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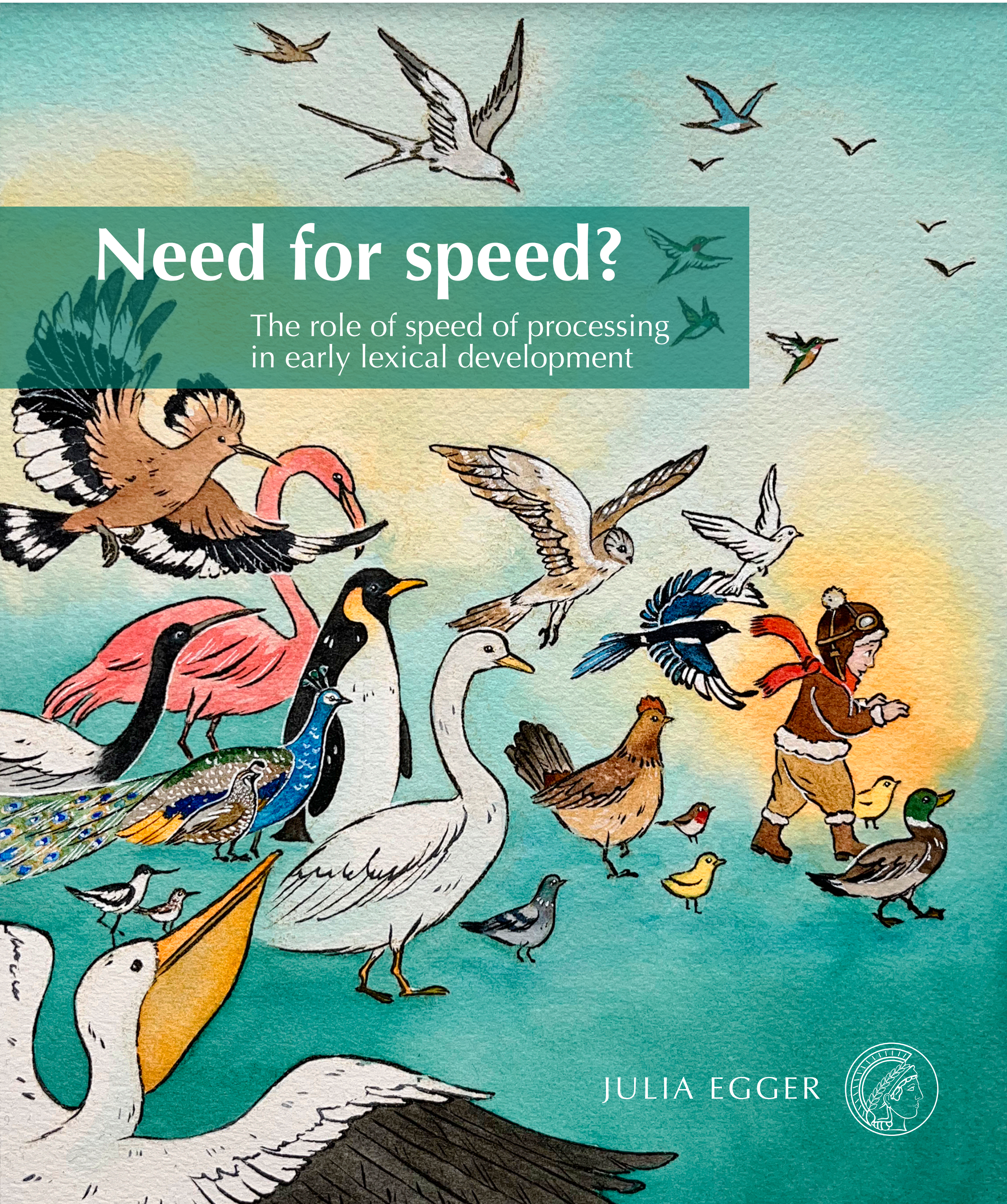

Need for speed?

The role of speed of processing in early lexical development

JULIA EGGER

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For Anna and Mathilde.
Even though I did not get to meet you,
you will always be a part of me.

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Summaries

Chapter 1

General Introduction

One of the outstanding questions in developmental research is why children differ widely in how quickly they acquire their first language, in particular, in how quickly they grow their lexicon. In this thesis, the term lexicon refers to the internalised vocabulary of a person, meaning all the words they know together with linguistic information for each word, such as word forms, meaning and other associations (Fernández & Cairns, 2010). The nature of lexical representations and how we acquire word knowledge across the lifespan are subject to various productive lines of research. For example, according to my mother’s notes on our childhood, I started uttering my first ‘real’ words around 15 months, my older brother around 17 months and my younger brother around 19 months. Data from Wordbank, an open database of children’s vocabulary development (Frank et al., 2017), shows that Dutch learning 18-month-old infants can vary from producing 14 to 157 words, with the average being 61 words. While we continuously learn more and more about the contributing factors to this variation (as described in more depth in the Introductions to Chapters 3-5), we are still a long way away from being able to explain or even predict individual differences in the trajectory of children's language development. However, explaining and predicting individual differences in lexicon growth have key implications both for theories of language processing specific and human learning more broadly, as the following questions are currently unanswered: Which aspects in the input do children pay attention to and is this attention modulated by different environments, for example different cultures or input modalities? Are some capabilities, such as fast information processing, innate and thus not dependent on the environment or are they crucially shaped by the input? At the same time, vocabulary size is intimately linked to school-readiness and success in formal education (Kastner et al., 2001; Milton & Treffers-Daller, 2013; Ouellette, 2006; T. C. Smith et al., 1991). Therefore, identifying risk factors for slow vocabulary growth allows for early, targeted intervention; a key practical implication of better mapping out early language learning. This thesis takes a first step in the direction of addressing these key theoretical and practical questions.

Language development research has shown that environmental influences play a role (see Hoff, 2006). The amount of child-directed language input a child receives from their caregiver(s), for example, has been identified as one of the biggest contributors to the speed of child language growth (cf. Rowe, 2012). However, as the anecdote above suggests, even if children receive quite comparable input (e.g. by growing up in the same family), they can have very different word learning trajectories. Thus, we must also consider the contribution of the child's own individual knowledge and abilities. Particularly important are two factors: the current vocabulary knowledge of the child (existing knowledge can be used to bootstrap into new knowledge) and the speed with which children can process incoming information (the faster a learner can process incoming information, the more incoming information can be processed for learning before the system forgets it, or has to attend to new information). One widely used method to assess infants' processing capabilities is to measure their reaction time in word recognition tasks; or, in other words, the speed of (lexical) processing**.** To solve the puzzle of individual differences, we thus might have to consider a child's own skills and their input together.

In this thesis, I take a closer look at the early lexical development of infants through the lens of *speed of processing.* In particular, I ask: what role do individual differences in speed of processing play in early lexical development, and why? To this end, I will track environmental and individual factors and examine their interaction with, and possible causal relation to, lexical speed of processing. This dissertation focuses on the acquisition of spoken Dutch and British English[1], thereby both adding to the languages studied and directly assessing the generalisability of my findings across two languages. To answer my questions, I will combine various methods: a novel eye-tracking paradigm, parental questionnaires, observations, and computational modelling. This multi-method approach makes it uniquely possible to begin to disentangle different causal explanations of the links between lexicon size and processing speed.

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[1] There is little work to date into the effect of processing speed on sign language, so whether the results in this thesis extend to children acquiring a sign language, or even to spoken languages acquired in very different societies and cultures, remains to be explored in future work – a point I will return to in the General Discussion.

Speed of processing

Speed of processing in the context of this thesis refers to the speed with which young infants recognise the words that they know. In the literature it is also called lexical speed of processing or (lexical) processing efficiency. It is measured in a looking-while-listening paradigm (Fernald et al., 2008; which used to be called the intermodal preferential looking paradigm, see Golinkoff et al., 1987), which takes advantage of the fact that infants, like adults, tend to look at objects when they hear them named (Cooper, 1974). Infants are presented with two pictures, for example an apple and a jacket, on a screen (Fernald et al., 1998, 2008). After a short period of silence during which the infants can view both pictures, one of the pictures is then named, usually in a sentence frame or with a preceding exclamation (e.g. “Look, an apple!”). The time (in milliseconds) that it takes the infant to disengage from the distractor image and direct their attention to the target in response to the spoken sentence is then measured and is defined as the infant’s processing speed (e.g. Weisleder & Fernald, 2013)[2] Note that this means that only trials in which the infant is looking at the distractor image at the onset of the audio stimulus can be analysed. Other trials (e.g. those in which the child is looking away or already looking at the target image) have to be discarded (see Chapter 2 for more on this topic and how we can overcome this limitation).

Fernald et al. (1998) were among the first to use this method, in a study that assessed the timeline of online word recognition in children. They video-recorded children's eyes as they listened to audio stimuli directing them to (for example) *look at the jacket,* hand-coded the children's eye movements offline, and then calculated how long it took children to move their eyes to look at the named target object. They reported (Fernald et al. 1998) that the older the children were, the faster they were at recognising the named objects, with 24-month-olds even looking to the target word before having heard the whole word (since the distractor started with a different sound sequence). Swingley et al. (1999) replicated this finding, showing that 24-month-old infants can process words quickly and

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[2] Research in the field often investigates the accuracy (proportion looks to target after labelling) as well as the reaction time in the paradigm (speed of processing) together. In some studies the accuracy scores are also dubbed processing efficiency (e.g. Weisleder & Fernald, 2013). However, in the present thesis I solely focus on the reaction time measure.

incrementally while listening to the speech signal, with performance comparable to adult-like looking behaviour. Swingley et al.'s (1999) study was also the first to investigate the relationship between speed of processing and expressive vocabulary size, reporting negative correlations between these two factors, such that children with faster processing speed had bigger vocabularies. Expanding these results to younger ages, Fernald et al. (2001) tested 21- and 18-month-old infants on word recognition tasks in which, in one condition, only the first half of the word was audible for the infants. They reported that infants in both age groups could recognise the correct picture upon hearing only half the word just as quickly as when they listened to the full word. Similarly to Swingley et al. (1999), Fernald et al. (2001) also investigated the relationship between processing speed and the vocabulary of the infants in both age groups. Interestingly, they reported an interaction; while 21-month-old infants with expressive vocabularies above 100 words were faster at recognising full or partial words than their peers with fewer than 60 words, the effect was reversed for the 18-month-olds. In an exploratory analysis, they then divided all the infants, regardless of age, into fast/slow processors using a median split. The results showed that the infants in the fast processing group had significantly bigger vocabularies than the infants in the slow processing group, indicating that there might be a connection between vocabulary size and speed of processing, regardless of age.

Further research on infants' speed of processing has revealed that children are slower to recognise objects when the word labels for them have been mispronounced (Swingley & Aslin, 2000, 2002) and that words embedded in familiar sentences are recognised faster than words in isolation or those preceded only by an attention cue (Fernald & Hurtado, 2006). Investigating how the presence of morphosyntactic cues in a sentence might affect speed of processing, Zangl and Fernald (2007, experiment 1) tested how 18-, 24- and 36-month olds reacted to different types of noun phrases: either with no determiner, a nonce determiner (a short syllable acting as pseudo-determiner) or a grammatical determiner ("the"). The results of the control condition with the grammatical determiner showed the predicted age-related effects (i.e. the older the participants were, the faster they could process the utterances). Having no determiner did not make a significant difference to processing speed for any age group, but the presence of the nonce determiner slowed down word recognition in 18-month-olds. Similarly, Lew-Williams and Fernald (2007) studied whether 34 to 42-month old Spanish-learning children could use grammatical gender to their advantage in a word recognition task. In languages that possess grammatical gender such as Spanish or German, the target object can already be predicted at the onset of the gender-marked determiner, as long as the two depicted objects have different genders. Lew-Williams and Fernald (2007) showed that, even as young as 34-42 months, children, like adults, were faster to react in trials where they could use information from the grammatical genders of the depicted object to predict the identity of the upcoming noun. The results also showed that, once again, vocabulary size accounted for more variance in processing speed than age.

However, none of these studies focussed primarily on the role of speed of processing in explaining individual differences. The first to do so were Zangl et al. (2005), in a replication and expansion of Fernald et al. (2001). They conducted a word recognition study with infants aged between 12 and 31 months, measuring the accuracy and processing speed of word recognition. In two analyses, one analysing the data according to the infants' age and one according to their expressive vocabulary, they reported that the infants' expressive vocabulary size was a better predictor of speed of processing than age. Fernald et al. (2006) followed this up by studying the speed of processing and vocabulary growth of infants longitudinally from 12 to 25 months. They reported a negative correlation between speed of processing and concurrent expressive vocabulary size at 25 months as well as links between the speed of processing of 25-month-olds and expressive vocabulary from 12 to 21 months. Except for a correlation between the speed of processing and the receptive vocabulary at 15 months, they found only non-significant correlations between speed of processing and receptive or expressive vocabulary at other age points. They concluded that, over the second year of life, infants with faster processing also grew their vocabulary more rapidly. These findings led to a conceptual shift in the speed of processing literature, from a focus on the method as a tool to better understand how infants process speech on a group-level in different conditions (e.g. Fernald & Hurtado, 2006; Lew-Williams & Fernald, 2007; Swingley & Aslin, 2000), towards a focus on the method as indexing important individual differences in children's processing ability throughout development.

Since then, a number of studies have replicated the result that vocabulary size is a better predictor of differences in processing speed than age (Fernald et al., 2001; Zangl et al., 2005; Lew-Williams & Fernald, 2007). This suggests that, where studies have reported a relationship with age (e.g. Fernald et al., 1998, 2006), this is probably because age is a relatively robust index of vocabulary size as older children usually know more words. However, not all studies show evidence for this hypothesis. For example, Hurtado et al. (2007) tested Spanish-learning infants with ages ranging from 18 to 30 months, assessing their speed of processing and their vocabulary sizes. While their results showed a negative correlation between speed of processing and age, they were unable to disentangle age and number of words, which were highly intercorrelated, as unique contributors in their analyses. In sum, in general, even when the primary objective of the study differed, most studies published since 2005 have reported correlations between speed of processing and concurrent, subsequent or (see Fernald et al., 2006) preceding expressive vocabulary size in infants from as young as 18 months of age[3], with varying effect sizes.

The effect of age on speed of processing and vocabulary during early development

As multiple studies have shown correlations between speed of processing and vocabulary size, which in some cases even exceeded the strength of the relationship between age and processing speed, future research has turned to exploring this effect for different age groups, with varying results. In the following section, I will provide a short overview of the literature and at what ages the relationship between speed of processing and vocabulary size has

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[3] Note that with some exceptions (e.g. Fernald et al., 2006; Marchman et al., 2016; Lany, Shoaib, et al., 2018), most studies conducted the correlation analyses only with the *expressive* vocabulary size of the participants.

been found. Note that at the time of writing, research has only been conducted with (American, Australian or British) English and Mexican Spanish learning children.

Starting with the youngest children tested in the literature, Lany, Giglio, et al. (2018) assessed the speed of processing of 12-month-old-infants. To increase the possibility of detecting individual differences in children this young, they made some changes to the analysis approach of previous papers. They tested separately the speed of processing of "easy" words, which were most likely known by all of their participants, and "hard" words, which on average should only be familiar to a few of the participants. Despite these changes, they did not find a significant correlation between the reaction time of word recognition and the infants' expressive vocabulary (easy condition: $r = -.26$, $p > .05$; hard condition: $r = -.27$, $p > .05$).

By 15 months old, there is evidence of a relation; Fernald et al. (2006) reported a correlation between speed of processing and receptive vocabulary at this age ($r = -.30$; $p < .05$). This finding was replicated by Lany, Shoaib, et al. (2018) in their first experiment with infants aged 15 to 16 months ($r = -.33$, $p < .05$), but note that, in the second experiment with a stricter age range (closer to 15 months), they did not report a significant correlation ($r = .24$, $p > .1$). For 17-month-old infants, Lany (2018) did not find a relationship between lexical processing speed and expressive vocabulary ($r = .03$, $p > .05$). However, in a follow up study using identical measures with 15 and 19 month olds, Lany, Giglio, et al. (2018) reported a negative correlation between processing speed and vocabulary size ($r = -.65$, $p < .001$).

Although earlier studies (Fernald et al., 2006; Hurtado et al., 2008) did not find significant correlations between speed of processing and concurrent vocabulary at 18-months, this age became a key point for many further studies on individual differences in language processing: Brookman et al. (2020; $r = -.61$, $p < .01$), Donnelly and Kidd (2020; $r = -.25$, $.001 < p < .01$) and Fernald and Marchman (2012; $r = -.32$, $p < .004$) all reported significant negative correlations between processing speed and concurrent expressive vocabulary. Similarly, Marchman et al. (2019) showed a relationship between speed of processing and vocabulary at 18 months for both full term and age-adjusted preterm-born infants ($r = -.30$, $p < .001$). In contrast, Fernald et al. (2013) found a weaker correlation than the others, which was only significant at the .07 level (*r* = -.25, *p* < .07).

Predicting future, rather than concurrent, vocabulary based on processing speed at 18 months has only been reported in a few studies. It was not significant in Fernald et al. (2013, *r* = -.18, *p* > .07), but Marchman et al. (2016) reported that the lexical speed of processing of their 18-month-old preterm-born participants, adjusting the age to degree of prematurity, could predict their receptive vocabulary at 36 months (*r* = -.81, *p* < .001), measured via the Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 2007). Additionally, Donnelly and Kidd (2020) reported significant negative correlations between processing speed at 18 months and the infants' later expressive vocabulary at 21 (*r* = -.32, *p* < .001) and 24 months (*r* = -.35, *p* < .001).

Turning to slightly older infants, Peter et al. (2019) found significant negative relationships between processing speed at 19-month-olds and expressive vocabulary size at 18, 19, 21, 24, 27, 30, 31 and 36 months (*r*s were between -.45 and -.34; *p*s for most <.05; see Table 2 in Peter et al., 2019), but they reported no significant correlations with vocabulary between 8 and 16 months, nor at 34 or 37 months (*r*s between -.31 and -.02, *p* > .05). Ronfard et al. (2022) measured the processing speed of 18 to 24-month-olds and found no relationship with concurrent vocabulary size even when controlling for age (*r* = -.17, *p* = .33). Contrariwise, Donnelly and Kidd (2020) showed negative correlations between the speed of processing of 21-month-old infants and their expressive vocabulary at 18, 21 and 24 months (-.41 < *r* < -.33, *p* < .01).

For 24-month-olds, Swingley et al. (1999) reported negative correlations between speed of processing and expressive vocabulary in two similar experiments. While the correlation was not significant for the first experiment (*r* = -.20, *p* = .29), the second revealed a significant relationship (*r* = -.44, *p* < .03). Hurtado et al. (2008) also found expressive vocabulary and speed of processing in 24-months-old to be negatively correlated (*r* = -.55, *p* <.01). In additional analyses, they showed that speed of processing at 24 months was also correlated with vocabulary growth between 18 and 24 months (*r* = -.55, *p* <.01) and that, after conducting a median split, infants who were faster processors at 24 months olds also had a bigger vocabulary at the same age. Testing children from families with different socio-economic statuses longitudinally, Fernald et al. (2013) reported a significant correlation between processing speed and vocabulary size at 24 months (r = -.47, p <.01). Similar to the findings reported by Hurtado et al. (2008), the processing speed of the 24-month-olds was also highly correlated with vocabulary six months earlier, at 18 months (r = -.42, p <.01). Donnelly and Kidd (2020) reported a significant relationship between speed of processing of 24-month-olds and concurrent vocabulary (r = -.24, .01 < p < .05) as well as vocabulary at 21 months (r = -.20, .01 < p < .05). However, processing speed at 24 months was not correlated with the expressive vocabulary at 18 months (r = -.18, .05 < p < .10).

Newbury et al. (2015) found a negative correlation between vocabulary and speed of processing in 24 to 30-month-olds (average age 26 months, r = -.29, p < .01). However, while Fernald et al. (2006) reported a negative relationship between the processing speed of 25-month-old infants and their concurrent vocabulary (r = -.38, p < .05) as well as with previous vocabulary sizes at 12, 15, 18 and 21 months (rs between -.45 and -.35; most ps < .05), Peter et al. (2019) could not replicate these findings. They assessed the speed of processing at 25 and 31 months, but at neither age was it correlated with neither preceding, concurrent or future vocabulary sizes (rs between -.23 and, ps > .05; see Table 2 in Peter et al., 2019). Lany (2018) reported a negative correlation between speed of processing and vocabulary at 30 months in experiment 1 (r = -.41, p < .05), but, in experiment 2, there was no relationship between these measures at the same age (r = -.05, p > .05).

Overall, the literature shows a very mixed pattern regarding the relationship between lexical speed of processing and vocabulary size and subsequent vocabulary growth at different ages. Effect sizes tend to be in the predicted direction (negative) overall but differ widely between studies and between children at different ages, sometimes reaching traditional levels of significance (p < .05) and sometimes not. One of the reasons for this is the noisiness of the measurement: As mentioned above, speed of processing can only be assessed in *distractor-initial* trials, meaning that the infant has to be looking at the distractor when the target is named, so that the shift of the gaze from the distractor to the target can be measured, and the reaction time properly calculated. For very good reasons, target and distractor are chosen such that they are equally likely to be looked at before naming, because often both items are used as targets in different trials across the experiment. However, this does mean that analyses can usually only be performed on a subset of the trials, since children are equally likely to be looking at the target as the distractor at the onset of the naming event. Several authors note their discussion sections that certain analyses were not possible or difficult, because too many trials were missing or because a large number of missing trials made the data noisier than expected (Fernald & Marchman, 2012; Lany, Giglio, et al., 2018; Thorpe & Fernald, 2006; Zangl & Fernald, 2007). Thus, improving the reliability of the measurement is one of the objectives in Chapter 2, where we also examine the measure itself more closely in order to better understand it and then build on our insights in subsequent chapters.

Relationship between speed of processing and vocabulary: Outstanding questions

Although the literature is impacted by noisy data and shows varying effect sizes, the relationship between speed of processing and vocabulary seems most robust (in recent studies at least) at around 18 months of age. Thus, what we might be seeing here is an age-related effect on the role of processing speed in vocabulary growth. Just as we see that the role of different features of language input change with age (see Rowe, 2012), it might also be that processing speed is more important to vocabulary development at some ages than others.

However, even if this is true, there are still many unknown factors. In particular, we still do not know *why* we see this relationship with vocabulary size and growth. Although there are many studies studying when and whether we find a relationship, there are few positing, and testing, specific hypotheses about what drives the relationship. Some authors do speculate.

