the child's personality). More work is needed to determine how well these measures map onto each other.

A second question concerns just how processing speed affects vocabulary and syntactic growth. That is, what mechanism might be involved in this process? A few possibilities have already been suggested. Being faster at processing familiar words might free up cognitive resources that can then be dedicated to the learning of new words and syntax (Fernald & Marchman, 2012). In addition, processing of familiar words might help in the tracking of co-occurrences between words, which is a necessary skill for syntactic development (Marchman & Fernald, 2008). Alternatively, it may be that language processing has to become more efficient for children who already have larger vocabularies because these children need to be able to categorise the larger number of words that they have in their lexicon. Faster processors then find it easier to learn new words and syntax.

All of these accounts are a little underspecified. There is, however, one detailed mechanistic model of vocabulary learning, which proposes that it is the extent, and diversity of lexical and sub-lexical information stored in the lexicon that is driving both the speed of processing of familiar words, and the speed of new word acquisition: the CLASSIC model (Jones & Rowland, 2017; Jones, 2016; Jones, Gobet, Freudenthal, Watson, & Pine, 2014). The key parameters of the model are (a) a chunk-based learning mechanism that learns by gradually chunking information in the model's internal representational system on the basis of incoming input and (b) a probabilistic processing constraint such that, on average, only a certain number of chunks can be accessed in any given input; this mimics processing limitations that prevent young children from processing long utterances in full (Gathercole, 2006).

The model receives input in the form of real utterances (i.e., naturalistic data) which are presented as strings of word-delimited phonetic symbols (e.g., */w ɒ t/ k æ t/ for 'what cat?')*. It learns first by coding a word into as few chunks as possible on the first exposure, and then by combining adjacent chunks on each subsequent exposure until the whole word is represented as one chunk. Thus, faced with a phonetically coded word, the model, at first, is only able to learn sub-lexical information in the form of phonemic sequences *(/k/, /æ/, /t/)*. However, on each subsequent exposure, adjacent sub-lexical chunks are combined (e.g., /ca/ and /at/) until eventually the whole word can be encoded as one chunk (/cat/). Thus, as more input is seen, it is increasingly likely that the chunks learned will correspond to lexical items, as well as sub-lexical chunks.

The way in which CLASSIC learns provides a potential explanation of the relationship between speed of processing and vocabulary. Models with larger vocabularies are able to process familiar words more quickly, because their larger lexicons mean that they are more likely to be able to represent a familiar word with a smaller number of larger chunks (e.g., one (/cat/) instead of three (/c/, a/ and /t/)). Each chunk takes the same time to process, regardless of its length, so the fewer chunks needed to process a word, the faster the processing speed of that word. Models with larger vocabularies are also able to learn new words more quickly, because they have a larger store of sub-lexical chunks that they can use to encode new words; this means that they can encode new words in fewer exposures, and explains why children with larger vocabularies not only process words faster but learn new words more quickly. Finally, once vocabulary reaches a certain size, all highly frequent familiar words are stored as one chunk, and there is no longer any meaningful variation in processing time in the model. This explains why we see no correlation between vocabulary and speed of processing at 25 and 31 months, unless we restrict our analysis to the adjective-noun phrase stimuli, and potentially why the relationship is stronger in children with low vocabulary levels at earlier ages. Whether or not children process words in the way we suggest, using chunking, however, remains to be investigated. Whilst there is preliminary evidence in favour of chunking as a processing mechanism (e.g., Gobet et al., 2001), there is also evidence to suggest that lexical processing unfolds in line with the phonetic signal. For instance, work with both adults (e.g., Allopenna, Magnuson, & Tanenhaus, 1998) and children (Swingley, Pinto, & Fernald, 1999) reveals that phonological onset competitors (like **do**g and **do**ll) slow lexical processing – an effect that would not be seen if, as proposed by the CLASSIC model, familiar words are processed as sub-lexical chunks.

In sum, the CLASSIC model provides a theoretically plausible explanation of our main results. However, further experimental work is required to determine the psychological plausibility of chunking as a mechanism for lexical processing, and to assess whether the model can replicate the effects of processing speed on syntax acquisition.

5. Conclusion

Overall, our results indicate a relatively direct relationship between processing and syntax, in which fast processing speeds can promote the growth of vocabulary and of syntax, perhaps because fast processors have more deeply entrenched, more easily retrieved lexical representations, or because they have a larger store of lexical and sub-lexical chunks to call on in new word learning. When viewed as a whole, this work illustrates two broader points about the mechanisms by which children acquire linguistic, and perhaps more broadly cognitive, representations; (1) that the child's developing processing system is likely to play a key role in shaping the acquisition process, and (2) that the knowledge that a child has accumulated at the point of learning may critically determine not only how quickly they process their input, but also how and what they learn from their environment.

Acknowledgements

This work was supported by the International Centre for Language and Communicative Development (LuCiD) at the University of Liverpool. The support of the Economic and Social Research Council [ES/L008955/1] is gratefully acknowledged. Thanks also go to the team at the Center for Infant Studies at Stanford University for kindly sharing their stimuli with us, and particularly to Virginia Marchman for her invaluable input throughout.

Appendix A. Sample characteristics

See Tables A1–A6.

Table A1
Ethnic Background.

	N
White British/Irish	88
Mixed ethnicity: White and Other	1
Asian/Asian British	0
Black/African/Caribbean/Black British	0
Other ethnic group	1

Table A2
Maternal age.

	N
Up to 20 years	2
21–25 years	4
26–30 years	26
31–35 years	36
36 + years	22

Table A3
Paternal age.

	N
Up to 20 years	1
21–25 years	1
26–30 years	18
31–35 years	38
36 + years	32

Table A4
Maternal education.

	N
No formal qualifications	0
GCSE/O level/NVQ level 1or 2/similar	6
A level/NVQ level 3/similar	10
University degree/HND/HNC/NVQ level 4 or 5/similar	34
Postgraduate/similar e.g. (PGCE, PhD, MA etc)	40

Table A5
Paternal education.

	N
No formal qualifications	2
GCSE/O level/NVQ level 1or 2/similar	13
A level/NVQ level 3/similar	16
University degree/HND/HNC/NVQ level 4 or 5/similar	42
Postgraduate/similar e.g. (PGCE, PhD, MA etc)	17

Table A6
Household income.

	N
£0–£14,000	0
£14,001–£24,000	3
£24,001–£42000	24
£42001 or more	62
Declined to answer	1