One possible explanation is that children who are fast at processing familiar words also learn new words faster and, because of this, possess bigger vocabularies than their slower processing peers. For example, Fernald and Marchman (2012) suggested in their discussion that fast processing frees up cognitive resources that children can dedicate to learning new words. Alternatively, Law and Edwards (2015) propose that children who recognise familiar words faster will be able to identify, and thus, learn novel words more quickly. Both of these suggestions are based on the hypothesis that faster processing speed leads to a larger vocabulary. Lany (2018) tested this directional hypothesis of the relationship with 17- and 30-month-olds, by investigating the children's performance in a novel word learning study together with their individual processing speed. The results revealed that at 17 months, faster processors had higher accuracy scores in the novel word learning task, while there was no difference for the older participants. In a second experiment with 30-month-olds, Lany (2018) manipulated the difficulty level of the novel word learning experiment, for which she then reported a facilitatory effect of processing speed on word learning. Explaining these results post-hoc, Lany (2018) concluded that speed of processing can facilitate word learning if the task is difficult for the participant, thereby lending first support for the causal link from faster processing speed to larger vocabulary. In Chapter 4 of the present thesis, her findings and the directional hypothesis are investigated further.

A second explanation for the relationship between speed of processing and vocabulary is that infants who have a bigger lexicon have stronger representations of familiar words and can therefore recognise them faster. This suggests a different direction of the effect - from vocabulary to processing speed. Peter et al. (2019) posited this idea as a possible explanation of why they did not find a correlation between speed of processing and vocabulary sizes at 25 and 31 months of age (though they did at 19 months). They argued that, at the later ages, the words used in the speed of processing task were so familiar to the infants that variation in performance no longer reflected meaningful variation in how well the words were processed, but other factors (e.g. overall attention). This explanation also fits with the evidence from studies on lexical speed of processing in bilingual children (Hurtado et al., 2014; Marchman et al., 2010) that have shown that the processing speed of the children tested in one language was associated with the size of their lexicon in that language, not the size of the lexicon in the other language or overall lexicon size across both languages. Chapter 5 of this dissertation explores this idea in more detail, repurposing a computational model of non-verbal working memory to make precise, testable predictions about how vocabulary size differences could cause differences in processing speed (CLASSIC, Jones & Rowland, 2017).

Relationship between speed of processing and language input

Apart from the close relationship with vocabulary size, past research has also shown that certain environmental factors are associated with individual differences in processing speech. For example, the educational level of the children's mothers, often used as a proxy for socio-economic status, is associated with processing speed, even when the child's vocabulary size is taken into account. Hurtado et al. (2007) reported that maternal level of education was strongly correlated with speed of processing in children of around two years of age, in that those children whose mothers had fewer years of education tended to be slower processors than their same-aged peers with higher educated mothers. Fernald et al. (2013) also reported that children from a lower socio-economic background were significantly slower at processing utterances, concluding that 24-month-olds from a family with low socio-economic status were at the same level as 18-month-olds with a higher socio-economic status.

The socio-economic status of the family (often assessed via the educational level of the mother or both parents) is, of course, a proxy for a variety of environmental factors that could cause individual differences in children's development, such as resources (e.g. child-care arrangements, toys or books at home, time that can be spend with the children, etc.) or language beliefs and attitudes (for a review see Bradley & Corwyn, 2002; Pace et al., 2017). Most pertinently for the present thesis, Hoff (2003) has reported that the influence of socio-economic status on children's language development is mediated by different factors of maternal speech input, showing that one of the possible effects of different socio-economic status might be on the child-directed language input the children receive.

However, it is important to note that, while socio-economic status is strongly associated with child language development, studies have shown that these associations might differ for families living in countries with social policies in place to provide more equal access to education and healthcare (Pace et al., 2017; see also Tucker-Drob & Bates, 2016). Berglund et al. (2005), for instance, did not report any effects of socio-economic status on the language abilities of 18-month-old Swedish learning infants. It is thus unclear whether the observed differences reported in Hurtado et al. (2007) and Fernald et al. (2013) would hold true for other language communities, especially for families who, like in the Netherlands, are supported by a strong welfare state system.

Even if there is not an effect of socio-economic status, there may still be an effect of parental input itself, the hypothesised mediator in the aforementioned observed links. Other studies have also investigated the direct relationship between caregiver speech input and lexical speed of processing. Hurtado et al. (2008), reported that infants who received a larger quantity of parental speech input at 18 months were faster to recognise familiar words at 24 months of age (see also Weisleder & Fernald, 2013). More on the relationship between speed of processing and parental speech input will be discussed in Chapter 3.

How to measure language abilities and aspects

The sections above have outlined the issues that will be addressed in this thesis. Here I turn to the methods. The robustness of all experimental results and the theories and models we build on them crucially depends on the validity and the reliability of the methods used. This section provides an overview of the methods used to conduct the studies in this thesis, explaining why these were chosen over alternatives.

Looking-while-listening

Conducting research with young children can be difficult, given that their attention span is short and that it is difficult or impossible to ask them to respond to direct questions about their knowledge and skill. For example, opening a picture book and asking an 18-month-old infant to name different pictures is unlikely to yield robust, usable data. They might answer, but they might be too shy to answer, or not have enough language yet to produce the label of the object out loud (or even to tell the experimenter that they do not know; see also the 'yes-bias', Moriguchi et al., 2008).

As a result, researchers have turned to other methods to assess the language abilities of young children. One well known method takes advantage of the fact that on hearing the label of an object that is visible, humans will unconsciously and rapidly move their eyes to look at the object named (Cooper, 1974). If the label is abstract or the object is not present, humans will look at something related (for example, for the word "winter", they might look to snowflakes, warm clothing, cf. Huettig & Altmann, 2005; Yee & Sedivy, 2006). This finding is reliable and occurs at any age, provided that the person can understand and process the auditory label accordingly (for a review see Huettig et al., 2011).

This method has opened up new opportunities to test infants' and children's understanding of language. The *looking-while-listening* paradigm used in the speed of (lexical) processing literature builds upon this method. The child sees two or more objects presented simultaneously on a computer screen (Fernald et al., 2008). After a set period of time, one of the objects is named. If children then direct their gaze towards the named object, we assume that they have understood the label and know that it refers to that object. This method allows us to test what words infants know from as early as six months on (Bergelson & Swingley, 2012). Furthermore, and most relevant to the present thesis, it allows us to take a reaction time measure that assesses how quickly infants can identify the word's referent; i.e. the infants' processing speed.

In order to measure speed of processing, children must first fixate on the distractor, and then switch their attention to the named target.

Therefore, we have to discard trials in which the child was already looking (by chance) at the target when the target was named because, in this situation we do not know how long it took them process the target label. We also have to discard trials in which the children were looking away from the screen when the target was labelled; as we do not know how far they have to move their eyes to focus on the target. Thus, speed of processing is measured only if the child looked at the distractor when the target was being named and then moved their eyes to look at the target. This leads to many lost trials, on which I will expand more in **Chapter 2**.

The looking-while-listening paradigm originally used hand-coded eye movement data (for example, see Fernald et al. 1998; Fernald & Marchman, 2012; Lany, 2018). Infants' eye movements were video-recorded during the study and later (offline), coders watched the videos and coded the location of the infants' eye gaze (usually coding 'target', 'distractor', 'looks away' etc). However, the resulting data can be noisy, as it is not always easy to identify where the infants' eyes are focussing. To decrease the noisiness of the data, past studies usually checked for inter-coder reliability, which means that part of the videos have to be coded by two individual coders and their assessments compared. If the agreement between both coders is high, the data is said to be reliable, but this method is not ideal. Additionally, hand-coding is done frame by frame, and those frames are usually around 30ms long. This makes it difficult to identify shifts in looking behaviour that are shorter than 30ms. While past research has not indicated that this might be problematic, it does increase noise in the data. Finally, the biggest issue with hand-coding is that it is very time-consuming and therefore costly. Both the training and the coding process itself are laborious and repetitive, which makes it error-prone and unsuitable for time-sensitive projects.

An alternative is to use an eye-tracker to collect data on eye movements automatically (see Carter & Luke, 2020). An eye-tracker shines infrared light onto the face of the participant sitting in front of it. This light is then reflected by the cornea, the front part of the eye, but is not reflected by the pupil. The eye-tracker identifies the reflection and the location of the absence of the reflection, which is then used to identify the focus of the participants' attention, moment by moment. In the beginning of each eye-tracking experiment, a calibration is conducted, during which the participant looks at pre-specified points on the screen. These looks to the calibration points are registered either automatically or confirmed manually by the experimenter. The eye-tracker measures the position of the pupil and cornea during calibration and creates a model of the eye that is specific to the participant. If the calibration was successful, this tells us that the position of the eye gaze can be assessed accurately by the programme.

The advantages of using an eye-tracker, instead of offline hand-coding of videos, are that it costs less time (the eye-movement data is extracted automatically) and the information is more time-sensitive and fine grained (shorter millisecond intervals than for hand-coding). The drawbacks of eye-trackers are that they might not be accessible for use in diverse cultures or societies since they are sensitive equipment that may not be robust enough to use in remote locations. They are also expensive, and thus beyond the means of less well-funded labs. In addition, there are often decisions programmed into the eye-tracker software that the researcher needs to be aware of, as they might impact their results. For example, eye-tracking software often code into the pre-processing pipeline assumptions about the definition of fixations (dwelling on an object or region) and saccades (quick shifts between fixations) that researchers who do not carefully read the manual are not aware of. In these cases, it is important to check whether the eye-tracker's pre-set definitions are in line with the researcher’s theories, as this might affect the results. There are also different models of eye-trackers that differ in their set-ups or settings, which researchers need to be aware of when interpreting their results.

For the studies in this thesis, we used an Eyelink eye-tracker by SR Research. The Eyelink is ideal for us with children as it has a head-free tracking mode and can thus be used without a chin rest to keep the head still. In head-free tracking mode, a sticker is placed on the forehead of the participant, which the eye-tracker uses to 'track' the eyes during head movements, and to find the eyes again after loss (after eye blinks, for example). Of course, this is also a slight disadvantage, because this means when a child refuses to wear the sticker or takes it off, no looking behaviour can be recorded. In contrast to other eye-trackers, the Eyelink can record eye-movements between 500 and 1000 Hz in the head-free tracking mode, which means that the location of the eye gaze on the screen can be sampled for every 2 or 1ms, allowing for time-sensitive analyses. For our analyses, we extracted sample level data from the eye-tracker, meaning that we retrieved the eye-movements without using any of the predetermined fixations or saccades created by the Eyelink software, so we could assign these criteria ourselves. More information on the eye-tracking set-up can be found in **Chapters 2**, **3**, **4** and **5**, in the Method sections.

Caregiver Questionnaires

The *looking-while-listening paradigm* can also be used to assess what words a young child knows already, but it would be impractical to use this as the only measure of child vocabulary. Given the short attention span of infants, it would be unfeasible to test them on all the words they might be familiar with. Additionally, they might know the word, but could be unable to map it to the referent shown by the experimenter, due to fussiness or due to an unfamiliar picture as the referent (for example for the word “dog” it might be a different breed from the family dog, etc.). Therefore, we often use caregiver report to assess infants' language knowledge. With younger children, caregiver report questionnaires are preferred to traditional standardised tests (e.g. PPVT, Dunn & Dunn, 2007, 1997) because it is often difficult to elicit behavioural (verbal or non-verbal) responses from young children. Parents are surprisingly accurate at reporting on their children's language development at these young ages (see Alcock et al., 2020; Fenson et al., 2007, for examples).

To study children's vocabulary knowledge via caregiver report, a widely-used tool is the MacArthur-Bates Communicative Development Inventories (Fenson et al., 2007; forthwith CDI). The CDI was first developed for American English-learning children, but has been further developed and adapted for many other languages, including Dutch (N-CDI; Zink & Lejaegere, 2002; adapted from Fenson et al., 1993). For each adaptation, there are usually different versions of the CDI, varying in length and targeted age group. For the studies in this thesis, we used the Dutch CDI *Words & Sentences,* which was developed for children from 16 to 30 months[4]. It is important to note that the cross-language adaptations of the CDI are not merely translations of the questionnaire, but take account of specific linguistic and cultural differences. To fill out the Words & Sentences CDI, caregivers are asked to go through a long list of lexical items (*N* = 702 for N-CDI), grouped in different semantic categories such as food, household items or animals, and indicate which of these words the child can 'understand' and which they can say 'understand and say'. The psychometric properties of CDIs are good, and caregivers' reports on their children's vocabulary knowledge tend to be valid and reliable, at least while children are still young (Fenson et al., 2007a). Additionally, they are non-invasive and easy to administer, especially now online versions are available (see deMayo et al., 2021, for a description of a new web-based CDI).

To collect background information about demographic and health factors that have been reported to affect language development, we constructed our own questionnaire. Questions covered possible speech, hearing or visual impairments, parental education, which other caregivers might provide input for the child and which languages are spoken to and around the child. The questionnaire was central to the studies conducted in this thesis, as it provided insights into the children's health and environment and allowed for a non-intrusive check on the inclusion criteria for the different studies. **Chapters 2** and **3** used a preliminary version of the LaDD family questionnaire (https://osf.io/pm94d/) and provided useful information for developing this questionnaire further. **Chapter 4** used a shortened version of the final questionnaire.

Free play sessions

One of the most well studied, and important, factors that affects children's vocabulary growth is the language input they receive over the course of their development. However, it is also one of the most difficult factors to properly quantify for research purposes. While it is possible to ask caregivers about

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[4] The N-CDI was normed with monolingual Dutch learning children living in the Dutch speaking regions of Belgium.

the behaviour and activities in the life of their child, unfortunately, caregivers cannot be asked to report on the input they offer the child, since they would be unable to respond reliably. Social desirability biases and beliefs about how parents should behave, or what researchers might like to hear, can distort the data (for examples of possible systematic reporting biases by parents see Byers-Heinlein et al., 2020). One of the methods for observing parental speech input and their interaction with the child is to record (part of) a day in the child's life at home, either via a camera or audio recorder, often supplemented by a researcher taking notes. While this might be the most natural way to obtain insights into family life, it is accompanied by several additional problems: It might be considered intrusive for the family and other persons involved, it involves a lot of work for the research team who need to annotate everything afterwards, and the observations made might not be as natural as anticipated given that the caregivers (and in some cases perhaps also the children) are aware that they are being recorded. Additionally, there is the difficulty of balancing ecological validity and control. At home there are often a number of confounding and noise variables, such as background electronic noise, the presence of other adults and/or children and the fact that either child, adult, or both, can leave the room at any point. Home recordings also make it challenging to compare between families reliably, since some might use the recording time for a reading activity, while others might spend the time watching TV, because this is what they would *normally* do at this specific time of day. Thus, recordings might reflection situational differences, rather than stable caregiver input differences. Finally, researchers can only record a small amount of input, a sample of the normal input so to say, which raises questions about the representativeness of the sample (Rowland & Fletcher, 2006; Tomasello & Stahl, 2004).

Another way to assess parental input is to invite the dyad to a free play session at the lab, which is the method we opted for in **Chapter 3.** In this scenario, the caregivers are asked to play with their child the way they normally would at home, but in the lab and using toys provided by the researcher. The session usually has a time limit and is recorded, with the researcher leaving the caregiver child dyad to play together. Of course, these sessions are not as natural as home life observations, since they take place in an unfamiliar environment, since the dyad is aware that they are being recorded and they are undisturbed during an instructed task. At home, a parent might not be able to spend an intensive time period with their child, as there often is work to be done or other distractions, for example phone calls or other family members. Nevertheless, a study by Tamis-LeMonda et al. (2017) has shown that short instructed play sessions can be a valuable observation in terms of how variable the input individual children receive can be. They visited families at home and video recorded five minutes of instructed play with toys provided by the experimenter, followed by 45 minutes of normal everyday life. For the latter, the parent was asked to just go about their day as they usually would, so they could complete chores, receive phone calls and also leave the room. The results of the study showed a strong correlation between the five minutes of instructed play and the five minutes of the 45-minute session with the highest amount of parental speech input and variation. We are, therefore, convinced that the 20-minute play session we conducted in **Chapter 3** is a reliable proxy for the parental speech input the children would receive at home.

Thesis outline

In summary, an important question in language acquisition research is how to explain the wide variation in how quickly infants acquire language, specifically, in how fast they acquire their lexicon. Previous research has suggested that the speed with which infants recognise familiar words might impact their lexical development. However, there are still many unanswered questions in the literature. Most relevant to the current work is the fact that the role of speed of processing in explaining individual differences in vocabulary acquisition has not yet been determined. Addressing this issue is the goal of the current thesis, in four empirical chapters.

Chapter 2 describes a study that trialled an adaptation to the looking-while-listening procedure that was designed to increase the robustness of the speed of processing measure. Since speed of processing can only be measured when children look at the distractor object when the target audio is played, at least half of the trials are often lost. In this chapter, we propose a manipulation to the original looking-while-listening paradigm in order to increase the number of usable speed of processing trials per infant and, therefore, the robustness of the measure. The new paradigm relies on automatically identifying the object that the infant is looking at, and then playing the audio that corresponds to the other object. This means that the object the infant is fixating becomes the distractor and the other object becomes the target. In this way most, if not all, trials become distractor-initial usable trials. We compare performance on this adapted looking-while-listening task to performance using the original design.

A second goal was to replicate the finding from the literature of a relationship between speed of processing and concurrent vocabulary size in Dutch infants. This provides an important cross-linguistic comparison given that the vast majority of previous studies have been conducted with American English learning children. Eighteen-month-old infants participated an eye-tracking study in which both the original and the manipulated paradigm were tested in a within-subject design. The parents were asked to fill in the N-CDI Words and Sentences to provide an indication of their children's expressive vocabulary size.

Chapter 3 replicates and extends findings on the links between parental speech input, speed of processing and vocabulary size as demonstrated by Hurtado et al. (2008). Specifically, we tested 1) whether speed of processing moderates the association between vocabulary size and the complexity of parental speech, 2) whether lexical diversity impacts on vocabulary learning and 3) whether input quantity is linked to speed of processing. We examined these factors in relation to both concurrent vocabulary size and later vocabulary growth. The data for **Chapter 3** was collected at the same time, with the same participants, as data for **Chapter 2.** After the eye-tracking session (reported in Chapter 2), we conducted a free play session in which we asked the parent to play with their 18-month-old infant as if they were at home, using toys we provided. The play sessions were video-recorded and then segmented, transcribed and analysed for amount of speech input, lexical diversity of the input and morphosyntactic complexity (mean length of utterance of the input). The parents were also invited to complete further N-CDIs when their children were 24 and 30 months, so we could follow the child's lexical development longitudinally. As a comparison dataset, we also analysed a pre-existing dataset of British English learning children, for whom similar measures at similar ages were available, to test our hypotheses with a larger cross-linguistic sample size.

Chapter 4 investigates the relationship between speed of processing and vocabulary size while also exploring the underlying nature of speed of processing. Following the work of Lany (2018), we tested the prediction that fast speed of processing leads to a larger vocabulary because it facilitates novel word learning. This idea has been suggested in previous research (Fernald & Marchman, 2012; Law & Edwards, 2015) and was empirically tested by Lany (2018). Her results showed, as predicted, that fast processors had better performance in a word learning task at 17 months. In the chapter we conducted a replication to Lany (2018) with 17-month-old Dutch learning infants. Additionally, we extended the study by also measuring the processing speed of the newly learned words, allowing us to assess word familiarity as predictor of processing efficiency. Our results can thus disentangle how broad or narrow lexical speed of processing is and help us better understand the origin of its link with language skills across the lifespan. Contrasting these three measures provides greater insight into the nature of speed of processing.

Chapter 5 describes a Stage 1 Registered Report (an elaborate pre-registration) for a study to explore the relationship between vocabulary size and speed of processing, to test the prediction that having a large vocabulary leads to faster processing. In this study, we propose to test the prediction from the chunking model CLASSIC (Jones & Rowland, 2017) that speed of processing effects vary depending on the way in which vocabulary (lexical and sub-lexical knowledge) is stored in the lexicon. The chapter describes a study to assess whether the predicted differences in processing speed on the item level are present in British English learning 24-month-olds. Data collection for this study was planned but did not occur due to the COVID-19 pandemic, as testing in the UK lab ceased during 2020 and 2021.

In **Chapter 6**, I summarise the findings of the previous chapters, integrate them into the larger context of our current understanding of early lexical and cognitive development and discuss open and newly emerging questions that in the future can shed further light on this crucial stage in language learning.

Chapter 2

Improving robustness of infant lexical speed of processing measures

This chapter is based on Egger, J., Rowland, C.F., & Bergmann, C. (2020). Improving the robustness of infant lexical processing speed measures. *Behavioral Research Methods, 52*(5), 2188–2201.

Abstract

Visual reaction times to target pictures after naming events are an informative measurement in language acquisition research, because gaze shifts measured in looking-while-listening paradigms are an indicator of infants' lexical speed of processing. This measure is very useful as it can be applied from a young age onwards and has been linked to later language development. However, to obtain valid reaction times, the infant is required to switch the fixation of their eyes from a distractor to a target object. This means that usually at least half the trials have to be discarded - those where the participant is already fixating the target at the onset of the target word - so that no reaction time can be measured. With few trials, reliability suffers, which is especially problematic when studying individual differences.

In order to solve this problem, we developed a gaze-triggered looking-while-listening paradigm. The trials do not differ from the original paradigm apart from the fact that the target object is chosen depending on the infant's eye fixation before naming. The object the infant is looking at becomes the distractor and the other object is used as the target, requiring a fixation switch, and thus providing a reaction time. We tested our paradigm with forty-three 18-month-old infants, comparing the results to those from the original paradigm. The gaze-triggered paradigm yielded more valid reaction time trials, as anticipated. The results of a ranked correlation between the conditions confirmed that the manipulated paradigm measures the same concept as the original paradigm.

Introduction

Studying the language of children and infants is challenging. Even though infants and children comprehend utterances early on, taking measures that tell us what they understand can be difficult. To address this, Fernald et al. developed the looking-while-listening paradigm (Fernald et al., 1998, 2008) based on a key insight from adult studies: that people tend to look at objects as they are labelled. In the looking-while-listening paradigm, participants are typically presented with two or more pictures of familiar objects at the same time and hear the label of one of the depicted objects. If they understand and recognise the label, participants will fixate on the labelled object (target) unconsciously and quickly. If they do so correctly significantly more often than we would expect by chance, we conclude that they comprehend the label. This way, children's language comprehension can be measured online from a very early age onwards (the paradigm has been used successfully even in six-month-olds; e.g. by Bergelson & Swingley, 2012). This paradigm has been vital in unravelling how infants begin comprehending words in real time (Fernald et al., 2008; Frank et al., 2016; Von Holzen & Bergmann, 2021).

However, the looking-while-listening paradigm can be used to do more than determine whether an infant understands a word: It can be used to study the dynamics of infant's sentence processing, which can then inform theories of *how* and *why*, not just *when,* infants acquire different linguistic skills. In particular, the speed with which young infants orientate their eyes to look at a familiar object in response to a label (e.g. *look at the dog*) - so called lexical speed of processing - predicts new vocabulary growth. This finding has stimulated a number of suggestions about the relationship between familiar word processing and novel word learning. Specifically, Fernald and Marchman (2012) have shown a positive link between 18 month old infants' speed of processing and their expressive vocabulary as reported by parents at 18, 21, 24 and 30 months (using the MacArthur-Bates CDI, Fenson et al., 2007); Fernald et al. (2006) have demonstrated that the speed with which 25 month old infants process words was positively related to their expressive vocabulary at 12, 18 and 21 months, and Marchman and Fernald (2008) have shown that children's speed of processing at 25 months predicted working memory, IQ, and expressive vocabulary in the same children at eight years of age.

These findings suggest an important link between how quickly infants can process familiar words and how easily they acquire new words. For example, Law and Edwards (2015) have speculated that there is a causal link between processing speed and new word acquisition. They suggest that infants who can quickly recognise familiar words will, in consequence, be quicker to recognise unfamiliar words as novel, and thus will be able to more rapidly add new words to their vocabulary. Similarly, Fernald et al. have suggested that faster processing of familiar words frees up resources that can then be dedicated to the learning of new words (e.g. Fernald & Marchman, 2012). Beyond linking speech processing and later lexical development, Hurtado et al. (2008) have also reported a correlation between speed of processing and maternal speech input. For the first time, then, we have evidence that maternal input not only affects the trajectory of vocabulary acquisition, but also that it affects the speed with which infants process familiar words online. This, too, has important implications for our theories of acquisition, particularly those debating the role of the linguistic environment in infants' language learning. In sum, the ability to measure lexical speed of processing in the looking-while-listening paradigm has opened up new ways to think about the language acquisition process itself. Table 2.1 provides an overview of studies that have measured speed of processing and the findings it has engendered.

However, the looking-while-listening paradigm has one very important methodological limitation, which has serious consequences for its usefulness, and limits the reliability of the lexical speed of processing data collected. The visual reaction time data used to calculate the speed of processing measure requires that the infant shifts their fixation towards the target object upon hearing the object’s label. Thus, if their eyes are already fixated on the target object at the point of labelling on a particular trial, that trial cannot be included. In other words, we can only include trials in which the infant’s eyes are first fixated on the distractor, the second object on the screen, and the move towards the target object after it has been labelled. In addition, this shift has to occur in a specific time window after naming, to allow us to make the inference that the shift is a consequence of the naming event (i.e. that it is causally linked to the naming event). When no gaze shift occurs, for example, because the infant is already fixating on the target object before naming, speed of processing cannot be calculated and the trial has to be discarded.

Since infants are, in principle, equally likely to fixate on either image before labelling, at least half the trials, but usually many more, are discarded in each experiment. Consequently, as shown in Table 2.1, most studies measure speed of processing based on only a few trials per infant (e.g. there were between 3 and 32 usable trials per infant, out of a total of 64 total trials reported, in Fernald & Marchman, 2012). Table 2.1 shows that much fewer than 50% of the trials can typically be used to calculate speed of processing.

With few trials, reliability suffers, for two reasons. First, calculating a measure from only a few trials per participant means that it is difficult to accurately estimate the true processing ability of any individual participant, which requires multiple observations. If a participant, for example, provides two reaction times, one very slow and another fast, the mean would be calculated and taken to index her individual speed of processing. However, from only two trials it is impossible to determine whether one of these should be seen as an outlier, or whether this average value between the two extremes indeed reflects the participant’s abilities accurately. Second, the paradigm often results in large variation in the number of usable trials for each participant, which means that we have a better estimate of the performance of participants with more trials, possibly skewing the results in a direction that deviates from the population, as fewer trials might lead to more extreme estimates. In addition, we currently have very little reliability data for speed of processing. Few previous studies measure speed of processing multiple times in the same children, and those that do have not reported correlations across time points (an exception is Peter et al., 2019, but their measures were taken six months apart). Speed of processing predicts vocabulary development, which allows conclusions about the validity of the measure, but not its reliability. In other words, if we measure the same infants twice, we do not know whether we would achieve similar results, particularly for those participants with only very few data points.

Table 2.1

An Overview of Studies Measuring Lexical Speed of Processing With Participants in the Second Year of Life

Study	*N* Participants	Age of participants (in months)	Number of trials	Mean number of RT trials	Range of RT Trials	Time window for RT analysis (in ms)
Buckler et al. (2017) - Experiment 1: Canadian accent condition	16	24	32	9.5	-	300-2300
Buckler et al. (2017) - Experiment 1 Non-native accent condition	16	24	32	9.9	-	300-2300
Donnelly & Kidd (2020)	113	18	48*	14.2*	4 – 26*	300-1800
Donnelly & Kidd (unpublished)	112*	21*	40*	13.63*	3 – 21*	300-1800
Donnelly & Kidd (unpublished)	107*	24*	48*	11.91*	3 – 22*	300-1800
Fernald & Hurtado (2006) - Experiment 1: Sentence frame	24	18	12	-	-	367-1800
Fernald & Hurtado (2006) Experiment 1: Word in isolation	24	18	12	-	-	367-1800
Fernald & Hurtado (2006) Experiment 2: Sentence frame	24	18	12	-	-	367-1800
Fernald & Hurtado (2006) Experiment 2: Words with attention cue	24	18	12	-	-	367-1800
Fernald & Marchman (2012) - Typically developing children	46	18	64	19.8	4 – 31	300-1800
Fernald & Marchman (2012) - Late talkers	36	18	64	18.9	3 – 32	300-1800
Fernald et al. (1998)	24	15	8	4.04*	-	200-2000*
Fernald et al. (1998)	24	18	8	4.91*	-	200-2000*
Fernald et al. (1998)	24	24	8	4.75*	-	200-2000*
Fernald et al. (2013) - High SES	47*	18	32	8.8*	2 – 16*	300-1800
Fernald et al. (2013) - Low SES	47*	18	32	8.8*	2 – 16*	300-1800
Fernald et al. (2013) - High SES	48	24	16	4.97*	2 – 10*	300-1800
Fernald et al. (2013) - Low SES	48	24	16	4.97*	2 – 10*	300-1800

Study	*N* Participants	Age of participants (in months)	Number of trials	Mean number of RT trials	Range of RT Trials	Time window for RT analysis (in ms)
Fernald et al. (2006)	49*	15	24	5.77*	2 – 14*	300-1800
Fernald et al. (2006)	44*	18	24	4.55*	2 – 9*	300-1800
Fernald et al. (2006)	52*	21	24	6.48*	2 – 12*	300-1800
Fernald et al. (2006)	57*	25	24	10.21*	2 – 17*	300-1800
Fernald et al. (2001) - Experiment 1: Whole word condition	32	21	8	4.6* (across both age groups and conditions)	-	367-2000*
Fernald et al. (2001) - Experiment 2: Whole word condition	32	18	8	4.6* (across both age groups and conditions)	-	367-2000*
Hurtado et al., (2007)	18	18	16	6.3	2 – 13	367-1800
Hurtado et al., (2007)	15	24	16	6.3	2 – 13	367-1800
Hurtado et al., (2007)	16	30	16	6.3	2 – 13	367-1800
Hurtado et al. (2008)	27	18	32	8	2 – 18	300-1800
Hurtado et al. (2008)	27	24	36	13	7 – 21	300-1800
Lany (2018) - Experiment 1	35	17	40	10	2 – 20	300-1800
Lany (2018) - Experiment 1	31	30	40	10	3 – 21	300-1800
Lany (2018) - Experiment 2	34	30	40	10	3 – 17	300-1800
Lany, Giglio, et al. (2018) - Easy words condition	45	12	16	2.76	2 – 6	300-1800
Lany, Giglio, et al. (2018) - Hard words condition	36	12	16	2.82	2 – 8	300-1800
Lany, Giglio, et al. (2018)	34	15-19	24	4.65	2 – 15	300-1800
Lany, Shoaib, et al. (2018) – Experiment 1	38	15 - 16	24	-	-	367-2200
Lany, Shoaib, et al. (2018) – Experiment 2	30	15 – 15.9	24	-	-	367-2200

Study	*N* Participants	Age of participants (in months)	Number of trials	Mean number of RT trials	Range of RT Trials	Time window for RT analysis (in ms)
Marchman et al. (2019) - Full term born children	63	18	64	19.8	2 – 32	300-1800
Marchman et al. (2019) - Preterm born children	69	18	64	15.7	2 – 33	300-1800
Peter et al. (2019)	80	19	64	11.95	2 – 27	300-1800
Peter et al. (2019)	73	25	60	10.41	2 – 24	300-1800
Peter et al. (2019)	74	31	64	10.48	2 – 24	300-1800
Swingley & Aslin (2000) - Correct pronunciation condition	56	18-23	12	7.26* (across both conditions)	-	367-2000*
Swingley & Aslin (2002) - Correct pronunciation condition	50*	15	24	5.86* (across both conditions)	-	367-2000*
Swingley & Fernald (2002) - Experiment 1	24	24	26* (including filler trials)	11.04* (across conditions)	-	367-2000*
Swingley & Fernald (2002) - Experiment 2	24*	24	28* (including filler trials)	10.79* (across conditions)	-	367-2000*
Swingley & Fernald (2002) - Experiment 3	24*	24	26* (including filler trials)	10.04* (across conditions)	-	367-2000*
Swingley et al. (1999) - Experiment 1	32	24	16*	5.59*	-	200-2000*
Swingley et al. (1999) - Experiment 2	32	24	16*	5.56*	-	200-2000*
Weisleder & Fernald (2013)	28*	19	32	9.21*	3 – 18*	300-1800
Weisleder & Fernald (2013)	29	24	36	12.38*	4 – 18*	300-1800
Zangl et al. (2005) - Unaltered speech condition	95	12-31	24	45% of trials were distractor initial	-	625-2000

Note. Information was extracted from the publications, unless marked with *, in which case the authors provided data directly

The issue of the reliability of estimating infants' speed of processing through visual reaction times has already received some consideration. For example, Fernald and Marchman (2012) have argued that more trials are important for an accurate measurement. They attributed their finding of a positive relationship between speed of processing and vocabulary growth at 18 months to the number of trials they secured per infant, in contrast to the results of Fernald et al. (2006), who did not find this effect. Fernald et al. (2006) obtained only a small number of trials per infant (range: 2-4), whereas Fernald and Marchman (2012) increased the number of trials per infant by introducing a second testing session. They concluded “[...] that meaningful individual differences in the efficiency of familiar word recognition are evident at ages younger than 2 years, if appropriate steps are taken to increase the stability and robustness of experimental measures of infants’ real-time interpretation of spoken language[...]” (p. 215). This example illustrates how securing more trials leads to a better estimate of the infant’s true capabilities. For those effects that have been shown repeatedly, most saliently the link with later lexical development, more reaction time trials and thus more precise measures lead to more accurate effect size estimates. This, in turn, facilitates planning follow-up studies that aim to examine the cause of this relationship, for example, by allowing for sample size estimates that yield sufficient power.

The goal of the present paper was to introduce a manipulation to the classic looking-while-listening paradigm that selects the target based on the infant’s own gaze (Gaze-triggered). We anticipated that our manipulation would increase the number of usable visual reaction time trials without increasing the duration or number of test sessions, and thus yield more reliable estimates of individual infants' speed of processing. We tested Dutch infants at 18 months to facilitate comparison with data from previous studies, since this is an age group that has been frequently assessed on their speed of processing, (see Table 2.1).

Infants took part in a looking-while-listening study with two conditions: one with our manipulated design (Gaze-triggered) design and one with the original design. To test our main objective, we ran two pre-registered analyses. First, we assessed whether the manipulation yielded more reaction time trials per infant than the original paradigm. Second, we correlated the reaction time data from the manipulated paradigm with the data from the original paradigm to determine whether the new design measured the same construct as the original design. We predicted that the correlation between reaction times in the two conditions would be high, suggesting that the two paradigms yield comparable individual differences rankings. In a final set of exploratory analyses, we a) assessed correlations of infants' ranking within conditions to establish a baseline to compare against our between-condition correlation, since two separate tests cannot correlate more highly with each other than two instances of the same test; b) tested whether there was an increase in reaction time over the course of the experiment in the novel paradigm to ensure that it did not have undesired effects on the speed of processing measure; c) tested whether our conclusions hold both when taking into account all items tested, or only those that infants are reported to understand (see also Fernald et al., 2006), and d) explored the relationship between speed of processing and the infants' concurrent vocabulary size.

Method

All materials we could freely share, depersonalised data, and analysis scripts are available on the Open Science Framework project website (https://osf.io/8fwrb/).

Participants

The main study included 43 Dutch-learning infants (mean age in days = 557.4, *SD* = 6.31, range = 548 – 570; 27 girls). Participants were recruited via a local babylab database of families who had signed up to take part in studies on child development. At the time of recruitment, we excluded infants who had a low birth weight (under 2500g), any known visual or hearing impairments (including regular or recent prolonged ear infections), who were born prematurely (defined as 33 weeks of gestation or less), or whose parents had dyslexia. We also asked parents to estimate the amount of Dutch their infant heard regularly. We excluded infants who heard Dutch for fewer than six and a half days per week (equivalent to 93% Dutch input; this cut off allowed us to include only infants who are considered typically monolingual, in line with other infant language studies; Byers-Heinlein, 2015).

We asked for parental education as a proxy of socio-economic status, in order to assess the homogeneity of our sample. On average, the parents of our participants had 17 years of formal education (range = 12 – 18 years), meaning that all of them obtained a qualification beyond high school level and the majority of them hold a university degree. The parents of one infant declined to answer this question.

Parents were contacted via phone or email and provided with information about the study. After agreeing to participate, they were invited to the lab and received several questionnaires by mail or email to be filled in at home beforehand: the Dutch adaptation of the MacArthur Communicative Development Inventories (N-CDI; Zink & Lejaegere, 2002, adapted from Fenson et al., 1993), and lab-created questionnaires that contained questions about family background, daily activities, and home life (all these questionnaires are shared on the OSF project page). Scores on the questionnaires were not known to the experimenter at the point at which they tested participants.

Seventeen additional participants took part but were excluded after data collection for the following reasons: refusal to wear the target sticker needed for the eye-tracker (*n* = 3), technical failure (*n* = 3), fussiness (*n* = 1), visual impairment (*n* = 1), not fulfilling our monolingual input criterion after screening (*n* = 1), not providing enough valid trials for both experimental conditions (*n* = 6, see Analysis section below for details), having no trials where reaction time could be measured, or only providing reaction times in one condition (*n* = 2).

The study was first piloted with 13 participants in order to ensure that a within-subject-design would be feasible for 18-month-olds (i.e. we tested whether infants would complete a sufficient number of trials per condition to allow for analyses with sufficient power for our planned analyses; see below improved before testing the main sample. None of the pilot participants were included in the final analyses.

Materials

Visual stimuli

Stimuli were pictures of 16 different objects from four categories (food, animals, clothes, and toys). Four additional objects (cookie, spoon, baby, bear) were chosen for the filler trials. We decided on our objects with the aim that all of them would be familiar to 18-month-old infants and easy to depict. For each object category, we used four different pictures of four different objects. The pictures appeared in yoked pairs, which we list in Table 2.2. The pairs were not matched in salience or frequency. Side of presentation was counterbalanced across trials.

Table 2.2
List of Stimuli in their Respective Pairs

Item 1 (category) – Dutch translation	Item 2 (category) – Dutch translation
Apple (food) – Appel	Jacket (clothes) – Jas
Banana (food) – Banaan	Book (toys) – Boek
Bottle (food) – Fles	Ball (toys) – Bal
Bowl (food) – Kom	Shoe (clothes) – Schoen
Cat (animals) – Poes	(Woolen) Hat (clothes) – Muts
Cow (animals) – Koe	Sock (clothes) – Sok
Dog (animals) – Hond	Bike (toys) – Fiets
Horse (animals) – Paard	Car (toys) – Auto

As attention getters at the beginning of the trials we picked six different animated videos with sound (from The ManyBabies Consortium, 2020; retrieved via https://osf.io/xbv95/). The calibration stimulus was the face of a cartoon character that moved to the five calibration points. This was used instead of a dot in order to engage the infants' attention more effectively. The experiment started and ended with a child friendly cartoon accompanied by instrumental music in order to draw the infants' attention to the screen.

Auditory stimuli

A female native speaker of Dutch recorded the auditory stimuli in a sound-attenuated booth and was instructed to speak in a lively voice as if talking to an infant. Unlike previous studies, we did not present the target word in sentence context (Fernald et al., 1998; Fernald & Hurtado, 2006). Fernald and Hurtado (2006) have investigated the difference between presenting targets in sentence frames and in isolation, showing that while RTs might be slower, they still fall in the same distribution of RTs reported in the wider literature and are linked to identifying the correct target (see Table 2.1). This was to allow us to allow for a more flexible onset of the target word in the Gaze-triggered paradigm. However, to remain as close as possible to the previous literature, we chose four exclamations that provided the context for our target words but that could be followed by a small pause in case the infant did not fixate on one of the objects immediately (see Procedure for details). We wanted the combination of the carrier sentence and the target noun phrase to sound natural to the infant, even if there was a longer break between these. The main goal of the paradigm was to have as many usable trials as possible, taking into account other limitations. Four variations per exclamation were chosen ("Kijk!", "Wat is dat nou?", "Wat leuk!", "Zie je het?"; English translation: "Look!", "What is this?", "How nice!", "Do you see it?") and were recorded with various intonations. The speaker also recorded all object labels combined with the indefinite article several times (for example: "een poes"; English translation: "a cat"). We selected four variations per item for the experiment. Additionally, eight filler sentences were recorded ("Waar is de baby/koekje/lepel/beer?" and "Zie je de baby/koekje/lepel/beer?"; English translation: "Where is the baby/cookie/spoon/bear?" and "Do you see the baby/cookie/spoon/bear?"). Parents listened to masking music via headphones. The music consisted of songs mixed with voices speaking at the same time.

Equipment

The study took place in an observation lab equipped with four cameras. The eye-movements were recorded using the Eyelink Duo Portable recording at 1000Hz. Participants saw the visual stimuli on a HP Laptop Elitebook 859 G3 Notebook with a 15.6-inch screen (resolution: 1600x900). The audio was presented at approximately 55dB via two Genelec monitor speakers positioned on each side of the laptop. For creating as well as presenting the experiment, we used Presentation Version 20.0 Build 10.19.17. To be able to observe the participants' general state and record the session, we linked a Logitech webcam livestream to a second HP laptop. The parents wore noise-cancelling headphones (Sony WHCH700N) and listened to the masking music on an MP3 player (SanDisk Clip Sport Plus Player) that was set to a comfortable level.

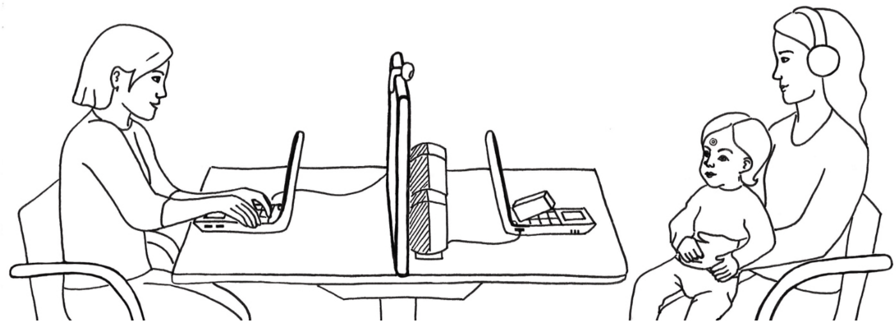
Procedure

The experiment took place in a darkened room. The infant sat on their parent’s lap approximately 50cm away from the laptop screen. While the participant was watching a video with music, the experimenter placed a target sticker on the infant’s forehead, adjusted the eye-tracker and arranged the headphones with masking music for the parents. The experimenter also started a recording of the session via a separate webcam. The experimental setup is depicted in Figure 2.1.

After these preparations, participants completed a five-point calibration. Once calibration was successful, the first trial started. Figure 2.2 illustrates the course of a trial for both conditions. Each trial started with an attention getter, which was shown until the infant fixated on it for 500ms or the experimenter pressed a button. Afterwards, two pictures appeared, one on the left and one on the right side of the screen. After two seconds silent viewing, the infant heard one of the exclamations (see Materials). In the *Original* condition, one of the displayed items, the predetermined target, was named after 100ms silence. This condition models the standard looking-while-listening setup. In the *Gaze-triggered* condition, the target was chosen depending on the infant’s gaze. As soon as the infant looked at one of the two items for 100ms in a set time window after the exclamation, this item became the distractor and the other item was named as target. The gaze of the infant was registered automatically by the eye-tracker. In case the infant was not looking on the screen, the experimenter could trigger the onset of the target label by pressing a button to continue with the experiment. In both conditions, the trial continued for an additional two seconds after the onset

Figure 2.1

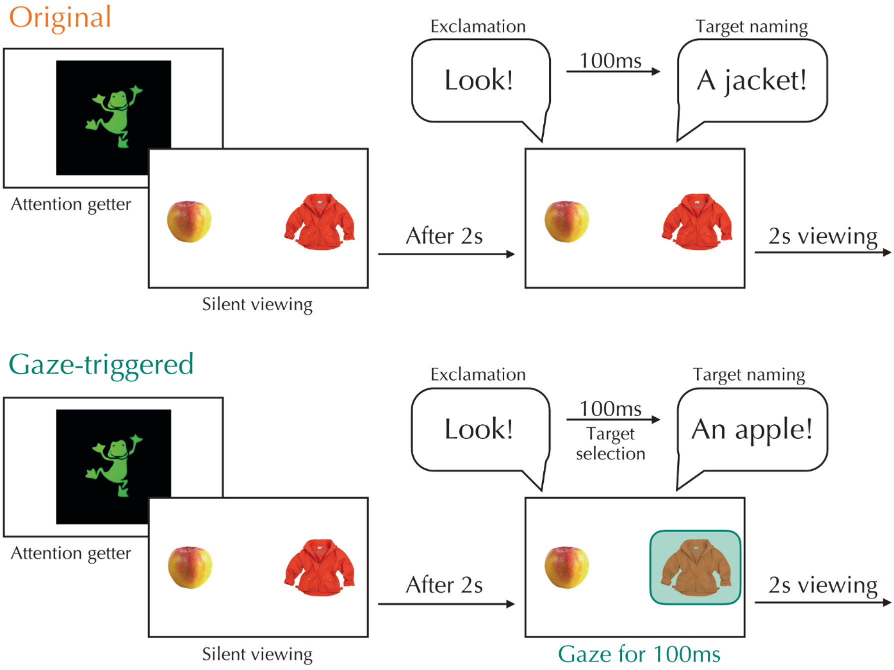
The Experimental Set-up



*Note.*The infant sat on their parent's lap in front of the laptop with the eye-tracker wearing a target sticker used by the eye-tracker. The parent was listening to masking music via headphones. The experimenter sat on the other side of the table, not visible to the infant. They could control the experiment and view the infant via a webcam mounted on the partition. Reprinted from Methods, by N. Nota, 2019, Retrieved from https://doi.org/10.6084/m9.figshare.9976751.v1. Copyright 2019 by Naomi Nota. Reprinted with permission.