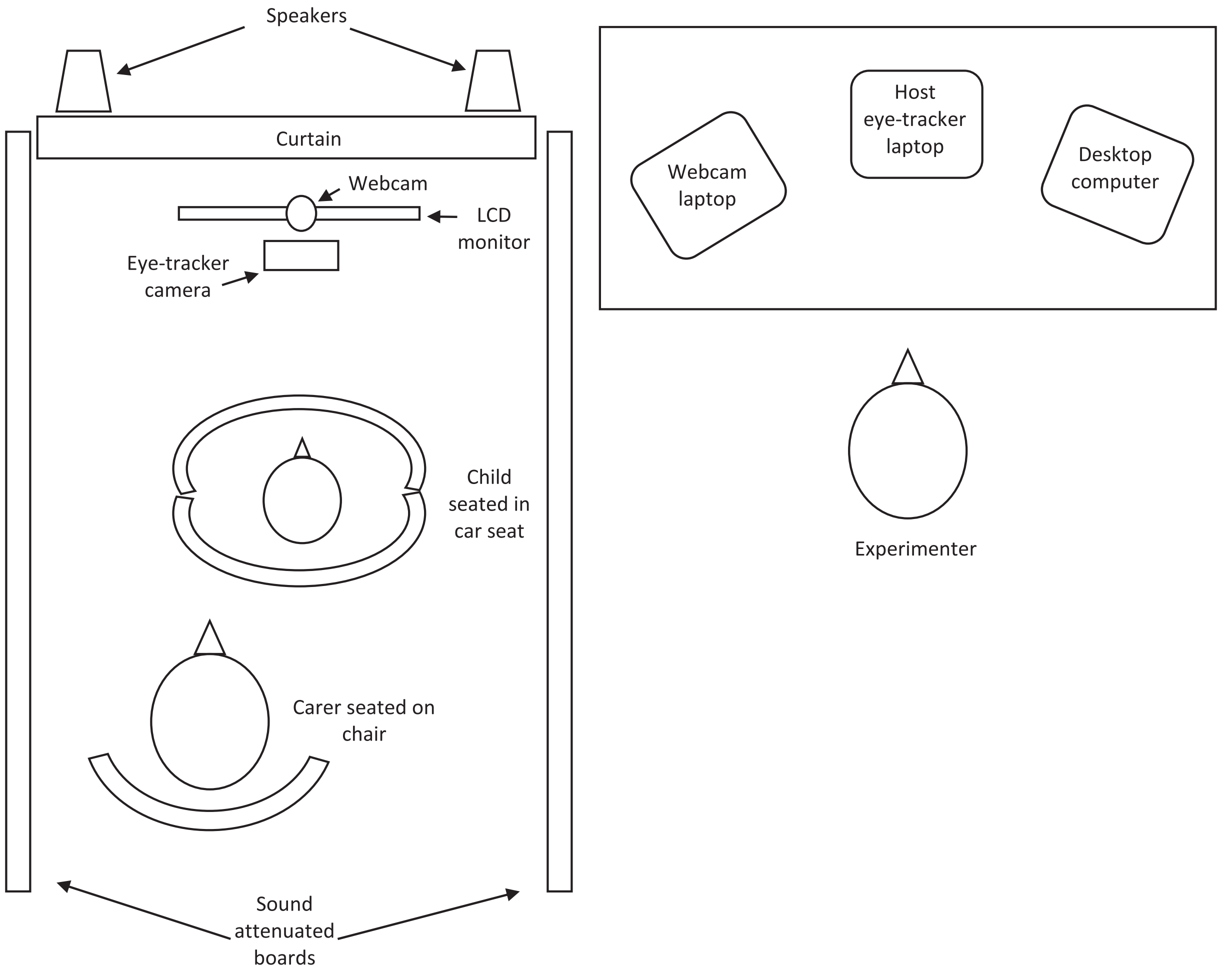
Appendix B

See Table B7.

Table B7
Target words as they were paired in the speed of processing task at 19, 25, and 31 months.

Age	Target words	
19 months	baby	doggie
	book	car
	ball	shoe
	cat	bird
25 months	baby	doggie
	cat	bird
	juice	car
	book	biscuit
	blue shoe	red ball
	red shoe	blue ball
31 months	baby	doggie
	bunny rabbit	monkey
	book	juice
	little sock	big sock
	little flower	big flower
	little biscuit	big biscuit
	little spoon	big spoon
	blue ball	red ball
	blue shoe	red shoe
	blue car	red car
	blue house	red house

Appendix C. Schematic diagram of experimental set-up



Appendix D

See Table D8.

Table D8

Descriptive statistics for Words understood and Words produced on the UK-CDI, Lincoln CDI, and CDI III between 8 and 37 months.

	Measurement point	*N*	Mean (*SD*)	Range
Words understood: CDI W & G[a]	8 months	79	24.66 (26.37)	0–140
	9 months	70	37.27 (219)	1–220
	11 months	75	59 (51.01)	0–306
	12 months	79	80.78 (66.06)	5–329
	15 months	83	146.6 (83.21)	13–375
	16 months	79	202.4 (95.41)	26–395
	18 months	82	245.57 (86.18)	1–324
Words understood: L-CDI[b]	19 months	79	321.7 (131)	54–627
	21 months	81	379.3 (129.4)	126–655
	24 months	75	501.5 (116.4)	176–684
	25 months	73	531.4 (108.3)	249–686
	27 months	73	575.9 (89.37)	322–684
	30 months	73	609.4 (82.57)	317–686
Words produced: CDI W & G[a]	8 months	79	0.97 (1.3)	0–4
	9 months	70	1.77 (2.46)	0–12
	11 months	75	3.77 (4.02)	0–25
	12 months	79	6.8 (8.36)	0–47
	15 months	83	26.13 (33.25)	0–240
	16 months	79	47.78 (50.48)	0–262
	18 months	82	86.07 (73.77)	1–324
Words produced: L-CDI[b]	19 months	79	115.7 (102.8)	3–417
	21 months	81	192.7 (133.2)	8–516
	24 months	75	375.3 (159.2)	39–679
	25 months	73	418.6 (157)	13–673
	27 months	73	498.1 (142.6)	8–683
	30 months	73	569.1 (134.1)	24–686
Words produced: CDI-III[c]	31 months	75	61.92 (19.58)	13–100
	34 months	63	73.30 (19.13)	22–100
	36 months	71	77.24 (16.69)	26–99
	37 months	70	79.94 (17.39)	32–100

Note.