Figure 2.2

Illustration of a Trial in Both Conditions



Note. The Gaze-triggered condition does not differ visually from the Original paradigm. The blue area represents the infant's gaze triggering the naming event.

of the target label. The average duration of a trial including the attention getter was seven seconds.

The experiment consisted of 80 trials in total: 32 Gaze-triggered trials and 32 Original trials and 16 filler trials. The order of the conditions was mixed, alternating between blocks of eight Gaze-triggered trials and eight Original trials. Two filler trials were added to each eight-trial block, inserted pseudo-randomly between the first and eighth trial. This means that a filler trial was scripted to occur at any point, but never as the first or last trial of a block. Furthermore, there were never two consecutive filler trials. The condition that infants saw first was counterbalanced across participants. The experiment continued as long as the infant was attentive to the trials. If the participant failed to complete five trials in a row, the experimenter ended the session manually. At the end, regardless of whether the experiment was ended manually or the infant completed all 80 trials, the same video as shown at the beginning would play again. Participants completed on average 68 trials (range: 37 – 80), including filler trials.

We also introduced a feature that compensated for any bias in the Gaze-triggered condition that might be introduced if the infant always fixated on one of the objects (e.g. the apple in the pair in Figure 2.2), which would mean that they always hear the other object (e.g. the jacket) labelled. We resolved this by deviating from the Gaze-triggered approach if the infant fixated on the same object of a pair for the third time in a row; in this case the fixated object was labelled as a target. The same deviation occurred if the child fixated on the same object in the fourth trial in which the pair appeared. This manipulation meant that the infant heard the labels for all objects equally often. The experiment was programmed to keep track of the objects to control for this bias automatically. For each infant, a maximum of 16 trials could be affected by this bias correction (half of the Gaze-triggered trials). In our study, 11.5% on average of all possible trials were bias-corrected (range: 0-25%). We included trials with bias-correction as usable trials but we could not compute speed of processing for these trials as the necessary shift in fixations did not occur. In theory, the infants were able to hear all items four times and see all pairs eight times throughout the experiment. This might have not been the case when the experiment had to be stopped earlier, because the infant has not been attentive to the trials five trials in a row.

The fact that the infants had to fixate on one of the items for at least 100ms in the Gaze-triggered condition in order to elicit the target label meant that in some cases the delay between the onset of the exclamation and the onset of the target was longer in the Gaze-triggered condition (mean = 1285.32ms, *SD* = 843.79, range = 710 – 7250ms) than in the Original condition (mean = 961.91, *SD* = 171.52, range = 710 – 1220ms) for trials analysed here. This means participants saw the two images on average over 300ms longer before onset of the label in the Gaze-triggered condition. We will address possible consequences of this in the discussion section.

The eye-tracking session was followed by a 20-minute play session in the same room (these data were used for Chapter 3). The play session was video recorded and afterwards transcribed and annotated. As a follow-up study, we were also tracing the language development of participants at 24 and 30 months by inviting parents to fill in the N-CDI online. These data pertain to a different research question and we will not discuss them further in this chapter; they are mentioned for procedural completeness and form part of Chapter 3.

Analysis

All analysis scripts can be found on the Open Science Framework project website https://osf.io/8fwrb/. Our analysis plan was pre-registered on the Open Science Framework after data collection was completed, but before any analyses were performed (https://osf.io/fqmuz/ on March 8, 2019). Additional analyses, including visual examination of the data, can be found on the project website. Deviating from our pre-registered plan, we decided to not report the analysis on accuracy (i.e. the proportion of fixations to the target after naming) here, given that our new paradigm changes the baseline considerably (from on average 50% pre-naming fixations on the target to near 0% fixations on the target).

We compared two conditions in this experiment, Gaze-triggered (i.e. dynamic selection of the target object based on infant gaze) and Original (i.e. the unchanged looking-while-listening design for measuring lexical speed of processing). The conditions did not differ from each other until the labelling of the target object took place (see Procedure for more details). We used a within-subject design with condition as the independent variable. We include number of valid trials, reaction time, trial number and target as dependent variables, depending on the analysis.

Pre-processing

Before analysis, the raw eye-tracking data were transformed from edf-files to asc-files using the edf2asc translator program (documentation on http://download.sr-support.com/dispdoc/page25.html). These data were then pre-processed in R Version 3.5.0 (R Core Team, 2018) using RStudio Version 1.1.447 (RStudio Team, 2015) and the tidyverse package Version 1.2.1 (Wickham, 2017). Before further analysis, we removed the eye-movements recorded during calibration, filler trials, and attention getters. Additionally, we filtered the fixations assigned by the eye-tracker, such that we only included fixations that last for at least 100ms in our analysis (cf. Casillas & Frank, 2017).

Data analysis

For the analysis, all trials in which the infant looked at the screen for less than a total of 100ms during the critical time window (0-2000ms after target word onset) were excluded. This time span covers our reaction time window (300-1800ms after target word onset). This yielded 21.02 (*SD* = 7.12) Gaze-triggered and 20.06 (*SD* = 7.46) Original potentially valid trials on average. The speed of processing (i.e. visual reaction time) measure was calculated only on trials where the infant looked at the distractor at the onset of the target label noun phrase. In order to be considered a valid visual reaction time, the shift in fixation from the distractor to the target had to occur between 300ms and 1800ms after the noun phrase onset. We chose the most commonly used time window based on the previous literature (see Table 2.1). Shifts that occurred earlier than 300ms after onset were excluded, as infants are unlikely to be able to process the input and initiate the shift this quickly. Later shifts were excluded as these delayed shifts are most likely not a reaction to the target word. We only included participants who provided at least one trial with a valid reaction time for each condition. While in the literature most studies only include participants with at least two reaction time trials, we opted for having at least one trial, because the aim of our study is to compare how many reaction time trials we obtained, on average, in each condition, within participants.

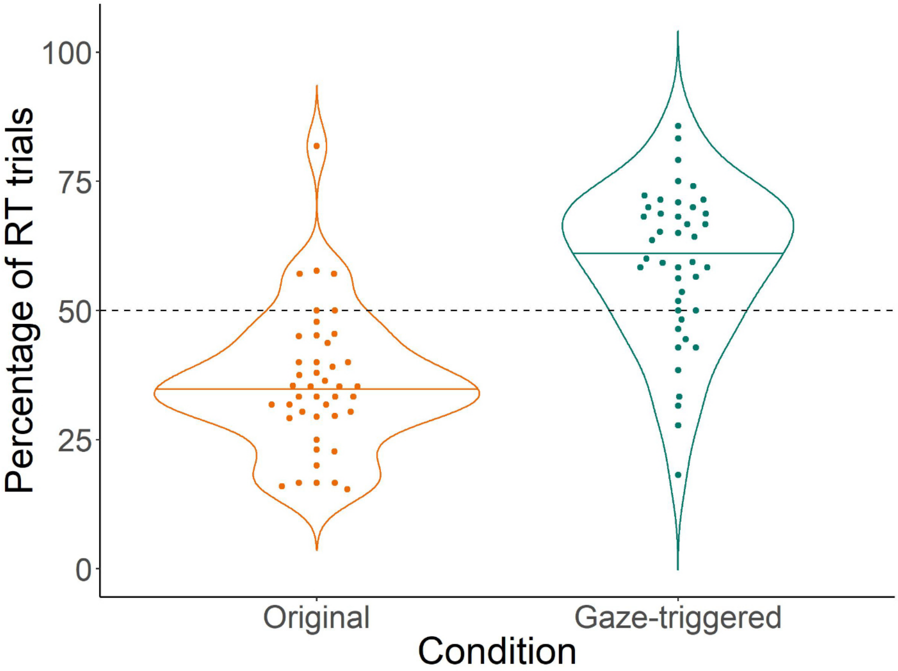
The analyses were conducted in RStudio, using the following additional R packages: DescTools Version 0.99.28 (Signorell et al., 2019), dplyr Version 0.7.5 (Wickham et al., 2018), lme4 Version 1.1-21 (Bates et al., 2015), lmerTest Version 3.1-0 (Kuznetsova et al., 2017), openxlsx Version 4.1.0 (Walker, 2018), reshape Version 0.8.8 (Wickham, 2007) and tidyr Version 0.8.1 (Wickham & Henry, 2018). For visualisation, we used the packages ggplot2 Version 3.1.0 (Wickham, 2016) and ggbeeswarm Version 0.2.3 (Clarke & Sherrill-Mix, 2017).

Results

Our main objective was to increase the number of reaction time trials. Thus, the first analysis tested the prediction that the Gaze-triggered manipulation would yield more valid trials than the Original paradigm. To quantify the number of valid trials and to account for the fact that infants completed different numbers of total trials or might have been distracted during the experiment, our dependent measure was the number of valid reaction time trials expressed as a percentage of total trials completed per condition. To obtain this percentage, we calculated the number of completed trials per condition for every participant as well as how many of these yielded a reaction time measure (i.e. yielded a shift from distractor to target within the pre-set time window; henceforth, valid trials). We then calculated the percentage of completed trials that yielded a valid reaction time measure for each condition.

Figure 2.3 visualises the mean percentage of valid trials per condition as well as the variance we observed. The Gaze-triggered condition yielded more valid trials than the Original condition (mean Gaze-triggered = 12.48, *SD* = 5.74, range: 4 – 25; mean Original = 7.2, *SD* = 3.7, range: 1 – 15). In comparison, past studies that have been administered similarly (32 trials at 18 months) have had a mean of 8 to 9 trials per participant (e.g. see Table 2.1; Fernald et al. 2013; Hurtado et al. 2008). We performed a one-sided paired t-test with Condition as the predictor variable and mean percentage of valid reaction time trials as the outcome variable. The test was one-sided because our prediction was directional in favour of the Gaze-triggered condition. We found a significant difference between conditions in the predicted direction ($t(42) = 8.2$, $p < .001$). As predicted, our manipulation increased the number of valid reaction time trials, yielding nearly twice as many valid trials on average as the Original design.

Figure 2.3
Violinplots of the Percentage of Valid Reaction Time Trials per Condition



Note. The dashed line represents the 50% mark. Each dot indicates a participant per condition. The coloured lines within the violins are the median across participants for each condition, while the violin outlines illustrate the distribution of participants.

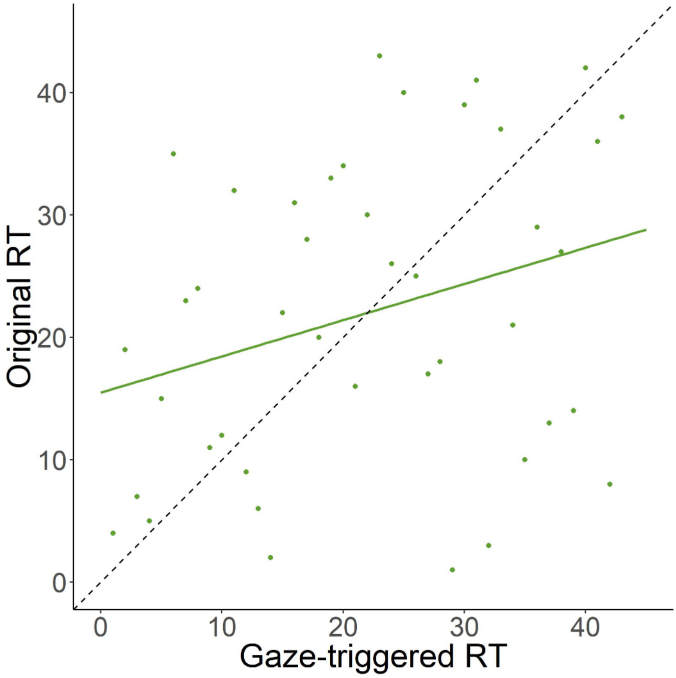
The mean reaction time across participants was 929.54ms (*SD* = 141.05, range = 658.38 – 1314.4ms) in the Gaze-triggered condition and 948.5ms (*SD* = 166.76, range = 672.91 – 1418ms) in the Original condition. Our reaction times are in line with the literature for our age group (see Table 2.1, particularly e.g. Fernald et al., 2006; Fernald & Hurtado, 2006; who tested the same age group). There is no significant difference in the mean reaction times between the conditions (*t*(42) = -0.69, *p* = .75). The lower standard deviation for reaction time in the Gaze-triggered condition compared to the standard deviation of the Original paradigm can be seen as an indicator that the measures taken in the manipulated paradigm are less noisy, and are therefore more precise.

Our second objective was to test whether the Gaze-triggered paradigm measures the same construct as the Original condition, by determining whether the individual ranks of speed of processing ability correlated between the two conditions. We decided to compare the ranks instead of the numeric values of the estimated reaction times, given that the conditions differ in the number of trials available to measure reaction times, which we expected to affect precision. Therefore, we computed the Spearman rank correlation coefficient between each participant's mean reaction time across conditions (Figure 2.4). There was a significant, positive monotonic relationship between the scores in the two conditions (*rho* = .29, *n* = 43, *p* = .027, 95% CI [-0.004, 0.54]).

The Spearman rank correlation coefficient between each participant's mean reaction time across conditions was significant but not large. However, since infant data tends to be noisy, it is difficult to judge whether this correlation is high enough to conclude that the two conditions are largely measuring the same construct. To aid with our decision-making, we decided to assess the correlation within conditions in an exploratory analysis to provide a comparison score against which to judge the between-condition coefficient. We reasoned that a between-condition coefficient is unlikely to be much higher than the correlation coefficient yielded by comparing subsets of trials from the same condition. We randomly split the available trials per condition and per participant in half and assigned them to dummy conditions to compare visual reaction time values within participants

Figure 2.4

Scatterplot of the Ranked Average Reaction Time (RT) Values for Each Participant Between Both Conditions

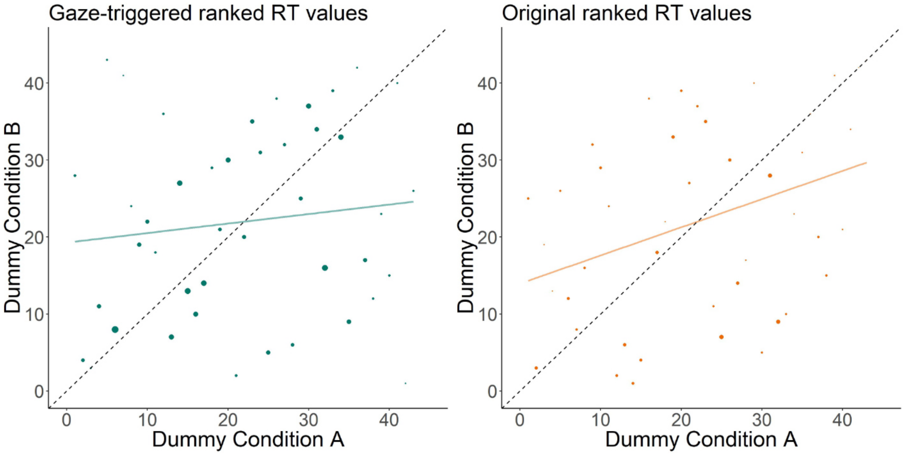


Note. The dashed line indicates what the ideal distribution of the data would be and the coloured line represents the best fit to the data.

and conditions. Note that power is necessarily lower in this analysis. Figure 2.5 presents scatterplots with the ranked reaction time values within condition (for the Original condition, we had to exclude four additional participants, as we had only one reaction time value available for these). For both the Gaze-triggered (*rho* = .12, 95% CI [-0.18, 0.4], *n* = 43, *p* = .43) and the Original (*rho* = .26, 95% CI [-0.04, 0.53], *n* = 41, *p* = .08) condition, the rank correlation was smaller than for the between-conditions analysis. Thus, we concluded that the gaze triggered manipulation is measuring the same construct as the Original method; the speed with which individual infants are able to process lexical items.

At the same time, these values provide us with a test-retest reliability estimate for each condition, which is not available from previous studies, and provides an indicator of how accurate the estimate of visual reaction time is within participant. The fact that the correlation coefficients are small (below .3) indicate that even with the optimised Gaze-triggered design, there is a large amount of noise in the data, further underlining the need to obtain as many trials as possible per participant.

Figure 2.5
Scatterplot of Dummy Conditions Created by Subsetting Reaction Times (RTs) Within Participant Within the Gaze-triggered (Left) and the Original (Right) Condition



*Note.*The size of the dots reflects the number of trials that were used for computing the mean reaction time per participant (range: 4 – 25 in the Gaze-triggered, 2 – 15 in the Original condition). The dashed lines indicate what the ideal distribution of the data would be and the coloured lines represent the best fit to the data.

Initial feedback to the authors led to the concern that the infants might learn a pattern for the Gaze-triggered condition, given that they always have to shift their fixation after the onset of the target word. In the Gaze triggered condition, is might be possible that the infants could learn, during the course of the experiment, that they would be required to shift their gaze from one object to another after hearing the exclamation uttered (e.g. “Kijk”). We thought this unlikely because the within-subjects design, plus the inclusion of the fillers, meant that under half the trials were Gaze-triggered. However, to investigate this, we added a further exploratory analysis. We reasoned that if learning occurred, infants would become faster at reacting to the trials over the course of the experiment. Thus, we added a linear mixed effects regression model over the reaction times within the Gaze-triggered condition, to test if reaction time decreased with increasing trial number. We used trial number as a fixed effect and we included participant, target object, and target by participant as random factors.

RT ~ trial + (1 | Participant) + (1 | target) + (1 | target/Participant)

Table 2.3 shows the results. There was no effect of increasing trial number on the reaction times of the participants. Figure 2.6 further illustrates this finding.

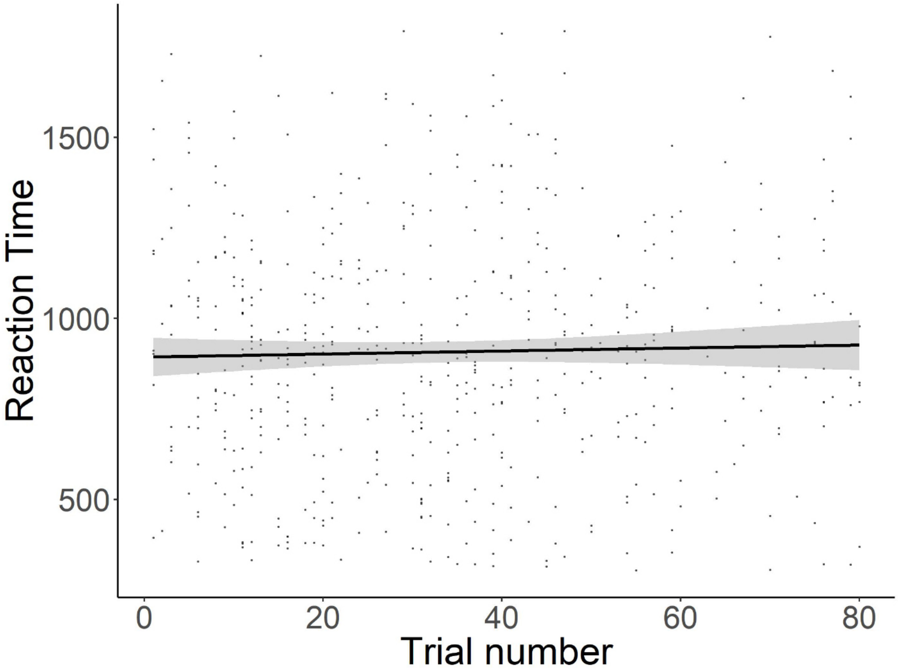
Table 2.3

Linear Mixed Effects Model on the RTs in the Gaze-triggered Condition Over the Course of the Experiment

	Estimate	Std. Error	df	*t* value	Pr (>|t|)
(Intercept)	865.0883	41.483	42.403	20.854	<.001
trial	1.174	0.722	499.086	1.626	0.104

Figure 2.6

Scatterplot of Gaze-triggered Reaction Times Across Trial Numbers



Note. Each dot indicates the reaction time of a participant during a given trial. Towards the end of the x-axis there are fewer dots as not all participants completed all 80 trials. Note that the order of conditions (Gaze-triggered and Original) were counterbalanced. The black line is the regression line, the grey area resembles the standard error.

Additionally, since we collected CDI data from our participants at the time of testing, we were able to see if the infants comprehended the words we used in our experiment, according to their parents (see also Fernald et al., 2006). On average, 2.27 words (range = 0 – 11) of our items were reported as not comprehended by the parents. Thus, we re-ran the above analyses excluding the trials that contained the words that were unfamiliar to each participant, according to their parents. The results and conclusions do not differ substantially from those reported here, so we do not report further on these here (the plots and further reports on these analyses can be found in the supplemental materials on our project page on OSF). We also conducted a linear mixed effects regression model over the reaction times, to see whether the infants differed in their reaction times when a word was unfamiliar. We used whether the word was familiar as fixed effect (WordKnown) and added participant, target item, and target item by participant as random factors.

$$RT \sim WordKnown + (1 \mid Participant) + (1 \mid target) + (1 \mid target/Participant)$$

There was no significant change in the reaction times depending on the receptive familiarity of the word, as can be seen in Table 2.4.

Table 2.4

Linear Mixed Effects Model on the RTs With Word Knowledge as Fixed Effect

	Estimate	Std. Error	df	*t* value	Pr (>|t|)
(Intercept)	974.11	45.33	94.99	21.491	<.001
WordKnownTRUE	-63.15	41.09	344.48	-1.537	0.125

Overall, the CDI scores of our infants reveal that they comprehend an average of 279.62 words (*SD* = 137.92, range = 48 – 684) and were able to produce an average of 57.35 words (*SD* = 48.18, range = 7 – 271). The individual scores can be found on the OSF project website (https://osf.io/8fwrb/).

Finally, we also explored the relationship between speed of processing and concurrent vocabulary size. This link has been frequently tested in the previous literature. We opted for a Spearman rank correlation because we wanted to investigate the link between processing speed and lexicon size without making strong assumptions regarding the exact numerical relationship between RTs (in milliseconds) and vocabulary (as measured by words produced according to parental report).

For this analysis, we took the mean RTs of our infants across conditions, so that we would have at least two reaction times per infant. Following the literature, we used expressive CDI score as measure for concurrent vocabulary size. There was a negative relationship between the rank of the RTs and the expressive vocabulary size that was significant at 0.06, though not at 0.05 (*rho* = -.24, *n* = 43, *p* = .054, 95% CI [-0.51, 0.05]). The effect size is within the range reported in the previous literature.[1]

Discussion

The aim of this study was to improve the robustness of the looking-while-listening paradigm regarding the measurement of infants' speed of processing. Our first objective was to increase the number of speed of processing trials with our manipulated, Gaze-triggered paradigm. Therefore, we compared the percentage of usable reaction time trials per participant between conditions. Our results showed that the Gaze-triggered paradigm yielded a significantly higher percentage of valid reaction time trials than the Original paradigm. Because we increased the overall number of trials used to compute an estimate of participants' speed of processing, we conclude that the new paradigm allows us to obtain a more reliable estimate of their underlying abilities. Moreover, given that we observed a smaller range and standard deviation (i.e. less extreme values) in the Gaze-triggered condition, we conclude that the Gaze-triggered condition measures speed of processing more precisely and with less noise. Overall, our mean RTs of both conditions fall within the range of RTs reported in the literature (see Table 2.1, particularly studies testing the same age group: Fernald & Hurtado, 2006; Fernald et al., 2006; Fernald et al., 2001; Hurtado et al., 2007; Weisleder & Fernald, 2013).