[a] UK-CDI Words and Gestures.

[b] Lincoln CDI Words and Sentences.

[c] CDI-III.

Appendix E. Summary of vocabulary growth curve models

See Tables E1–E3.

Table E1
The effect of 19 M RT on expressive vocabulary growth between 19 and 30 months (95% confidence interval in brackets).

Fixed effects	Estimated Coefficient [CI]	SE	*t* value	*p* value
(Intercept)	362.68 [337.74, 387.44]	12.68	28.61	–
Linear term	385.28 [358.67, 410.86]	13.31	28.94	=.001
Quadratic term	−56.64 [−75.28, −38.23]	9.45	−5.99	=.001
RT19: Intercept	−0.39 [−0.56, −0.21]	0.09	−4.22	=.001
RT19: Linear	0.02 [−0.16, 0.21]	0.09	0.26	=.583
RT19: Quadratic	0.16 [0.02, 0.29]	0.07	2.29	=.286
Random effects	Variance	Std. Dev.		
Participant (Intercept)	12,198	110.44		
Participant (Linear)	10,472	102.33		
Participant (Quadratic)	4578	67.66		
	AIC	BIC	logLik	Deviance
	5106.3	5159.4	−2540.1	5080.3

Table E2
The effect of 19 M RT on expressive vocabulary growth between 19 and 25 months (95% confidence interval in brackets).

Fixed effects	Estimated Coefficient [CI]	SE	*t* value	*p* value
(Intercept)	278.49 [250.94, 304.67]	13.70	20.32	–
Linear term	252.15 [228.63, 274.59]	11.72	21.51	=.001
Quadratic term	18.48 [8.41, 28.48]	5.12	3.61	=.001
RT19: Intercept	−0.41 [−0.59, −0.21]	0.10	−4.21	< .001
RT19: Linear	−0.10 [−0.27, 0.07]	0.09	−1.14	=.229
RT19: Quadratic	0.08 [0.01, 0.16]	0.04	2.25	=.031
Random effects	Variance	Std. Dev.		
Participant (Intercept)	13,013	114.07		
Participant (Linear)	8254	90.85		
	AIC	BIC	logLik	Deviance
	3486.4	3523.4	−1733.2	3466.4

Table E3
The effect of 19 M RT on change in expressive vocabulary growth between 19 and 25 months (95% confidence interval in brackets).

Fixed effects	Estimated Coefficient [CI]	SE	*t* value	*p* value
(Intercept)	162.24 [146.86, 177.27]	7.76	20.91	–
Linear term	255.32 [237.78, 272.64]	8.89	28.71	< .001
Quadratic term	18.05 [0.70, 36.02]	9.01	2.00	=.120
RT19: Intercept	−0.06 [−0.18, 0.05]	0.06	−1.05	=.199
Vocab19: Intercept	46.11 [14.34, 75.82]	15.69	2.94	=.008
RT19: Linear	−0.07 [−0.20, 0.06]	0.07	−0.99	=.323
RT19: Quadratic	0.04 [−0.09, 0.18]	0.07	0.59	=.220
Vocab19: Linear	39.29 [4.72, 75.36]	18.02	2.18	=.18
Vocab19: Quadratic	−38.66 [−74.87, −2.55]	18.45	−2.10	=.067
RT19: Vocab19: Intercept	0.13 [−0.10, 0.36]	0,12	1.13	=.323
RT19: Vocab19: Linear	0.3 [0.03, 0.57]	0,14	2.18	=.038
RT19: Vocab19: Quadratic	0.15 [−0.12, 0.41]	0.14	1.08	=.283
Random effects	Variance	Std. Dev.		
Participant (Intercept)	2418	49.17		
	AIC	BIC	logLik	Deviance
	2864.5	2913.6	−1418.3	2836.5

Appendix F. Summary of syntactic growth models

See Tables F1–F4.

Table F1
The effect of 19 M expressive vocabulary on growth in M3L between 19 and 30 months (95% confidence interval in brackets).

Fixed effects	Estimated Coefficient [CI]	SE	*t* value	*p* value
(Intercept)	4.74 [4.42, 5.07]	0.17	28.44	–
Linear term	4.98 [4.56, 5.39]	0.21	23.51	< .001
Vocab19: Intercept	0.01 [0.01, 0.02]	1.61e−03	8.02	< .001
Vocab19: Linear	7.79e−03 [0.004, 0.012]	2.07e−03	3.77	< .001
Random effects	Variance	Std. Dev.		
Participant (Intercept)	1.619	1.272		
	AIC	BIC	logLik	Deviance
	1736.0	1760.1	−862.0	1724.0

Table F2
The effect of 19 M expressive vocabulary and 19 M RT on growth in M3L between 19 and 30 months (95% confidence interval in brackets).

Fixed effects	Estimated Coefficient [CI]	SE	*t* value	*p* value
(Intercept)	4.85 [4.50, 5.21]	0.18	27.05	–
Linear term	5.04 [4.58, 5.48]	0.23	21.91	< .001
Vocab19: Intercept	0.01 [0.01, 0.02]	2.04e−03	6.87	< .001
RT19: Intercept	−8.10e04 [−0.004, 0.002]	1.40e−03	−0.58	=.534
Vocab19: Linear	8.39e−03 [0.003, 0.013]	2.58e−03	3.26	< .001
RT: Linear	−2.96e−04 [−0.004, 0.003]	1.76e−03	−0.17	=.861
Vocab19: RT19: Intercept	1.91e−05 [−5.14e−06, 4.36e−05]	1.24e−05	1.54	=.142
Vocab19: RT19: Linear	9.37e06 [−2.11e−05, 3.84e−05]	1.52e−05	0.62	=.559
Random effects	Variance	Std. Dev.		
Participant (Intercept)	1.54	1.24		
	AIC	BIC	logLik	Deviance
	1740.8	1781.0	−860.4	1720.8

Table F3
The effect of 19 M expressive vocabulary on growth in syntactic complexity between 19 and 30 months (95% confidence interval in brackets).

Fixed effects	Estimated Coefficient [CI]	SE	*t* value	*p* value
(Intercept)	12.86 [11.62, 14.11]	0.64	20.22	–
Linear term	21.87 [20.48, 23.32]	0.73	30.14	< .001
Quadratic term	1.74 [0.40, 3.10]	0.69	2.52	=.026
Vocab19: Intercept	0.06 [0.05, 0.07]	6.13e−03	9.80	< .001
Vocab19: Linear	0.03 [0.02, 0.05]	7.01e−03	4.67	< .001
Vocab19: Quadratic	−0.05 [−0.06, −0.03]	6.98e−03	−6.94	< .001
Random effects	Variance	Std. Dev.		
Participant (Intercept)	23.62	4.86		
	AIC	BIC	logLik	Deviance
	2927.3	2959.9	−1455.7	2911.3

Table F4
The effect of 19 M expressive vocabulary and 19 M RT on growth in syntactic complexity between 19 and 30 months (95% confidence interval in brackets).

Fixed effects	Estimated Coefficient [CI]	SE	*t* value	*p* value
(Intercept)	13.31 [12.01, 14.68]	0.68	19.54	–
Linear term	22.94 [21.45, 24.50]	0.78	29.56	< .001
Quadratic term	2 [0.54, 3.50]	0.76	2.64	=.026
Vocab19: Intercept	0.06 [0.05, 0.08]	7.68e−03	8.19	< .001
RT19: Intercept	−5.76e−03 [−0.016, 0.005]	5.28e−03	−1.09	=.270
Vocab19: Linear	0.04 [0.02, 0.06]	8.97e−03	4.72	< .001
Vocab19: Quadratic	−0.04 [−0.06, −0.02]	8.65e−03	−4.56	< .001
RT: Linear	−8.64e−03 [−0.020, 0.003]	5.82e−03	−1.48	=.126
RT: Quadratic	8.53e−03 [−0.003, 0.02]	5.80e−03	1.47	=.146
Vocab19: RT19: Intercept	7.65e−05 [−1.07e−05, 2e−04]	4.46e−03	1.71	=.091
Vocab19: RT19: Linear	1.74e−04 [7.84e−05, 3e−04]	4.91e−05	3.55	< .001
Vocab19: RT19: Quadratic	4.45e−05 [−5.49e−05, 1e−04]	5.13e−05	0.87	=.391
Random effects	Variance	Std. Dev.		
Participant (Intercept)	22.37	4.73		
	AIC	BIC	logLik	Deviance
	2918.0	2975.1	−1445.0	2890.0

References

Alcock, K. J., Meints, K., Rowland, C. F., Brelsford, V., Christopher, A., & Just, J. (2019). *The UK communicative development inventory: Words and gestures.* Guildford: J& R Press Ltd.