Second, we predicted that our new paradigm would measure the same construct as the Original paradigm. We tested this by correlating the

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[1] After publication of this paper, and upon re-analysing the data for Chapter 3, we realised that one participant could very strongly be considered an outlier (N-CDI Score = 271). If we were to exclude the outlier for this analysis as well, the effect size would be significant at $p < .05$, *rho* = -.30, *n* = 42, *p* = .027, 95% CI [-0.55, 0.01].

individual ranks of the participants' reaction time across conditions, and were able to demonstrate that the individual capabilities of the infants were comparable across conditions. We also conducted rank correlations within the conditions, which were smaller than the correlation between conditions. This supports our hypothesis that both the Gaze-triggered and the Original paradigm measure the same construct. However, the fact that the correlations were not large, both within and across conditions shows that, while the measure of speed of processing has been widely used, it is prone to noise and might lead to conflicting results, as indicated by Fernald et al. (2006) and Fernald and Marchman (2012).

Additional exploratory analyses ruled out two other interpretations. First, exploratory linear mixed effects model revealed that infants do not get faster over time in the Gaze-triggered condition. Thus, it is unlikely that the infants learnt, during the course of the experiment, that they would be required to shift their gaze from one object to another. Nevertheless, we would recommend including a substantial number of non-gaze-triggered trials (Fillers) when using the Gaze-triggered paradigm in order to disrupt any potential learning over the course of the experiment. Second, we explored post hoc if the reaction times differed when we excluded words that children did not know, according the parental reports using the N-CDI. Similar to results reported by Fernald et al. (2006), we did not find an effect of word knowledge on the reaction times. Third, we investigated the correlation between speed of processing and concurrent expressive vocabulary score. Our results showed a marginally significant relationship, comparable with results in previous literature (e.g. Fernald et al. 2013).

We also noted that because infants had to fixate on the target picture for at least 100ms to hear the label, there was a resulting difference of about 300ms in the duration of the pre-naming phase between conditions. Could this have affected our results? Indeed, infants might during this time become more familiar with the two images, possibly decreasing their reaction time. However, we do not observe a significant difference of reaction times between conditions and a correlation between ranks of reaction times within participants. Both results point to this difference not substantially altering our results, but further investigation is necessary to explore this issue.

In summary, we have shown that with a small manipulation of the Original looking-while-listening paradigm, we can improve the speed of processing measure taken from infants.

Future directions

With the new paradigm, we can measure lexical speed of processing more accurately and more robustly in future studies. The importance of this, especially in light of individual differences research, was already noted by Fernald and Marchman (2012). Past research has shown that lexical speed of processing predicts concurrent and future vocabulary size as measured by the CDI (e.g. Fernald et al., 2013) as well as aspects of maternal speech input (e.g. Hurtado et al., 2008). Are infants faster in processing familiar words due to their vocabulary knowledge or does their vocabulary grow faster due to their processing capabilities? With more trials and a more precise measure, it will be possible to address these questions, particularly using training or intervention designs to begin tapping into directional and causal relationships.

With more trials, it will also be possible to investigate the impact of item-level characteristics, such as frequency, semantic salience, priming, or phonological transparency on speed of processing. From the literature on adult language processing, we know that different features affect lexical processing as well as acquisition (e.g. Schilling et al., 1998; Sperber et al., 1979). We can now extend this to early first language acquisition, because the new paradigm allows for item level analyses. The Gaze-triggered paradigm thus opens up new paths of research possibilities.

Conclusion

This paper introduced a manipulated looking-while-listening paradigm to enhance the power of infants' speed of processing measures by drastically increasing the number of reaction time trials per infant. The new Gaze-triggered paradigm is shown to measure the same construct as the Original, but with a less noisy measure with increased power. With more trials, this new paradigm allows for more, and new, research opportunities.

Chapter 3

Investigating the interplay between processing speed, parental input, and vocabulary

This chapter is based on Egger, J., Rowland, C.F., & Bergmann, C. (n.d.). *Investigating the interplay between processing speed, parental input, and vocabulary* [Manuscript in preparation]. Language Development Department, Max Planck Institute for Psycholinguistics.

Abstract

The early lexical development of young children varies widely, partly due to differences in factors that influence acquisition speed such as the child's speech input and the child's individual abilities. However, it is still unclear if, and how, these factors might work together and interact to affect lexical development. Moreover, various aspects of speech input might impact children's vocabulary or processing speed differently. The present study therefore aimed to investigate and disentangle the relationship between three aspects of speech input (quantity, diversity and mean length of utterances) and particular infant's abilities (vocabulary knowledge and growth as well as speed of processing). We measured speed of processing in Dutch learning 18-month-olds in an eye-tracking paradigm and we observed caregiver-child interactions during a free play session at the lab. Additionally, we assessed the infants' concurrent vocabulary knowledge using parental questionnaires, which we followed up on at 24 and at 30 months. To then confirm our findings and probe their generalisability across languages, we also analysed a larger comparable dataset of British English learning children.

Our results showed no significant correlations between speech input and infant's speed of processing. For our Dutch participants, we see evidence that, at 18 months, they benefited from more lexically diverse and morphosyntactically complex input, but not from more input quantity. While the analyses did not reveal significant interactions or correlations between the infant's speed of processing and parental speech input, or its impact on vocabulary development for either participant group (Dutch or British English), the data shows interesting trends which could be investigated in future studies.

Introduction

Why there is such extensive variability in the speed and trajectory of early lexical development is still part of the unsolved puzzle of children's language development. So far, some parts of the puzzle have been identified. For example, we know that some of the individual processing abilities of the child, like lexical speed of processing, predict later language acquisition (Donnelly & Kidd, 2020; Peter et al., 2019), and we also know that environmental factors such as the quantity and quality of the child's speech input plays a role (see Hoff & Naigles, 2002; Rowe, 2012). However, it is still unclear how these parts fit together and interact to cause the differences we see in the trajectory of lexical development in young children. In this introduction, we first review the three factors that are the focus of the present chapter: (1) lexical speed of processing (2) parental speech input and (3) vocabulary acquisition, and then discuss the evidence for their interaction in early language acquisition. We end by outlining how our study intends to throw light on this issue.

Processing speed is typically measured in a looking-while-listening paradigm (Fernald et al., 1998, 2008), which provides a unique opportunity to investigate infants' online auditory processing. Children are presented with two familiar objects on a screen and hear one of the objects named. The time it takes the children to disengage from one object and shift their eyes to the named object is referred to as lexical speed of processing. This method can easily be used with children from a young age and has been widely used in developmental studies.

Past research using this method has shown that processing speed differs substantially between individual infants, and that these differences are robust, reliable and long lasting. Furthermore, they have been shown to predict language acquisition: Multiple studies, for example, have found that infants who are faster to recognise the auditory labels of familiar words also tend to have a bigger vocabulary than their slower processing peers (Fernald et al., 2006; Fernald & Marchman, 2012). More importantly, this does not only hold true for concurrent vocabulary size, but also for the infant's subsequent vocabulary growth (Donnelly & Kidd, 2020; Peter et al., 2019).

Thus, processing speed seems to impact the ability to acquire new words, as suggested by Fernald and Marchman (2012) and Law and Edwards (2015). This is supported by the finding by Lany (2018), who revealed that children with faster lexical processing speeds for known words were more successful in a novel word learning task. Additionally, Marchman and Fernald (2008) have found that lexical speed of processing at 25 months also predicts working memory and IQ at eight years of age, hinting that speed might be associated with general cognitive abilities.

However, it is not only individual abilities like speed of processing that determine how children expand their lexicon. Input is also a key requirement for language acquisition, and multiple studies have shown that the way parents talk to their children can impact their spoken vocabulary knowledge. A number of different properties of the input have been identified as associated with vocabulary growth, indicating which aspects of the input matter for vocabulary learning. A substantial number of papers have reported that the quantity of parental speech input that infants receive (measured in the number of different word tokens, meaning the number of word instances) impacts their lexical development (Hoff & Naigles, 2002; Huttenlocher et al., 1991, 2010; Rowe, 2012). For example, Huttenlocher et al. (1991) have shown that the amount of child-directed speech produced by mothers is positively associated with the infants' vocabulary development from 14 to 16 months. However, it is not just input quantity that matters; other aspects such as lexical diversity (the number of different word types that children hear, collapsing over multiple possible tokens, i.e. "dogs", "dog", "doggie" fall all under the same word type) and mean length of utterance (MLU, which is a measure of the morphosyntactic complexity) are also reliable predictors of vocabulary growth. For instance, Hoff and Naigles (2002), investigated several structural characteristics of child-directed speech to identify their impact on the expressive vocabulary size of two-year-old infants; number of word tokens as a measure of quantity (the total number of words in the input),) number of word types as an indicator of diversity (the number of different words in the input), and mean length of utterance (MLU) as an index for sentence complexity (the average number of morphemes per utterance). They reported that, at two years of age, children benefited from both lexical variation (many word types) and sentence complexity (MLU) in their input, in the sense that children who heard more lexically diverse and morphosyntactically complex language also produced more words themselves.

Note however, that such strong relationships between input and children's language development are not always reported. While Hoff and Naigles (2002) found a strong link between maternal MLU and the number of words two-year olds produced, a study by Hurtado et al. (2008) did not replicate this result. One difference is that Hurtado et al. (2008) used the MacArthur-Bates Communicative Development Inventories (CDI, in Mexican Spanish, Jackson-Maldonado et al., 2003) to measure children's vocabulary, whereas Hoff and Naigles (2002) used speech samples of two-year olds and determined their vocabulary by calculating the number of word types in the sample. Furthermore, in contrast to Hoff and Naigles (2002), who took all measurements when the children were two years old, Hurtado et al. (2008) measured parental MLU when the participants were 18 months old. Thus, these effects may be more elusive, and more task- and age-dependent, than previously assumed.

One study that supports the idea that the relationship between input and vocabulary size changes with age is that of Rowe (2012). Using a longitudinal approach, Rowe (2012) was able to disentangle the dynamic effect of input quantity (tokens) and lexical diversity (types) on language learning across early childhood. Her results showed that, at 18 months, the amount of parental speech input (input quantity) was the strongest predictor of subsequent vocabulary development, but that at 30 months, lexical diversity in the input (measured by number of different word types) was most strongly related to later vocabulary. Rowe suggested that that younger, more immature learners who are just beginning to build their lexicon benefit the most from quantity of input, as multiple exposures provide them more opportunities to learn new words. However, as the children grow older and already have a large vocabulary at their disposal, they are able to filter more diverse and sophisticated input for unknown words and can add these to their lexicon. Rowe concludes that what children need in their input changes over time as their own vocabulary skills develop (see also Jones & Rowland, 2017 for a simulation of this idea).

In sum, there is robust evidence in the literature both for an effect of lexical processing speed and for the effect of various properties of the input on children's vocabulary acquisition (at least at some ages). However, there is far less evidence about how these two factors (processing speed and input) may work together to influence acquisition. One paper that does focus on this is that of Weisleder and Fernald (2013), who reported that the impact of the amount of child-directed speech on later vocabulary size was mediated through accuracy in the speed of processing task at 19 months. This suggests that input affects speed of processing, which, in turn, affects acquisition. However, Hurtado et al. (2008) was unable to draw such strong conclusions. They demonstrated that infants who heard more maternal speech input (i.e. higher input quantity) at 18 months were faster to recognise familiar words and had bigger expressive vocabularies at 24 months of age but, in mediation analysis, were not able to distinguish between two possible theoretical models of this relationship. Their results were equally compatible with a model in which children who hear a lot of maternal speech are hypothesised to develop more efficient (familiar) word processing skills, which then has a positive effect on new word learning; and with an alternative model in which children who hear a lot of maternal speech develop a bigger vocabulary more quickly, which then has a positive effect on the speed of familiar word processing. The first aim of this paper was to build on this literature to determine how the two factors (processing speed and input) work together to influence lexical acquisition. We tested whether differences in parental input predict differences in speed of processing at 18 months, and whether these, together, subsequently predict vocabulary size between 18 and 30 months of age.

The second aim of the present paper was to investigate in more detail what types of parental speech input may be important to both lexical processing speed and vocabulary development, and why. Previous research has identified (at least) three aspects of parental input as potentially linked to children’s speed of processing and vocabulary: input quantity (number of word tokens), input diversity (number of word types) and morphosyntactic complexity (MLU), though, as discussed above, it is possible their relative influence changes with development. While amount of speech input might be most impactful for younger infants, this might change with age. Furthermore, most previous work on input and processing speed has focussed on input quantity. We do not know yet how apparent key aspects of the input for vocabulary learning, in particular, lexical diversity and morphosyntactic complexity, might interact with the infants' lexical processing abilities. Thus, the second goal of this paper was, for all three input measures, to determine whether they are correlated with children's speed of processing and how. In particular, we have derived a number of specific hypotheses mapping out the different ways that different input factors might influence vocabulary and processing speed, which we review in detail in the next paragraphs.

First is the idea that the quantity of parental speech input has a direct effect on both vocabulary and processing ability. On this view, we assume that the measure of input quality reflects both the number of words a child hears (so input quantity will correlate with vocabulary size) and that frequent, multiple exposures to a word will lead to stronger, more robust lexical representations (Kuperman & Van Dyke, 2013; L. Smith & Yu, 2008), which are likely to be processed quickly and efficiently (so input quantity will also correlate with processing speed). Thus, children who have been exposed both to more words, and to more frequent repetitions of those words in their input, are likely to not only have bigger vocabularies but also be more likely to respond quickly to familiar words in speed of processing tasks. This hypothesis predicts both a correlation between input frequency and vocabulary and between input quantity and speed of processing.

The second hypothesis concerns lexical diversity. While lexical diversity is also expected to correlate with vocabulary (since the more words you hear, the more words you can learn), it is unclear to us how lexical diversity could directly facilitate the faster processing of specific familiar words. It is more likely, we suggest, that any effect of diversity on processing speed will be moderated through vocabulary knowledge, on the assumption that children with a larger vocabulary will also be able to process words more efficiently. This idea has been proposed by Peter et al. (2019), stating that when children possess larger vocabularies, they are better able to process language fast and efficiently (see Chapter 5 for more on this). Thus, we hypothesise that lexical diversity will correlate with vocabulary directly, and that there will be an indirect effect of diversity on lexical speed of processing that is mediated by vocabulary.

The third hypothesis concerns morphosyntactic complexity. The possible link we propose between input morphosyntactic complexity, speed of processing and vocabulary learning is more complex than those discussed above. We suggest that longer, more complex input sentences may be more difficult to process, especially for slow language processors, given that we know that there is a limited processing window during which children can process incoming sentences (Montgomery et al., 2010). However, longer sentences also contain more linguistic information, which might benefit vocabulary acquisition in children who are able to take advantage of it. Thus, we speculate that the relationship between input morphosyntactic complexity and vocabulary acquisition may be different for fast and slow processors. Those children who are fast to process familiar words might be able to process even long, complex sentences completely, and be able to learn from the rich complex lexical information provided in the sentence. Thus, for fast processors, we might expect to see a positive association between input morphosyntactic complexity and vocabulary size. Slower processing infants might be capable of processing, and learn from short, simple, sentences, but benefit less from long, complex sentences, or might even be hindered by them. For slow processors, we might expect to see no, or even a negative association between input morphosyntactic complexity and vocabulary size. Our hypothesis is, thus, that parental mean length of utterance effects on vocabulary will be moderated by the child's lexical processing speed.

In sum, in this paper we focus on how infants’ lexical speed of processing and parental speech input, in particular its amount, diversity and complexity, might act together to influence the speed of lexical development. The first aim of this paper was to investigate if individual differences in parental input predict differences in speed of processing at 18 months, and whether these together subsequently predict vocabulary growth between 18 and 30 months of age. The second aim was to investigate, in more detail, what types of parental speech may be important to both lexical processing speed and vocabulary development, and how. Unravelling the relationship between different aspects of parental speech and particular infants' individual abilities, like lexical speed of processing and vocabulary, will help us to determine what it is about the input that influences the child's development.

We conducted two studies to test our hypothesis: In Study 1, Dutch 18-month-old infants' speed of processing was measured using the looking while listening task (a modified version of Fernald et al., 2008; see Chapter 2), their input was measured based on a recorded and annotated a lab-based play session between the infants and one of their parents, and we assessed their vocabulary using parental report instruments (N-CDIs) both concurrently with the lab session at 18 months and also prospectively six (24 months) and 12 (30 months) later. Given the nature of our research questions, which require large sample sizes, in Study 2, we broadened our scope, and also analysed data from a pre-existing dataset of British English learning children, for whom comparable measures at similar ages were available (the Language 0-5 Project data; see Peter et al., 2019; Rowland et al., unpublished).

Study 1: Dutch infants

Method

This study was part of a larger project (see Chapter 2). All materials pertaining to the looking-while-listening paradigm to measure lexical speed of processing can be found on the Open Science Framework project website https://osf.io/8fwrb/, including the questionnaires (without the N-CDI, which is copyrighted) sent to the parents. Derived data and analysis scripts used solely for this paper are available on the Open Science Framework sub-project website https://osf.io/pjdbz/.

Participants

For the analyses in this chapter, 39 of the 43 infants in the original sample (see Chapter 2) could be included (mean age in days = 556.28, *SD* = 5.6, range = 548 – 569; 25 girls). Families were recruited via the database of the local babylab, which consisted of families who had agreed previously to participate in studies on child development. We contacted parents via phone or email to provide information on this study and invite them. Inclusion criteria during recruitment were: Infants had to have a birth weight of at least 2500g, no known visual or hearing impairments (including regular or recent prolonged ear infections), not been born prematurely (i.e. had to be born at 34 weeks of gestation or later), and parents without dyslexia. Additionally, we asked parents about the amount of Dutch the infant heard on a regular basis. Infants were excluded if they had half a day per week of non-Dutch input (we aimed for a minimum of 93% of Dutch input). We also recorded parental education as a proxy for socio-economic status to assess the homogeneity of our sample. The parents in our sample had on average 17 years of formal education (range = 12 – 18 years), which means that all of them completed a qualification beyond high school level, with the majority of them holding a university degree. The parents of one infant declined to answer this question.

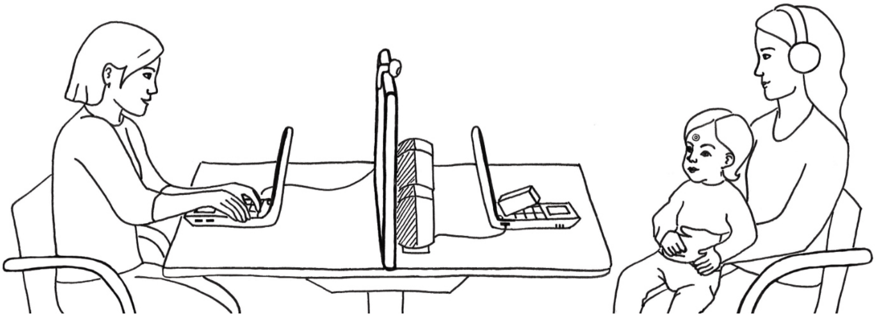
To arrive at our final sample, we tested 60 participants, but we had to exclude 13 infants during the eye-tracking session due to: technical failure (*n* = 3), refusing to wear the target sticker required for the eye-tracker (*n* = 3), visual impairment (*n* = 1), not enough valid trials (*n* = 5), or no trials with which reaction could be measured (*n* = 1). One participant was excluded for not indicating on the family questionnaire that they fulfilled our monolingual input criterion. Additionally, we excluded six participants whose parents did not complete the CDI follow-up questionnaire at either 24 or 30 months. Ten families only completed the CDI questionnaire at 24 months and eight completed it only at 30 months, but these participants were included. After starting data processing, we decided to exclude one more participant for their exceptionally high reported expressive vocabulary score at 18 months of age (for details, see Procedure: Questionnaires).

Procedure

The study took place in an observation room of the local babylab. Infants were first led to the eye-tracker to record their looking behaviour and then participated in a play session of about 20 minutes with their parents using a set of toys provided by the experimenter.

The eye-tracker set-up stood in one corner of the room behind a partition wall, which was placed to clearly separate the two parts of the study. In the middle of the room, there was a grey carpet to indicate the optimal location of the parent-child dyad during the play session so that our cameras, mounted in the room's four corners, could capture at least two angles of the interaction for later coding.

Figure 3.1
Experimental Set-up of the Eye-tracking Session



Note. The parent and the participant sat in front of the laptop (the infant on the parent's lap) and the participant wore a target sticker used for the eye-tracker, positioned on the laptop. On the other side of the table, behind a partition, the experimenter controlled the experiment. They could view the participant via a webcam placed on the partition. Reprinted with permission from Methods, by N. Nota, 2019, Retrieved from https://doi.org/10.6084/m9.figshare.9976751.v1. Copyright 2019 by Naomi Nota.

Eye-tracking session

The eye-tracker set-up is visualised in Figure 3.1 and consisted of an HP Laptop Elitebook 859 G3 Notebook with a 15.6-inch screen (resolution: 1600x900) which was used to present the stimuli to the infants, and the Eyelink Duo Portable recording at 1000Hz which was mounted on the laptop. The audio was played at approximately 55dB via Genelec speakers positioned on each side of the laptop. The experiment was programmed and presented in Presentation Version 20.0 Build 10.19.17. To be able to observe the participants' general state and record the session, we linked a Logitech webcam livestream to a second HP laptop. The parents wore noise-cancelling headphones (Sony WHCH700N) and listened to the masking music on an MP3 player (SanDisk Clip Sport Plus Player) that was set to a comfortable level. At the beginning of the study, the light in the room was dimmed and the parent-infant dyad was seated in front of the eye-tracker. The infant sat on the parent’s lap in front of the laptop at approximately 50cm distance. First, the infant was distracted by a cartoon video with music, while the experimenter checked the seating position and eye-tracker settings as well as placed a target sticker on the infant’s forehead. Additionally, the experimenter started the recording on the webcam. The parent received headphones with masking music from the experimenter, who confirmed the sound level with the parents before starting the study.

Then the experiment began with a five-point calibration, after which the first trial was presented to the infant. All trials of the looking-while-listening paradigm, with the exception of the filler trials, followed the same procedure: An attention getter appeared in the middle of the screen, to draw the infant’s attention. When the infant fixated upon the attention getter for 500ms, it disappeared and two pictures on each side of the screen appeared. In case of continued inattention, the experimenter could manually initiate trial onset. After two seconds of silent viewing, the infant heard an exclamation (e.g. *“Look!”*), followed by the label for one of the objects depicted. The pictures stayed on screen for additional 2500ms after the label started playing, before the next trial began. For the 32 trials of *the Original* condition, the target object was pre-determined for each trial and named after 100ms. In contrast, for the 32 trials of the *Gaze-triggered* condition, the target was selected automatically, depending on the infant’s gaze after the exclamation was played. When the infant looked at one of the displayed objects for 100ms, the object being fixated was treated as the distractor of the trial and the other one became the target and was labelled thereupon. The 16 filler trials also showed to pictures in silence for two seconds after the attention getter, but instead of an exclamation and a target label, the infant heard a pre-determined question.

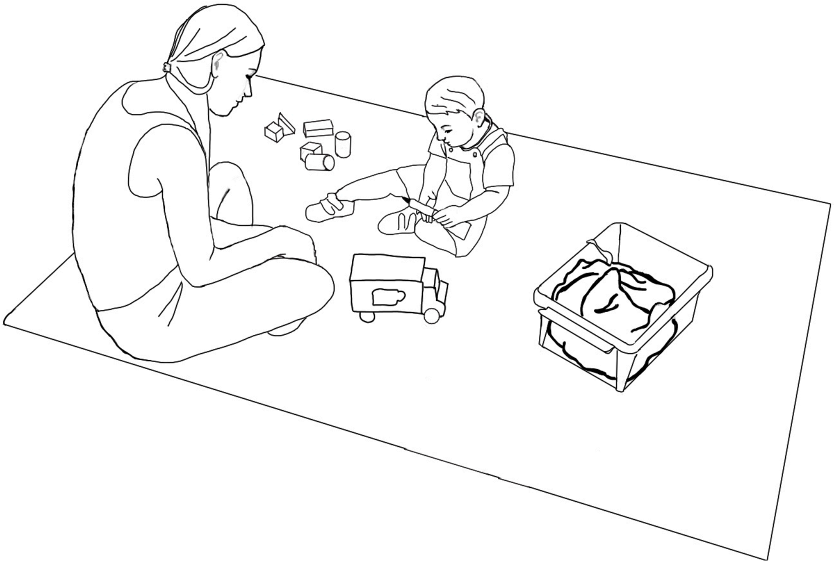
The 80 trials in total were distributed as follows: The trials of both conditions were grouped into four blocks of eight trials. Each block was expanded by two filler trials which were pseudo-randomly inserted after the first and before the last trial. The order of the conditions was alternating, but the starting condition was counterbalanced across participants. The experiment could be stopped at any point by the experimenter if the infant continued to be inattentive to the trials for at least five trials consecutively. At the end of the experiment, the cartoon video played again, signalling the end of the eye-tracking session.

The objects used in the looking-while-listening paradigm were chosen from words and pictures that should be familiar to, and recognisable by, infants of 18 months. They were presented in yoked pairs, which were selected to be part of different semantic categories: apple – jacket, banana – book, bottle – ball, bowl – shoe, dog – bike, cat – (woollen)hat, horse – car, cow – sock. We counterbalanced the number of times the objects were labelled as well as the side of presentation. The labels of the objects were preceded by four different exclamations: “Look”, “What is this”, “How nice”, “Do you see it” (Dutch translations: “Kijk!”, “Wat is dat nou?”, “Wat leuk!”, “Zie je het?”). For the filler trials, we used the objects bear-spoon and baby-cookie. In a filler trial, the infant heard a question, either asking where an object was or if they saw the object. The exclamations, the labels of the objects and the sentences for the filler trials were recorded by a female native speaker of Dutch in a child-directed manner inside of a sound-attenuated booth. The attention getters were six different animated videos with sound, which were taken from The Many Babies Consortium (2020; retrieved via https://osf.io/xbv95/), together with the masking music for the parent. The whole eye-tracking session is described in more detail in Chapter 2.

Play session

After the eye-tracking session, the infant and parent participated in a (roughly) 20-minute play session in the same room. At the beginning of the play session, the light was turned on again and the experimenter presented the parent-child dyads with a plastic box containing five blue bags with different toys. The bags were identical, so there was no indication of what could be inside. The experimenter then asked the parent to play and interact with the infant as they would normally do at home. They could select themselves which toys to use or how to play with them. After instruction, the experimenter left the room. The whole play session was recorded via four cameras (model Panasonic AW-HE120) using the Metus INGEST software (Version 5.5.4.1). When the 20 minutes were over, or if the infant showed signs of distress, the experimenter came into the room to end the experiment and debrief the parent. Figure 3.2 shows an example of the play session.

Figure 3.2
An Example set-up of the Play Session.



Note. The parent and child were playing on a carpet, but, while the parent was asked to stay on the carpet during camera set-up, the experimenter made clear that they could then move freely in the room. The box contained the bags with all the different toys the dyads could select from. Reprinted with permission from Methods, by N. Nota, 2019, Retrieved from https://doi.org/10.6084/m9.figshare.9976751.v1. Copyright 2019 by Naomi Nota.

The toys used in the play session were bought from a Dutch department store. They were a wooden kitchen set with pans, plates and cutlery, a wooden rainbow coloured stacking tower, a wooden truck with four zoo animals (including animal-shaped holes), a box with wooden blocks in different colours and shapes, including miniature persons resembling police, medical personnel or fire brigade, and two hand puppets: a monkey and Red Riding Hood. They were selected to promote different types of play activities, including building, pretend play, and puppet play.

Questionnaires

After parents agreed to participate in the study, we sent them two questionnaires and asked them to fill both in before their lab visit. They received the Dutch adaptation of the MacArthur Communicative Development Inventories *Words and Sentences* (N-CDI; Zink & Lejaegere, 2002, adapted from Fenson et al., 1993) and a questionnaire created in our lab asking about family background, daily activities, and home life. The latter questionnaire is shared on the OSF project page and was a precursor version of the LaDD family questionnaire (https://osf.io/pm94d/).

We invited the parents to complete follow-up N-CDIs when their children were 24 and 30 months old via email. This was not part of the original invitation to participate, therefore we relied on the good will of the parents to participate in these additional inquiries. They were also compensated separately for each follow-up questionnaire with a book for the child. Table 3.1 shows participants' expressive vocabulary knowledge at the different ages tested.

Table 3.1

Expressive Vocabulary Scores on the N-CDI

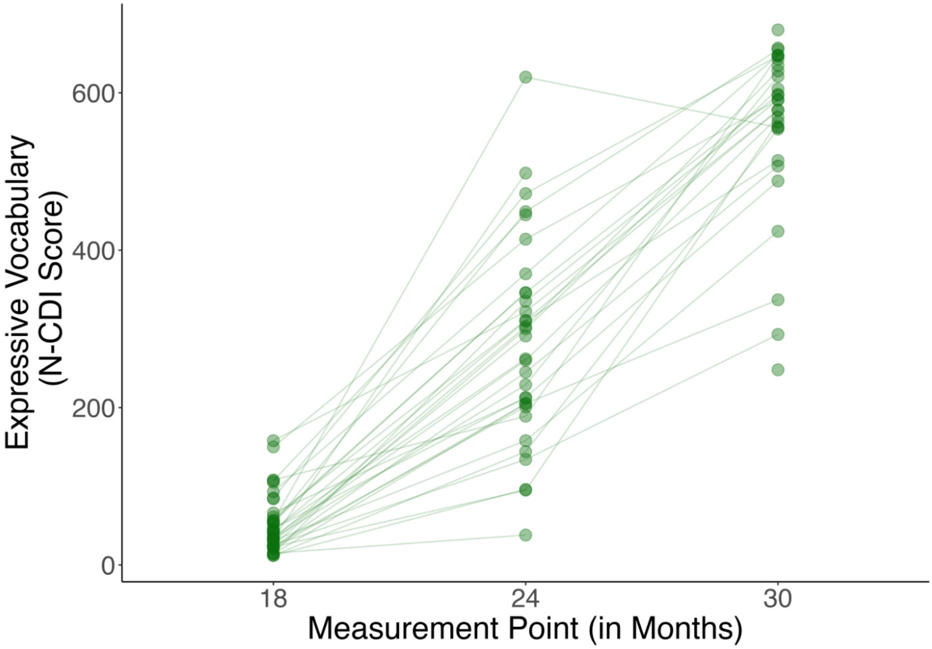
Age (in months)	*M*	*SD*	Range
18 (*N* = 39)	50.95	36.03	12 – 158
24 (*N* = 32)	281.81	129.38	38 – 620
30 (*N* = 29)	558.93	108.74	248 – 680

Note. Scores here refer to the number of words children were reported to produce. The maximum vocabulary score of the N-CDI *Words and Sentences* is 702.

The results of the N-CDI at 18 months were not known before data collection in the lab was completed. However, after seeing the distribution of the scores, we determined that one participant, who had an exceptionally high expressive vocabulary score at 18 months, was an outlier, since their score (271) was higher than the mean (56.45) plus twice the standard deviation (49.75). This way we arrived at our final sample size *N* = 39. Figure 3.3 shows the vocabulary growth for each individual participant with the CDI scores we obtained from the questionnaires.

Figure 3.3

Expressive Vocabulary Growth Between 18 and 30 Months as Measured by the N-CDI



Note. Each dot reflects an individual participant, whose progress across measurement points are indicated by the line.

Analysis

All analysis scripts can be found on the Open Science Framework project website https://osf.io/pjdbz/.

Pre-processing

Before analysis, the raw eye-tracking data were transformed from edf-files to asc-files using the edf2asc translator program (documentation on http://download.sr-support.com/dispdoc/page25.html). These data were then pre-processed in R Version 3.5.0 (R Core Team, 2018) using RStudio Version 1.1.447 (RStudio Team, 2015) and the tidyverse package Version 1.2.1 (Wickham, 2017). Before further analysis, we removed the eye-movements recorded during calibration, filler trials, and attention getters. Additionally, we filtered the fixations assigned by the eye-tracker, such that we only included fixations that lasted for at least 100ms in our analysis (cf. Casillas & Frank, 2017).

Regarding the play session, we transcribed all play sessions according to the ACLEW scheme[1] (Soderstrom et al., 2020) in ELAN Version 5.9 (The Language Archive, 2020). We then exported the transcripts into CHAT format in order to process them with CLAN (MacWhinney, 2000), which we used to first add a morphological tier to our transcriptions using the MOR program and then calculate parental mean length of utterance in morphemes using the *mlu* function and lexical diversity via the *vocd* function of the CLAN suite of programs.

Data analysis

The main dependent variable in the eye-tracking analysis was reaction time (i.e. the time it took infants to fixate on the target upon hearing its label after having previously looked at the distractor). All trials in which the infant looked at the screen for less than a total of 100ms during the preset critical time window (0-2000ms after target word onset) were excluded. Contrary to the analysis in Chapter 2, we included all usable trials across both conditions (Original and Gaze-triggered). This yielded 18.6 trials on average (range: 2 – 34). The speed of processing measure was calculated only on trials where the infant looked at the distractor at the onset of the target label noun phrase. In order to be considered a valid visual reaction time, the shift in

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[1] We expanded the ACLEW scheme by adding categories for each utterance made by the parent, distinguishing between descriptions, open questions, yes/no questions, directives, clarifications and exclamations. The utterance categories are not part of the analyses presented here and will therefore not be further discussed.

fixation from the distractor to the target had to occur between 300ms and 1800ms after the noun phrase onset. We chose the most commonly used time window based on the previous literature (see Chapter 2; Table 2.1 for an overview). Shifts that occurred earlier than 300ms after onset were excluded, as infants are unlikely to be able to process the input and initiate the shift this quickly. Shifts later than 1800ms were excluded as these are most likely not a reaction to the target word. We only included participants who provided at least two trials with a valid reaction time.

The analyses were conducted in RStudio, using the following additional R packages: DescTools Version 0.99.28 (Signorell et al., 2019), dplyr Version 0.7.5 (Wickham et al., 2018), lme4 Version 1.1-21 (Bates et al., 2015), lmerTest Version 3.1-0 (Kuznetsova et al., 2017), openxlsx Version 4.1.0 (Walker, 2018), reshape Version 0.8.8 (Wickham, 2007) and tidyr Version 0.8.1 (Wickham & Henry, 2018). For visualisation, we used the package ggplot2 Version 3.1.0 (Wickham, 2016).

Results

Table 3.2 presents the descriptive statistics of the different aspects of parental speech input we could extract from the 20-minute play session in the lab. All three of our measures were highly correlated with each other, as has been reported often in past research. Parents who used more word tokens also used a larger range of words (diversity), $r(37) = .41$, $p < .01$, and had a bigger MLU , $r(37) = .48$, $p < .002$. Also, if parents had a higher lexical diversity score, they had longer utterances on average, $r(37) = .63$, $p < .001$. On average, the infants took 929.84ms (*SD* = 119.15) to respond to the familiar words in the speed of processing task.

Table 3.2

Descriptive Statistics of the Parental Speech Input (Dutch Data)

Parental Speech	*M*	*SD*	Range
Word Tokens	1003.97	350.8	339 – 1703
Lexical Diversity (VOCD)	61.42	13.1	29.84 – 98.39
MLU	3.34	0.66	2.06 – 4.67

The first aim of our study was to investigate whether differences in parental speech input predict individual differences in lexical speed of processing in Dutch learning infants. Replicating the analysis strategy of Hurtado et al. (2008), we correlated (Pearson's *r*) our three parental input speech variables (word tokens, lexical diversity, MLU) with the infants' lexical speed of processing as well as their expressive vocabulary knowledge at 18, 24 and 30 months of age.

As shown in Table 3.3, contrary to past studies, we found no correlation between number of parental word tokens and expressive vocabulary at any age. However, we observe strong correlations between the two other input measures (lexical diversity and MLU) and expressive vocabulary at 18 months (depicted in Figure 3.4), though not at 24 or 30 months. Furthermore, no measures of parental speech input correlated significantly with infants' speed of processing (measured at 18 months).

Table 3.3

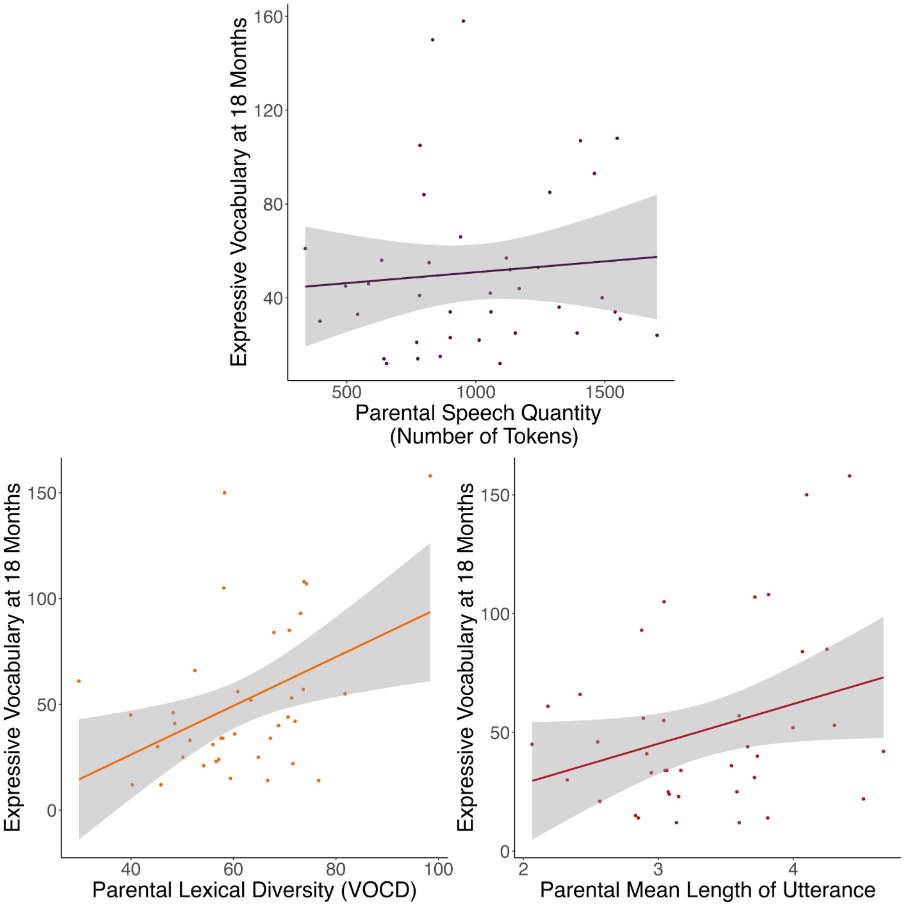
Correlations (r) Between Parental Speech Input and Individual Infant Abilities (Dutch Data)

Parental Speech		Expressive Vocabulary					Speed of Processing
	Age (in Months)	18	24	30	Δ18 – 24	Δ18 – 30	18
Word Tokens		.09	-.07	-4.73×10^{-4}	-.13	.01	-.11
Lexical Diversity (VOCD)		.42**	$.25^{!}$	.11	.13	-.04	.07
MLU		.31*	.19	.23	.1	.15	.05

Note. $^{!}p < .08$, $^{*}p < .03$, $^{**}p < .004$

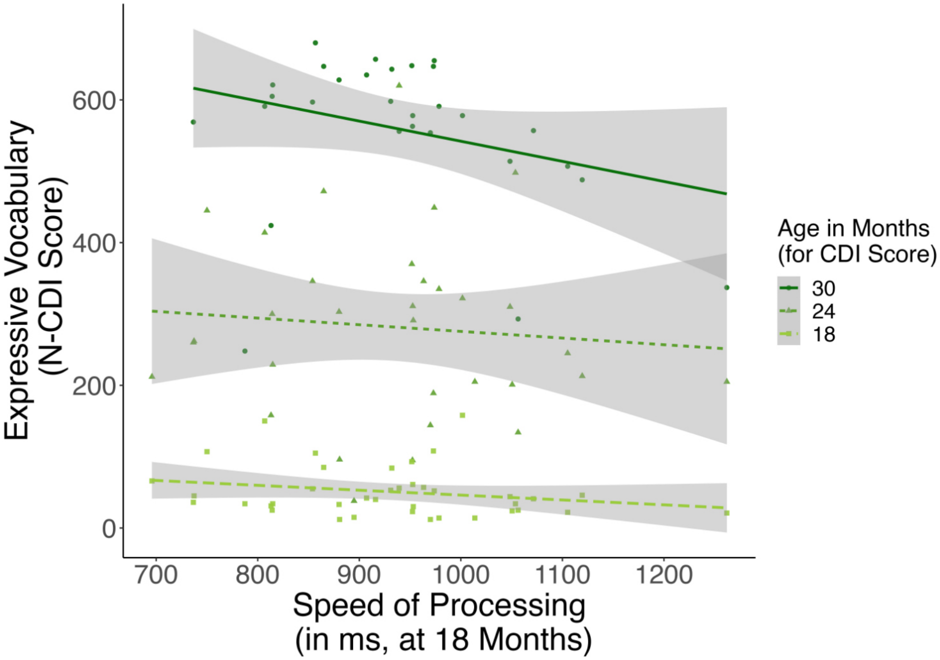
We next investigated whether speed of processing at 18 months predicted vocabulary at 18, 24 and 30 months. Using one-sided Pearson correlations, we found medium effect sizes in the right direction for each age point (a negative relationship) which are similar sized to the previous literature. However, in our sample the correlations did not reach conventional levels of significance (18 months $r(37) = -.23$, $p < .09$; 24 months, $r(30) = -.09$, $p = .31$; 30 months $r(27) = -.30$, $p < .06$). Figure 3.5 shows the relationships between speed of processing at 18 months and the expressive vocabulary scores at 18, 24 and 30 months.

Figure 3.4
Scatterplots of Expressive Vocabulary Score at 18 Months and the Three Aspects of Parental Speech: Quantity (Top), Lexical Diversity (Left), & MLU (Right)



Note. The parental speech aspects were recorded when the infants were 18 months old. Each dot stands for one participant, the coloured line represents the best fit to the data and the shaded grey area shows the standard error for the fitted line.

Figure 3.5
Scatterplot of the Production Vocabulary Score at the Three Different Age Points and Speed of Processing at 18 Months



Note. Each symbol reflects a participant and is coloured and shaped according to the age of when the CDI was measured. The coloured lines represent the best fit to the data and the shaded grey areas show the standard error for the fitted lines.

Our final set of analyses investigated different hypotheses about how different aspects of parental input may affect vocabulary learning and processing speed, either directly or indirectly. First, we predicted that there should be a direct relationship between input quantity (word tokens) and speed of processing, since we expect that repeated exposure to words would strengthen the mental representation of these words, and might make it easier to recall them. We also expected a correlation between quantity and later vocabulary. As reported above, contrary to this prediction, we found no relationship between input quantity (word tokens) and either vocabulary measure or speed of processing (see Table 3.3 above).

Second, we suggested that, while lexical diversity may facilitate the development of a bigger vocabulary, it is unclear how it could directly facilitate faster processing. Thus, we predicted that lexical diversity would directly correlate with vocabulary, but not speed of processing, though there might be an indirect effect of diversity on lexical speed of processing when we take vocabulary into account. As predicted (see Table 3.3 above), lexical diversity did not correlate with processing speed but did correlate with vocabulary size at 18 months (though not at 24 and 30 months). There was, however, no evidence of an indirect effect of lexical diversity on processing speed moderated by vocabulary, as measured by our linear moderation model (R^2 = .031, $F(3,35) = 1.40$, $p = .26$, see also Table 3.4).

Table 3.4

Linear Moderation Model Predicting Speed of Processing (RT) Through the Expressive Vocabulary at 18 Months, Parental Lexical Diversity (VOCD) and Their Interaction

	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	994.177	158.832	6.529	<.001
Vocabulary 18 months	-3.153	2.302	-1.37	.18
VOCD	-0.108	2.573	-0.042	.97
Vocabulary 18 months x VOCD	0.031	0.032	0.956	.35

For MLU, we proposed an interaction. We hypothesised that fast processors who receive longer utterances might be able to learn more from them, while slower processing infants might actually be hindered by longer utterances. For a visual inspection of the data, we divided our infants into fast and slow processors using a median split (at 945.49ms). Figure 3.6 presents the results, showing growth from 18 to 24 months (Figure 3.6a) and from 18 to 30 months (Figure 3.6b) for fast and slow processors (note that our dataset was partly incomplete because not all parents filled in the CDI at both 24 and 30 months).

Although from Figure 3.6 it looks like the data from fast processors might support the hypothesis that fast processors can benefit from more complex input, the inferential statistics did not bear this out, neither for vocabulary growth between 18 and 24 months (R^2 = -.083, $F(3,28) = 0.21$, $p = .89$, see also Table 3.5), nor for growth between 19 and 30 months (R^2 = -.015 $F(3,25) = 0.86$, $p = .47$, see also Table 3.6).