Allopenna, P. D., Magnuson, J. S., & Tanenhaus, M. K. (1998). Tracking the time course of spoken word recognition using eye movements: Evidence for continuous mapping models. *Journal of Memory and Language, 38*, 419–439.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*, 390–412.

Bannard, C., Lieven, E., & Tomasello, M. (2009). Modeling children's early grammatical knowledge. *Proceedings of the National Academy of Sciences, 106*(41), 17284–17289.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*(3), 255–278.

Bates, E., Bretherton, I., & Snyder, L. (1988). *From first words to grammar: Individual differences and dissociable mechanisms.* New York: Cambridge University Press.

Bates, E., & Goodman, J. (1999). On the emergence of grammar from the lexicon. In B. MacWhinney (Ed.). *The emergence of language* (pp. 29–79). Mahwah, NJ: Lawrence Erlbaum.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*, 1–48.

Bates, E., & MacWhinney, B. (1987). Competition, variation, and language learning. In B. MacWhinney (Ed.). *Mechanisms of language acquisition* (pp. 157–193). Hillsdale, NJ: Lawrence Erlbaum.

Bates, E., Marchman, V. A., Thal, D., Fenson, L., Dale, P., Reznick, S. J., et al. (1994). Developmental and stylistic variation in the composition of early vocabulary. *Journal of Child Language, 21*, 85–123.

Bent, T., Baese-Berk, M. M., Borrie, S. A., & McKee, M. (2016). Individual differences in the perception of regional, nonnative, and disordered speech varieties. *Journal of the Acoustical Society of America, 140*(5), 3775–3786.

Braginsky, M., Yurovsky, D., Marchman, V. A., & Frank, M. (2015). Developmental changes in the relationship between grammar and the lexicon. In D. C. Noelle, R. Dale, A. S. Warlaumont, T. Matlock, C. D. Jennigs, & P. P. Maglio (Eds.). *Proceedings of the 37th annual conference of the cognitive science society* (pp. 256–261). .

Carpenter, M., Nagell, K., & Tomasello, M. (1998). Social cognition, joint attention, and communicative competence from 9 to 15 months of age. *Monographs for the Society of Research in Child Development, 63*(4), 1–143.

Dale, P. (2007). *The MacArthur-Bates communicative development inventory III.* Baltimore, MD: Paul H. Brookes Publishing Company.

Delle Luche, C., Durrant, S., Poltrock, S., & Floccia, C. (2015). A methodological investigation of the Intermodal Preferential Looking paradigm: Methods of analyses, picture selection and data rejection criteria. *Infant Behavior & Development, 40*, 151–172.

Diependaele, K., Lemhöfer, K., & Brysbaert, M. (2013). The word frequency effect in first and second language word recognition: A lexical entrenchment account. *Quarterly Journal of Experimental Psychology, 66*, 843–863.

Elman, J. L., Bates, E. A., Johnson, M. H., Karmiloff-Smith, A., et al. (1996). *Neural network modeling and connectionism, No. 10. Rethinking innateness: A connectionist perspective on development.* Cambridge, MA, US: The MIT Press.

Federmeier, K. D., McLennan, D. B., De Ochoa, E., & Kutas, M. (2002). The impact of semantic memory organization and sentence context information on spoken language processing by younger and older adults: An ERP study. *Psychophsyiology, 39*(2), 133–146.

Fenson, L., Marchman, V. A., Thal, D., Dale, P., Reznick, J. S., & Bates, E. (2007). *The MacArthur-Bates communicative development inventories: User's guide and technical manual* (2nd ed.). Baltimore, MD: Paul H. Brookes Publishing Company.

Fernald, A., & Marchman, V. A. (2012). Individual differences in lexical processing at 18 months predict vocabulary growth in typically-developing and late-talking toddlers. *Child Development, 83*(1), 203–222.

Fernald, A., Marchman, V. A., & Weisleder, A. (2013). SES differences in language processing skill and vocabulary are evident at 18 months. *Developmental Science, 16*(2), 234–248.

Fernald, A., Perfors, A. F., & Marchman, V. A. (2006). Picking up speed in understanding: Speech processing efficiency and vocabulary growth across the second year. *Developmental Psychology, 42*(1), 98–116.

Fernald, A., Pinto, J. P., Swingley, D., Weinberg, A., & McRoberts, G. W. (1998). Rapid gains in speed of verbal processing by infants in the second year. *Psychological Science, 9*, 72–75.

Fernald, A., Swingley, D., & Pinto, J. P. (2001). When half a word is enough: Infants can recognize spoken words using partial phonetic information. *Child Development, 72*, 1003–1015.

Fernald, A., Thorpe, K., & Marchman, V. A. (2010). Blue car, red car: Developing efficiency in online interpretation of adjective-noun phrases. *Cognitive Psychology, 60*, 190–217.

Gathercole, S. E. (2006). Nonword repetition and word learning: The nature of the relationship. *Applied Psycholinguistics, 27*, 513–543.

Gobet, F., Lane, P. C. R., Croker, S., Cheng, P. C.-H., Jones, G., Oliver, I., et al. (2001). Chunking mechanisms in human learning. *Trends in Cognitive Sciences, 5*(6), 236–243.

Hollich, G. J., Hirsh-Pasek, K., Golinkoff, R. M., Brand, R. J., Brown, E., Chung, H. L., et al. (2000). Breaking the language barrier: An emergentist model for the origins of word learning. *Monographs of the Society for Research in Child Development, 65*(3), i-vi–1-123.

Hurtado, N., Grüter, T., Marchman, V. A., & Fernald, A. (2014). Relative language exposure, processing efficiency and vocabulary in Spanish-English bilingual toddlers. *Bilingualism: Language and Cognition, 17*(1), 189–202.

Hurtado, N., Marchman, V. A., & Fernald, A. (2007). Spoken word recognition by Latino children learning Spanish as their first language. *Journal of Child Language, 33*, 227–249.

Hurtado, N., Marchman, V. A., & Fernald, A. (2008). Does input influence uptake? Links between maternal talk, processing speed and vocabulary size in Spanish-learning children. *Developmental Science, 11*(6), F31–F39.

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (Transformation or Not) and towards logit mixed models. *Journal of Memory and Language, 59*, 434–446.

Janse, E., & Jesse, A. (2014). Working memory affects older adults' use of context in spoken-word recognition. *The Quarterly Journal of Experimental Psychology, 67*(9), 1842–1862.

Johnson, P. C. D. (2014). Extension of Nakagawa & Schielzeth'a R^2 GLMM to random slopes models. *Methods in Ecology and Evolution, 5*, 944–946.

Jones, G. (2016). The influence of children's exposure to language from two to six years: The case of nonword repetition. *Cognition, 153*, 79–88.

Jones, G., Gobet, F., Freudenthal, D., Watson, S. E., & Pine, J. M. (2014). Why computational models are better than verbal theories: The case of nonword repetition. *Developmental Science, 17*, 298–310.

Jones, G., & Rowland, C. F. (2017). Diversity not quantity in caregiver speech: Using computational modeling to isolate the effects of the quantity and the diversity of the input on vocabulary growth. *Cognitive Psychology, 98*, 1–21.

Kuperman, V., & Van Dyke, J. A. (2013). Reassessing word frequency as a determinant of word recognition for skilled and unskilled readers. *Journal of Experimental Psychology: Human Perception and Performance, 39*(3), 802–823.

Lany, J. (2018). Lexical-processing efficiency leverages novel word learning in infants and toddlers. *Developmental Science, 21*(3), e12569.

Law, F., II, & Edwards, J. R. (2015). Effects of vocabulary size on online lexical processing by pre-schoolers. *Language Learning and Development, 11*(4), 331–355.

Law, F., II, Mahr, T., Schneeberg, A., & Edwards, J. (2017). Vocabulary size and auditory word recognition in preschool children. *Applied Psycholinguistics, 38*(1), 89–125.

Loi, E. C., Marchman, V. A., Fernald, A., & Feldman, H. M. (2017). Using eye movements to assess language comprehension in toddlers born preterm and full term. *The Journal of Pediatrics, 180*, 124–129.

Luke, S. G. (2017). Evaluating significance in linear mixed-effects models in R. *Behavior Research Methods, 49*(4), 1494–1502.

Mainz, N., Shao, Z., Brysbaert, M., & Meyer, A. S. (2017). Vocabulary knowledge predicts lexical processing: Evidence from a group of participants with diverse educational backgrounds. *Frontiers in Psychology, 8*, 1164.