Table 3.5

Linear Model Predicting Vocabulary Growth from 18 to 24 Months from Speed of Processing (SoP), Parental Mean Length of Utterance (MLU) and Their Interaction (n = 32)

	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	-210.13	747.017	-0.281	.78
SoP	0.409	0.788	0.519	.61
MLU	153.11	239.362	0.64	.53
SoP x MLU	-0.144	0.252	-0.572	.57

Table 3.6

Linear Model Predicting Vocabulary Growth from 18 to 30 Months from Speed of Processing (SoP), Parental Mean Length of Utterance (MLU) and Their Interaction (n = 29)

	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	1108.322	892.622	1.242	.23
SoP	-0.693	0.904	-0.767	.45
MLU	-125.3	270.9	-0.463	.65
SoP x MLU	0.148	0.276	0.536	.60

Study 2: British English infants

Since there can be extensive data loss with longitudinal studies, one concern was that we might not have had enough data in study 1 to come to robust conclusions. Therefore, we ran a planned replication of our analyses using an existing dataset of children learning British English from the longitudinal Language 0-5 project (Peter et al., 2019; Rowland et al., unpublished).

Method

Details of the vocabulary and speed of processing measures taken from the British sample are available in Peter et al. (2019). More information of the play session data collection can be found in the readme docs accompanying the data deposited in the Language Archive (Rowland, 2021).

From the 95 infants participating in the Lang0-5 project, we were able to include 56 infants (32 girls) who provided at least two speed of processing trials, took part in the play session and whose parents responded to the CDI questionnaire at 19 and at either 25 or 30 months.

Figure 3.6a
Scatterplot of Parental MLU and the Expressive Vocabulary Growth Between 18 and 24 Months (Dutch Data)

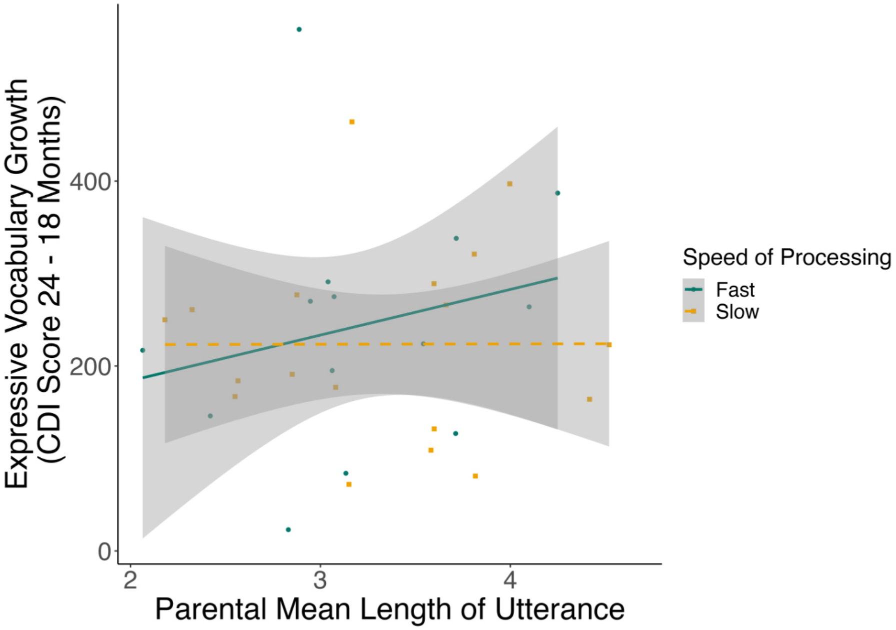
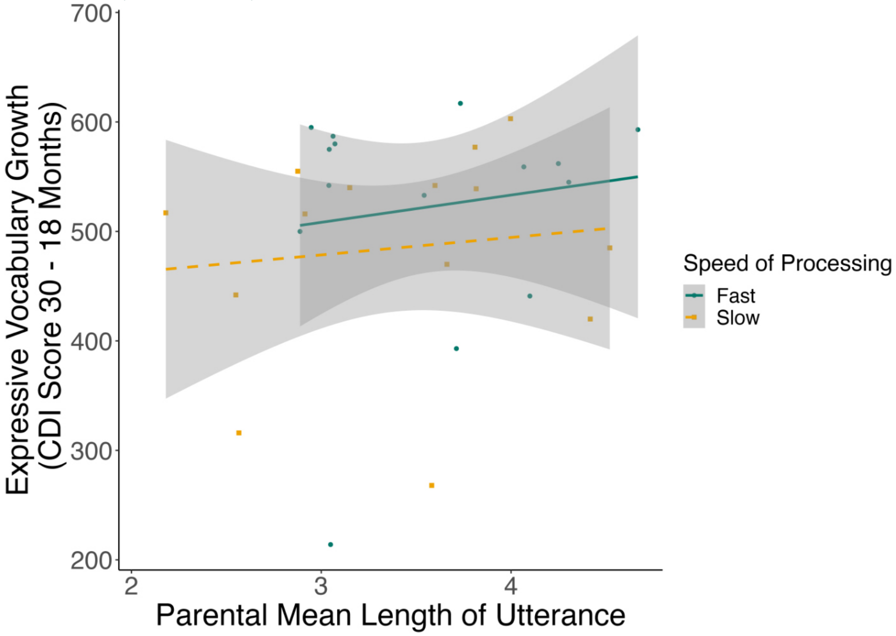


Figure 3.6b
Scatterplot of Parental MLU and the Expressive Vocabulary Growth Between 18 and 30 Months (Dutch Data)



Note. Each dot represents a participant, coloured and shaped to indicate their relative speed in the sample after a median split. The lines show the best fit to the data of either slow or fast participants and the grey areas indicate the standard error of each line.

Two families did not complete the CDI at 24 months and three at 30 months, but we still included these participants. In essence, the British English data collection procedure was similar to that for the Dutch data, and was collected at similar ages (18, 19, 25 and 30 months and 18, 24 and 30 respectively), with a few differences: (1) The speed of processing measurement was administered at 19 months instead of 18 in the UK data, (2) the parents were asked to fill in the Lincoln CDI Words and Sentences (Meints et al., 2017, max vocabulary score = 689), which is the UK version of the MacArthur-Bates CDI Words and Sentences, and (3) the play session that took place at 18 months was 30 minutes long in total, with different toys provided every 10 minutes. The longer session explains for example, why the English parents produce more word tokens than the Dutch parents, as can be seen in Table 3.7 (English equivalent to Table 3.2). Table 3.8 (English equivalent to Table 3.1) provides an overview of the participants' expressive vocabulary at the different ages tested[2] and Figure 3.7 (English equivalent to Figure 3.3) shows the vocabulary growth for each individual participant. This dataset also included some infants with exceptionally high vocabulary scores at 19 months, but since there were several children instead of just one, we decided to keep them in our analyses.

Table 3.7

Descriptive Statistics of the Parental Speech Input (English Data)

Parental Speech	*M*	*SD*	Range
Word Tokens	2032.1	519.78	889 – 3058
Lexical Diversity (VOCD)	41.67	5.85	29.77 – 57.01
MLU	3.46	0.46	2.45 – 4.63

---

[2] Note that over the course of the Language 0-5 project, parents were asked to complete the Lincoln CDI at 19, 21, 24, 25, 27 and 30 months. For better comparison with the Dutch data in the present study, we chose to include the CDI scores from 19, 25 and 30 months only.

Table 3.8

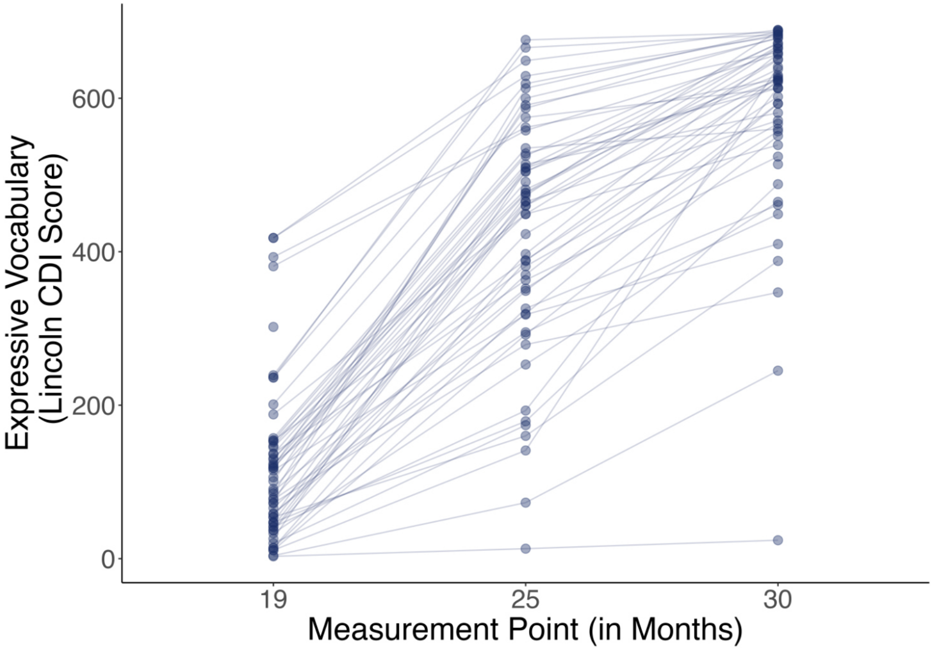
Expressive Vocabulary Scores of the English Participants on the Lincoln CDI

Age (in months)	*M*	*SD*	Range
19 (*N* = 56)	119.1	103.15	3 – 418
24 (*N* = 54)	426.46	155.52	13 – 676
30 (*N* = 53)	584.6	124.52	24 – 689

Note. Scores here refer to the number of words children were reported to produce. The maximum vocabulary score of the Lincoln CDI *Words and Sentences* is 689.

Figure 3.7

Expressive Vocabulary Growth Of The English Participants Between 19 And 30 Months As Measured By The Lincoln CDI



Note. Each dot reflects an individual participant, whose progress across measurement points are indicated by the line.

Results

As with the Dutch data, we found significant correlations between the different input measures. The parents who used more word tokens also used a wider variety of words, *r*(54) = .32, *p* < .01, and parents with more speech input overall also had longer utterances on average, *r*(54) = .34, *p* < .01. However, in contrast to the Dutch data, there was no correlation between the

MLU score and the lexical diversity measure, $r(54) = -1.3 \times 10^{-4}$, $p = .99$. The infants responded to the familiar words in the speed of processing task with an average reaction time of 751.27ms (*SD* = 128.95).

Following the structure we outlined in the Introduction and that we used with the Dutch data, we first investigated if the different aspects of parental speech input predict individual differences in lexical speed of processing or their vocabulary. We correlated (Pearson's *R*) the number of word tokens, lexical diversity and MLU with the English infants' speed of processing and their expressive vocabulary size at 19, 25 and 30 months.

Table 3.9

Correlations (r) Between Parental Speech Input and Individual Infant Abilities (English Data)

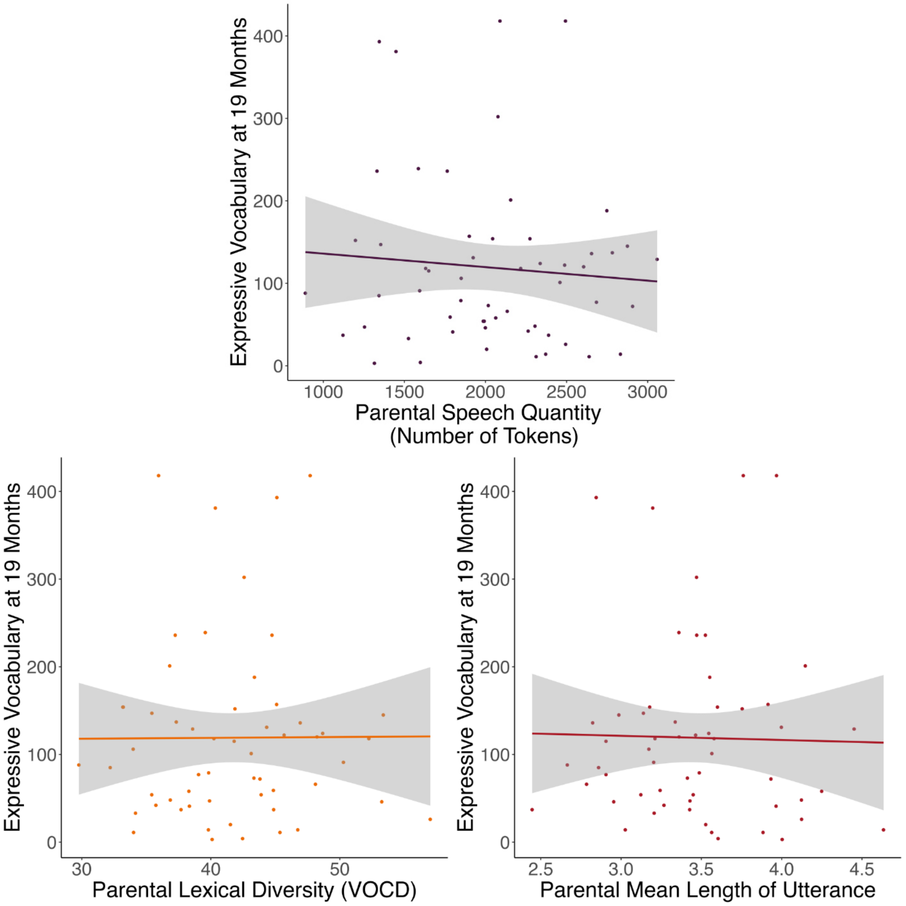
Parental Speech		Expressive Vocabulary					Speed of Processing
	Age (in Months)	19	25	30	Δ19 – 25	Δ19 – 30	19
Word Tokens		-.08	.07	.1	.15	.17	.1
Lexical Diversity (VOCD)		.01	.05	.04	.05	.03	-.07
MLU		-.02	-.05	-.01	-.04	.004	.13

As with the Dutch data, we found no significant correlation between any aspect of parental speech input and lexical processing speed. Additionally, and in contrast to the data of the Dutch infants, we found no significant relationships between parental speech input and vocabulary at any age point. For an overview of the correlations see Table 3.9 (English equivalent to Table 3.3). To facilitate comparison, we also recreated the scatterplots depicted in Figure 3.4 with the British English data, see Figure 3.8.

We next ran one-sided correlations between the speed of processing and the vocabulary size measures of the infants at the different age points (see also Peter et al., 2019, Table 2), predicting negative relationships in line with the speed of processing literature. As can be observed in Figure 3.9 (English equivalent to Figure 3.5), we replicated the negative correlations also presented in Peter et al. (2019) with our subset of the Language 0-5 data.

Figure 3.8

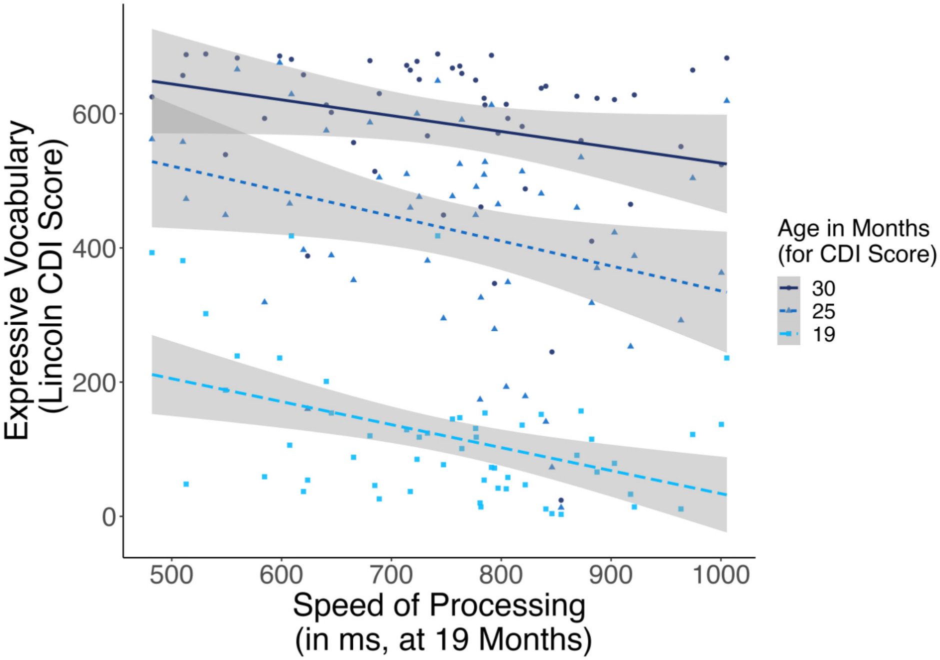
Scatterplots of Expressive Vocabulary Score at 19 Months and the Three Aspects of Parental Speech: Quantity (Top), Lexical Diversity (Left), & MLU (Right)



Note. The parental speech aspects were recorded when the infants were 18 months old. Each dot stands for one participant, the coloured line represents the best fit to the data and the shaded grey area shows the standard error for the fitted line. For the English data, these were not correlated.

Figure 3.9

Scatterplot of the Production Vocabulary Score at the Three Different Age Points and Speed of Processing at 19 Months



Note. Each symbol reflects a participant and is coloured and shaped according to the age of when the CDI was measured. The coloured lines represent the best fit to the data and the shaded grey areas show the standard error for the fitted lines.

There were significant relationship between speed of processing at 19 months and vocabulary at 19 months, $r(54) = -.43$, $p < .001$, 24 months, $r(52) = -.31$, $p < .02$, and 30 months, $r(51) = -.25$, $p < .04$.

Finally, we replicated our analyses testing how the different aspects of parental speech input might influence lexical development directly or indirectly via the infants' individual abilities: vocabulary knowledge or speed of processing. We first looked at input quantity (word tokens), predicting that the more often an infant is exposed to words, the stronger their mental representation of these words will be, which might impact how fast the infants are in recognising them. Thus, we expected a direct relationship between number of word tokens and speed of processing. At the same time, we also predicted a direct correlation between quantity and later vocabulary sizes. However, as with the Dutch data and as reported in Table 3.9, we did not confirm a relationship between word tokens and any of the individual infants' abilities.

Finally, we replicated our analyses testing how the different aspects of parental speech input might influence lexical development directly or indirectly via the infants' individual abilities: vocabulary knowledge or speed of processing. We first looked at input quantity (word tokens), predicting that the more often an infant is exposed to words, the stronger their mental representation of these words will be, which might impact how fast the infants are in recognising them. Thus, we expected a direct relationship between number of word tokens and speed of processing. At the same time, we also predicted a direct correlation between quantity and later vocabulary sizes. However, as with the Dutch data and as reported in Table 3.9, we did not confirm a relationship between word tokens and any of the individual infants' abilities.

Second, we hypothesised that lexical diversity would correlate directly with vocabulary size but only impact processing speed indirectly. In contrast to the Dutch data, lexical diversity did not correlate with vocabulary size at any age. Additionally, and in line with the results of the Dutch data, there was no correlation between lexical diversity and speed of processing, nor was there an indirect effect of lexical diversity via vocabulary, as measured by a linear moderation model ($R^2 = .14$, $F(3,52) = 4.091$, $p < .02$, see also Table 3.10).

Table 3.10

Linear Moderation Model Predicting Speed of Processing (RT) Through the Expressive Vocabulary at 19 Months, Parental Lexical Diversity (VOCD) and Their Interaction (English Data)

	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	805.86	182.97	4.4	<.001
Vocabulary 19 months	0.11	1.38	0.05	.93
VOCD	0.21	4.34	0.08	.96
Vocabulary 19 months x VOCD	-0.02	0.03	-0.47	.64

Third, we suggested that there might be an interaction effect between parental MLU and speed of processing on vocabulary growth. Fast processors who receive longer, more complex utterances might benefit more from the linguistic information provided compared to slower processing infants who might in turn be hindered by longer sentences. As with the Dutch data, we divided the sample into fast and slow processors using a median split (770.4ms). In Figure 3.10 we display our predictions for infants with fast or slow processing speed, for vocabulary growth between 19 and 25 months (Figure 3.10a) and between 19 and 30 months (Figure 3.10b).

Again, although from Figure 3.10 it looks like the data might support the hypotheses for the vocabulary growth of 19 to 25 months (though not the growth of 19 to 30 months) the inferential statistics did not conclusively support this: 19 to 25 months (R^2 = -.024, $F(3,50) = 0.585$, p = .63, see also Table 3.11), 19 to 30 months (R^2 = -.04, $F(3,49) = 0.334$, p = .8, see also Table 3.12).

Table 3.11

Linear Model Predicting Vocabulary Growth from 19 to 25 Months Through Speed of Processing (SoP), Parental Mean Length of Utterance (MLU) and Their Interaction (English Data, n = 54*)*

	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	-584.56	779.024	-0.75	.46
SoP	1.235	1.033	1.196	.24
MLU	271.184	226.028	1.2	.24
SoP x MLU	-0.373	0.298	-1.25	.22

Table 3.12

Linear Model Predicting Vocabulary Growth from 19 to 30 Months Through Speed of Processing (SoP), Parental Mean Length of Utterance (MLU) and Their Interaction (English Data, n = 53*)*

	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	-65.5	839.637	-0.078	.94
SoP	0.721	1.114	0.647	.52
MLU	128.722	243.144	0.529	.6
SoP x MLU	-0.176	0.321	-0.548	.59

Figure 3.10a

Scatterplot of Parental MLU and the Expressive Vocabulary Growth Between 19 and 25 Months (English Data)

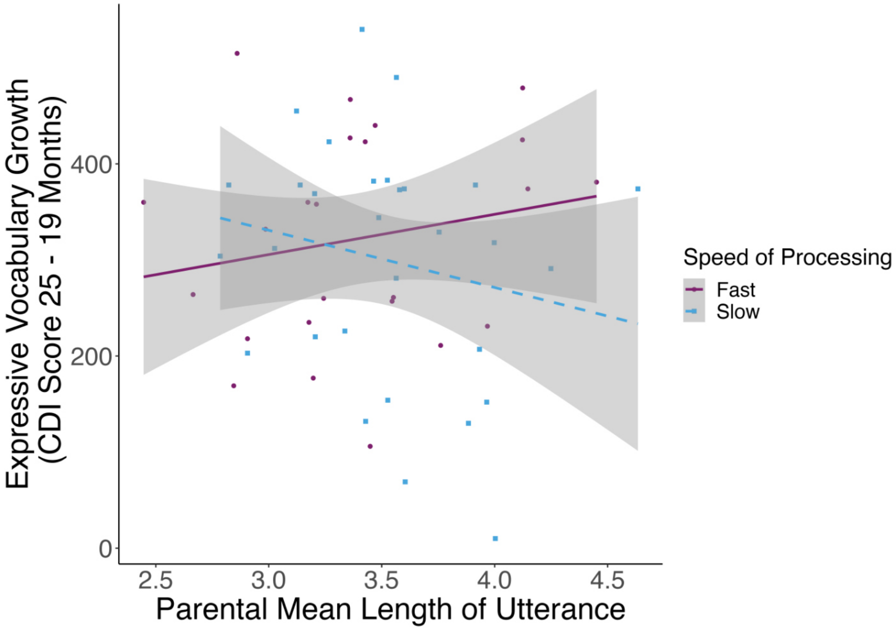
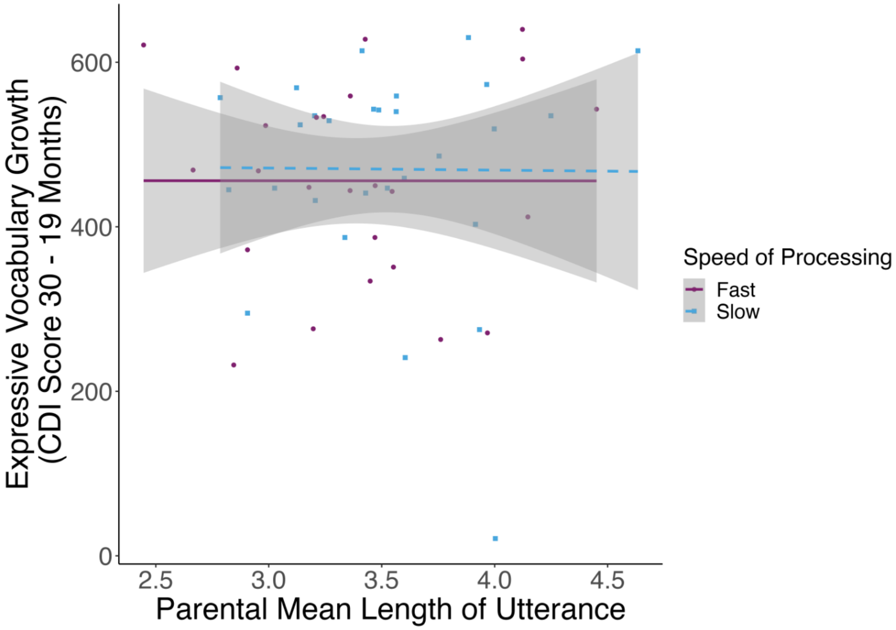


Figure 3.10b

Scatterplot of Parental MLU and the Expressive Vocabulary Growth Between 19 and 30 Months (English Data)



Note. Each dot represents a participant, coloured and shaped to indicate their relative speed in the sample after a median split. The lines show the best fit to the data of either slow or fast participants and the grey areas indicate the standard error of each line.