Marchman, V. A., Adams, K., Loi, L., Fernald, A., & Feldman, H. M. (2015). Early language processing efficiency predicts receptive language outcomes in preterm children. *Child Neuropsychology, 22*(6), 649–665.

Marchman, V. A., & Bates, E. (1994). Continuity in lexical and morphological development: A test of the critical mass hypothesis. *Journal of Child Language, 21*, 339–366.

Marchman, V. A., & Fernald, A. (2008). Speed of word recognition and vocabulary knowledge in infancy predict cognitive and language outcomes in later childhood. *Developmental Science, 11*, F9–F16.

Meints, K., Fletcher, K., & Just, J. (2017). The lincoln toddler communicative development inventory - A UK adaptation of the MacArthur-Bates communicative development inventory: Words and sentences (Toddler Form). https://cpb-eu-w2.wpmucdn.com/blogs.lincoln.ac.uk/dist/b/6736/files/2017/11/Lincoln_toddler_cdiv2-2.pdf. Accessed 11/04/2019.

Mintz, T. H., & Gleitman, L. R. (2002). Adjectives really do modify nouns: The incremental and restricted nature of early adjective acquisition. *Cognition, 84*, 267–293.

Mirman, D. (2014). *Growth curve analysis and visualization using R.* Chapman and Hall / CRC Press.

Nakagawa, S., Johnson, P. C. D., & Schielzeth, H. (2017). The coefficient of determination R^2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *Journal of the Royal Society Interface, 14*(134), 20170213.

Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R^2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution, 4*, 133–142.

Neter, J., Wasserman, W., & Kutner, M. H. (1985). *Applied linear statistical models: Regression, analysis of variance, and experimental designs.* Homewood, IL: Irwin.

Pine, J. M., & Lieven, E. (1997). Slot and frame patterns in the development of the determiner category. *Applied Psycholinguistics, 18*, 123–138.

Ramscar, M., Thorpe, K., & Denny, K. (2007). *Surprise in the learning of color words. Proceedings of the 29th meeting of the cognitive science society, Nashville, TN*.

R Core Team (2018). *R: A language and environment for statistical computing.* Vienna: R Foundation for Statistical Computing.

Sandhofer, C. M., Smith, L. B., & Luo, J. (2000). Counting nouns and verbs in the input: Differential frequencies, different kinds of learning? *Journal of Child Language, 27*, 561–585.

Smith, L. B., & Yu, C. (2008). Infants rapidly learn word referent mappings via cross-situational statistics. *Cognition, 106*, 1558–1568.

Swingley, D. (2003). Phonetic detail in the developing lexicon. *Language and Speech, 46*, 265–294.

Swingley, D. (2009). Onsets and codas in 1.5-year-olds' word recognition. *Journal of Memory and Language, 60*, 252–269.

Swingley, D. (2011). The looking-while-listening procedure. In E. Hoff (Ed.). *Research methods in child language* (pp. 29–42). Wiley-Blackwell.

Swingley, D., Pinto, J. P., & Fernald, A. (1999). Continuous processing in word recognition at 24 months. *Cognition, 71*, 73–108.

Thomas, D. G., Campos, J. J., Shucard, D. W., Ramsay, D. S., & Shucard, J. (1981). Semantic comprehension in infancy: A signal detection analysis. *Child Development, 52*(3), 798–983.

Tomasello, M. (2000). Do young children have adult syntactic competence? *Cognition, 74*(3), 209–253.

Waxman, S. R., & Booth, A. E. (2001). On the insufficiency of evidence for a domain general account of word learning. *Cognition, 78*, 277–279.

Weisleder, A., & Fernald, A. (2013). Talking to children matters: Early language experience strengthens processing and builds vocabulary. *Psychological Science, 24*(11), 2143–2152.

Yap, M. J., Balota, D. A., Sibley, D. E., & Ratcliff, R. (2012). Individual differences in visual word recognition: Insights from the English Lexicon Project. *Journal of Experimental Psychology: Human Perception and Performance, 38*(1), 53–79.

Yap, M. J., Tse, C.-S., & Balota, D. A. (2009). Individual differences in the joint effects of semantic priming and word frequency revealed by RT distributional analyses: The role of lexical integrity. *Journal of Memory and Language, 61*(3), 303–325.