Discussion

In the present paper we first investigated whether differences in parental speech input could predict individual processing speeds of 18-month-old infants and the vocabulary outcomes at the concurrent age and at later ages. We then attempted to disentangle three different aspects of parental speech input and their possible importance for lexical speed of processing and vocabulary development. To this end we tested 18-month-old Dutch infants, assessing their lexical speed of processing, recording parental speech input in a play session, and measuring their growing vocabulary through parental reports at 18, 24 and 30 months. Additionally, we analysed similar data of a pre-existing dataset of British English children (the Language 0-5 Project data; see Peter et al., 2019; Rowland et al., unpublished).

Regarding the first goal of the chapter, there were no significant correlations between lexical speed of processing and any of our input measures; neither in Dutch nor in English. This is in line with the findings of Hurtado et al. (2008), who did not report such relationships for their 18-month-olds. For the Dutch data, we reported significant correlations between the infants' vocabulary at 18 months and parental lexical diversity and MLU, but not for amount of input measured by tokens. While the latter might be surprising since the quantity of speech input has been one of the most frequent predictors of vocabulary outcomes (Hoff & Naigles, 2002; Huttenlocher et al., 1991), it might be that the 18-month-olds in our Dutch study were old enough such that they did not require a lot of input, but rather benefitted most from diversity and morphosyntactic complexity (as was reported also by Rowe, 2012). However, the correlations grew weaker and non-significant when we looked at the later vocabulary outcomes. Here we have to be careful not to draw strong conclusions, since we only have the parental speech input for when the infants were 18-months-old. The parents might have adapted their speech to the growing abilities of their children. In any case, the input we recorded could not explain substantial variance in later language development.

We found no correlations between any aspect of parental speech and vocabulary in the English data, and no relationship between parental MLU and lexical diversity. We suggest that this maybe because the way the input data was collected introduced more noise in the speech of the English parents. The parent-infant dyads were first provided with toys to elicit symbolic play (cooking tools, tea set, teddybear, etc.), then after ten minutes they received functional play toys (such as wooden instruments, block puzzle, hammer and peg, etc.). For the last ten minutes they could play with all the toys. It might be that the way in how the parents were asked to play with the infant minimised meaningful individual differences in their speech. Further work is necessary, with larger and more spontaneous play interaction data, to confirm these results.

The second goal of the paper was to explore the possible interplay between different aspects of parental speech and infant’s vocabulary and processing speed. We posited different hypotheses for different factors in parental input. First, we proposed that input quantity, measured by the number of word tokens in the present paper, might predict vocabulary size and growth, since studies have demonstrated this relationship, at least at younger ages (Rowe, 2012). We also suggested that repeated exposure to words might also strengthen the mental representations of words in the infant's lexicon, and therefore help them to process these words faster (see Peter et al., 2019 for a similar idea). However, neither for the Dutch nor for the British English data did we detect any relationships. This might be, as suggested above, because our infants were too old to be influenced by input quantity (Dutch data) or due to noise in our measurement (British English data).

Second, we hypothesised that input lexical diversity might predict infant vocabulary, since, by being exposed to new words, infants can add these to their lexicon. For processing ability, we could not deduce from the literature how diversity might help infants process words more efficiently. Thus, we proposed that any effect of lexical diversity on speed of processing might be mediated thought the vocabulary of the infants, as vocabulary and speed of processing seem to be closely related (see Fernald et al., 2006; Fernald & Marchman, 2012). For our Dutch data, we found a strong correlation between the variability of lexical input and vocabulary at 18 months, but not at later ages, as mentioned above. In addition, our moderation analysis did not show that lexical diversity might influence speed of processing through vocabulary. The data for the English infants showed similar results. Note however, that it might be the case that vocabulary size and speed of processing are too highly correlated to enable us to tease them apart in these types of statistical analyses. For this hypothesis, it seems relevant to further investigate the link between speed of processing and vocabulary, to gain more information on the direction of the causal relationship, or whether there is a causal relationship at all.

Third, we suggested that the influence of morphosyntactic complexity on vocabulary growth might be mediated through processing speech. As longer sentences contain more word and information (such as morphosyntax), they might be more difficult to process, especially, if an infant is slower at processing incoming speech. If infants would, however, be able to process all the information, they might actually benefit from the complexity of the input. Thus, we expected an interaction between slow and fast processing infants in how parental MLU might impact vocabulary development. There were no predicted significant effects for either the Dutch or the British English data. However, visual inspections of the plotted data showed that the data was in the predicted direction for vocabulary development between 18 and 24 months of age for the Dutch infants (and 19 and 25 months for the English infants).

Thus, further work, in a study with more power, is needed to determine whether these trends are robust. We might also consider longitudinal approaches, where speed of processing and parental speech input measures are also collected at later ages (see Rowe, 2012) to receive a better indication of the infants' developing skills as well as the input they receive at different ages.

Conclusion

This paper investigated the possible interactions between different aspects of parental speech input (quantity, lexical diversity and morphosyntactial complexity) and infants' language abilities (vocabulary size and growth as well as speed of processing) with datasets of Dutch and British English infants from one and a half to two and a half years of age. The predictions were not supported in our planned analyses, but the data show some interesting trends that need to be investigated further in a future study with more power.

Chapter 4

Examining the nature of infants′ lexical speed of processing

This chapter is based on Egger, J., Rowland, C.F., & Bergmann, C. (n.d.). *Examining the nature of infants' lexical speed of processing* [Manuscript in preparation]. Language Development Department, Max Planck Institute for Psycholinguistics.

Abstract

Children who are able to process familiar words quickly have been reported to have a larger expressive vocabulary than slower processing children. However, the underlying nature of the relationship between processing speed and vocabulary development is still unknown. Lany (2018) provided initial evidence that fast speed of processing can aid novel word learning, if the task is challenging. The present study replicates Lany (2018) with Dutch 17-month-olds, using the same novel word learning task with Dutch pseudowords and assessing their processing ability in an eye-tracking paradigm. Additionally, we measured the infants' processing speed of the newly acquired words, in order to extend the previous work and gain insights into the relationship between speed of processing and vocabulary.

Our data only provided weak evidence that Dutch infants with faster processing speed performed better in the novel word learning task than slower processing infants, even when using strict inclusion criteria. Lexical processing speed of familiar words explained accuracy in the word learning task above other predictors, such as vocabulary size. Overall, only infants with fast processing of familiar words were able to learn the new labels. We further found no correlations between visual reaction time, processing speed of familiar and novel words, which would indicate that processing speed may depend on word-specific knowledge. However, due to testing limitations, that we outline in the paper, our sample size was not suited to detect small effect sizes, which is why we advise caution when interpreting the results and suggest a more well powered study to further investigate the relation between processing speed and word learning.

Introduction

An ongoing puzzle in language acquisition research has concerned the substantial individual variation in early lexical development. Infants vary widely in how fast their vocabulary knowledge develops and, among other factors, internal capabilities have been identified as important contributors: Research has shown that individual lexical speed of processing (Fernald et al., 2006; Fernald & Marchman, 2012) impacts vocabulary size. Lexical speed of processing – also referred to as lexical processing efficiency (e.g. Lany, 2018) or speed of verbal processing (Fernald et al., 1998) – refers to the speed in which an infant recognises a familiar label for an object in a looking-while-listening paradigm (Fernald et al., 2008), which in turn is thought to reflect how fast a word is recognised (based on adult information processing literature, e.g. Janse & Jesse, 2014).

As the looking-while-listening paradigm is easy to use with children from a young age, lexical speed of processing has been widely studied, and has been shown to be a predictor of infants' concurrent vocabulary size as well as their subsequent linguistic development. For example, Fernald et al. (2006) have shown a positive link between the speed of processing of 25-month-old infants and their expressive vocabulary at 12, 18 and 21 months. Fernald and Marchman (2012) have reported that 18-month-old infants' speed of processing is related to their expressive vocabulary at 18, 21, 24 and 30 months (as rated by their parents using the MacArthur-Bates Communicative Development Inventories [CDI], Fenson et al., 2007). Additionally, Marchman and Fernald (2008) have shown that the lexical processing efficiency of 25-month-old infants can be linked to their expressive vocabulary at eight years old, alongside their working memory and IQ at that age. Thus, speed of processing predicts vocabulary well into school age.

However, there have been very few studies addressing the question of *why* there is a link between infants' processing speed and vocabulary size across development. One possibility is that infants who are able to process familiar words quickly have more resources available to acquire new words, which is supported by the results of Fernald and Marchman (2012), who report a relationship between speed of processing and vocabulary growth. Alternatively, or perhaps in addition, fast processors may add new words more easily to their lexicon, because they recognise unfamiliar words as novel more rapidly (Law & Edwards, 2015).

Lany (2018) was the first to directly test whether children with fast processing speed learn new words more easily in a laboratory setting. She exposed 17-and 30-month-olds to nonsense words paired with images of colourful objects, and subsequently tested whether the children accurately identified the just-taught name of the target image on being asked to ‘find the X’ by looking at the correct novel object. Additionally, she measured the infants' lexical speed of processing of familiar words. The prediction was that if fast processing speed facilitated novel word learning, there would be a relationship between processing speed and performance in the word learning task. This prediction was borne out for the 17-month-olds: There was, as expected, a significant negative correlation between the children's accuracy at identifying the target referent of the newly taught words and the speed with which they processed familiar words in a traditional speed of processing task. This relationship held after controlling for maternal education, vocabulary size and visual reaction time (as a measure of general attentiveness/responsiveness). To further investigate the enhanced word learning performance of fast processing 17-month-olds, Lany distinguished between fast and slow processers using a median split and conducted one-sample t-tests on the novel word accuracy results compared to chance. This showed that only the fast lexical processors were significant above chance at identifying the referent of newly learned (novel) words.

However, Lany's (2018) prediction that there would be similar results for the 30-month-olds was not upheld by her results. There was no relationship between the processing speed of familiar words of 30-month-olds and their accuracy at identifying the referent of newly learned (novel) words; nor was there a difference when the infants were split into fast and slow processors - both groups performed above chance in the novel word learning task. As a result, in a second experiment, the difficulty of the novel word learning task was increased by presenting the novel objects in movement, and embedding the words in more complex sentence frames.

The new task was conducted with another group of 30-month-old infants. Only then did the relationship between speed of processing and novel word learning accuracy re-emerge, as did the difference in performance between fast and slow processors. On the basis of these results, Lany (2018) speculated that speed of processing seems to facilitate novel word learning, but only if the learning task is sufficiently difficult.

The study by Lany (2018) thus provides initial support for the proposal that children with fast lexical processing are at an advantage when learning new words. However, the explanation for the unforeseen interaction with task difficulty was post hoc and further constrains how fast processing might aid novel word learning (i.e. only in challenging tasks). It is therefore important to test the proposed explanation in a confirmatory study. To this end, the first goal of the current study was to re-run the first experiment by Lany (2018) with 17-month-old Dutch learning infants to test whether we can replicate the relationship between familiar word processing speed and novel word learning.

Even if we replicate the relationship reported by Lany (2018), however, it is still unclear what cognitive capacity underlies the processing speed effect itself. One possibility is that speed of processing reflects an intrinsic broad *general cognitive capacity*, an idea that is endorsed by findings such as the one by Marchman and Fernald (2008), who have shown a relationship between processing speed at 25 months and other cognitive abilities later in life (working memory and IQ at eight years of age). On this model, some infants are intrinsically faster at processing information, including words, and then these infants have more resources available to acquire new words (e.g. Fernald and Marchman, 2012). Note however, that Lany (2018) did not find support for this hypothesis. She took a measure of visual reaction time as a non-linguistic index of individual information processing, and did not find a link between the reaction to purely visual information and lexical processing speed. These results are not expected according to a broad, domain-general cognitive capacity account, which would predict a strong link between visual and lexical processing speed. However, Lany (2018) remains the only test of this hypothesis so far.

A second possible interpretation of the link between vocabulary and lexical speed of processing is what we will call *lexicon-specific processing*, whereby a larger lexicon enables faster processing of known and new lexical information. According to this model, fast processors may add new words more easily to their lexicon, because their greater vocabulary knowledge means that they recognise unfamiliar words as novel more rapidly (Law & Edwards, 2015). This interpretation views performance on the speed of processing task as driven mainly (or even solely) by the size of the child's lexicon, and thus as a language-specific phenomenon that affects all lexical items similarly.

Donnelly and Kidd (2020) have proposed a third possibility, namely that speed of processing on the task is driven by *item-specific* knowledge, such that processing speed depends on the identity of the individual word in the task. On this account, the child's overall speed of processing in a specific study simply reflects an average over different items with varying associated processing speeds or, in their words, an "emergent capacity reflecting a collection of word-specific capacities" (Donnelly & Kidd, 2020; 1). They conducted a longitudinal study trying to tease apart the first and third accounts of speed of processing we present above, and showed that the modelled data of 18-month-olds fits both the general cognitive and item-specific theories equally well, leaving the nature of speed of processing unclear. They pointed out in their limitations section, though, that the data might have been too noisy to clearly differentiate between the two theories, due to having very few speed of processing trials per item and per child.

Therefore, the second goal of the present study was to investigate these three possible interpretations of what causes individual differences in the lexical speed of processing task. We do this by testing how quickly children process both familiar and newly learned words, as well as administering a non-linguistic processing task; thus, replicating and expanding the study by Lany (2018). If the origin of individual differences in lexical processing speed is a general cognitive capacity, we expect that this capacity will affect both new and familiar word processing, and non-linguistic (visual) processing. Thus, (contra the results of Lany, 2018) we would predict a strong relationship between the processing speed of new and familiar words and non-linguistic processing speed. If the underlying cause of differences in lexical processing speed is lexicon-specific (i.e. dependent on the size of the lexicon), we would not necessarily expect a relation between linguistic and non-linguistic processing speed, but we would predict a correlation between the processing speed of novel and familiar words, since both should be dependent on the size of the child's lexicon. However, if overall performance on the familiar word processing speed task reflects the average over a collection of familiar word-specific capacities (item-specific hypothesis), then we might expect novel word, familiar word and visual processing speeds to disassociate, and to also not see a relation between familiar word and visual processing tasks. Thus, we would might not expect to find a strong correlation between the three different processing tasks (familiar, novel words and non-linguistic processing). Note that there are also many different combinations of these three factors that might apply (e.g. speed of processing reflects both a general cognitive capacity and lexical-specific processing), the predictions of which we describe in detail in the pre-registration document (https://osf.io/59tvn) but do not spell out here because, to foreshadow the results, we do not find correlations between any of these variables.

In summary, the aim of the present study was two-fold: First, we replicated the study of Lany (2018) with Dutch 17-month-old infants. We predicted that fast processors will perform better at the novel word learning task than their peers with slower speed of processing. Second, we compared the lexical processing speed of newly acquired words, familiar words and non-linguistic (visual) stimuli in order to determine which of three models of the underlying origin of the effect best fitted the data. Infants took part in a novel word learning task, during which we also measured non-linguistic reaction time following Lany (2018). Then we measured the infants' speed of processing of both newly learned and familiar words in a gaze-contingent looking while listening paradigm (see Chapter 2). Using the Dutch adaptation of the CDI (N-CDI), we assessed infants' vocabulary size through parental reports. The results of the present study provide insights into the nature of the connection between speed of processing and vocabulary development in infancy.

Method

All materials we can freely share, depersonalised data, and analysis scripts are available on the Open Science Framework project website https://osf.io/b2m8g/.

Participants

In total, we tested 111 infants[1], all of whom were recruited via the local babylab database. We excluded two infants after testing as they did not fit our inclusion criteria: born at or after 34 weeks of gestation, a birth weight of at least 2500g, no known visual or hearing impairments, parents did not have dyslexia or a speech or language impairment, monolingual Dutch exposure. To assess exposure to Dutch, parents were asked to estimate the amount of non-Dutch language input the infant might be exposed to and we excluded any infant that might hear another language for longer than half a day per week. This is equivalent to 93% of Dutch input, a cut off that has been used in past research to identify children considered to be monolingual (cf. Byers-Heinlein, 2015, and Chapter 2 and 3).

In addition, we excluded infants whose parents did not provide vocabulary or parental education information (*n* = 3), who refused to wear the sticker needed for eye tracking (*n* = 2), during whose sessions equipment failure or testing mistakes occurred (*n* = 3), whose parents or siblings interfered during testing (*n* = 2) and who did not complete a sufficient number of trials as specified in the Analysis section (*n* = 56). This left 42 Dutch-learning infants (mean age in days = 521.2, *SD* = 7.9, range: 510 – 542; 19 girls) who produced enough data for the analysis for the first objective of our study.

For the second goal of our study, we excluded the same infants as above who did not fit the preset inclusion criteria (*n* = 2), whose parents did not fill in the questionnaire (*n* = 3), or where the eye-tracking did not work due to the missing sticker, experimental errors or interference (*n* = 7). We originally intended to apply an inclusion criterion of at least two trials for the

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[1] In our pre-registration, we were aiming for a test sample of 80 included infants, expecting we would need to test 100 infants to arrive at that sample. After testing 111 infants we only were able to include 42 participants. Unfortunately, we had to stop testing due to COVID-19-related time limits.

reaction time trials (speed of processing for novel and familiar objects and visual reaction time). However, after analysing the data for first goal of the present study we discovered that implementing stricter inclusion criteria yielded cleaner results (see Results section below). Thus, we decided to apply the stricter criteria for the second objective as well, deviating from our pre-registration. We included only infants who provided at least four speed of processing trials respectively for novel objects and familiar objects, as well as four trials for visual reaction time (for details see the Analysis section). However, for these analyses we did not require a completed training or test phase of the infants. Due to the prerequisite number of trials we had to exclude 71 infants, meaning we were able to include 27 Dutch-learning infants (mean age in days = 522.4, *SD* = 7.65, range: 510 – 542; 9 girls).

The high number of excluded infants is most likely because the experiment was quite long for such a young age group. Of the 56 infants who were excluded from the replication of Lany (2018), about 26 were removed due to not completing the training phase of the novel word-learning task, since it required them to complete forty trials with unfamiliar objects. If they did not finish the training phase, we did not start the test phase, as we could not know if they already learned the words or still needed more trials.

Before starting data collection for the main study, we conducted a pilot with 14 participants to ensure that the overall experiment was not too tiring and participants could complete a sufficient number of trials in each part of the study. Of the 14 pilot participants, six completed sufficient trials of the testing phase in the novel word learning task, though it is important to note that we introduced changes after the first eight pilot sessions, such as additional attention getters to increase variation. After these changes, only one infant out of six fussed out during the training phase. Four infants completed enough trials of our word learning task and one finished the training phase, but only completed three test phase trials. None of the pilot participants were included in the final dataset for this paper.

Materials and Procedure

The experiment took place in a darkened room. The infants sat on their parent's lap approximately 50cm from the computer screen and eye tracker.

Before the study started, the infants watched a short cartoon, while the experimenter put a sticker on their forehead and adjusted the eye tracker. The parent was given headphones with masking music to wear during the experiment. The infants first completed the novel word-learning task (about 15 minutes; 40 training phase trials and 24 test phase trials) and then, after an optional break, the speed of processing task (about 15 minutes; 60 trials). Before the start of each task, the infant completed a child-friendly five-point calibration.

Novel Word-Learning task

This task was split in a training phase and a test phase. In the training phase, the infants were presented with pictures of four novel objects (taken from Lany, 2018), which were paired with disyllabic Dutch pseudowords: meber /’mɛbər/, drijsem /’drɛɪ̯səm/, vluktel /’vlʏktəl/, and roefok /’rufɔk/. To create these, we followed the procedure used by Lany (2018) as closely as possible and used a list of bisyllabic Dutch words that were uncommon and most likely not known by infants (from Çetinçelik et al., 2023). These words were then read into the pseudoword generator Wuggy (Keuleers & Brysbaert, 2010). The Wuggy algorithm calculates the frequency of the syllables of the input list, and uses it together with the bigram frequency of a lexical database of the chosen language to create pseudowords (for Dutch, it uses the CELEX database; Baayen et al., 1995). With that information, Wuggy created ten pseudowords per word on the input list that matched the morphological, phonological and orthographic rules of Dutch. From the output, we chose four words and checked with Dutch native speakers that these words were Dutch-like but not too similar to existing Dutch words. The output word vlaktel was changed to vluktel after consulting the native speakers, to avoid resemblance to the Dutch word “vlakte” (English: “the plain”).

Each trial in the training phase followed the same structure: First, there was an attention getter, an animated picture accompanied by sound, which only disappeared after the infant looked at it for 500ms (we used the attention getters from The ManyBabies Consortium, 2020; retrieved via https://osf.io/xbv95/). The infant then saw one of the four novel objects moving slowly up and down on one side of the screen for seven seconds, with the novel label for the object embedded in a sentence.

Throughout the training, we used five different sentence frames: "Look, it's a X!", "Wow, it's a X!", "Wow, look at the x!", "I see an X!", and "What a nice X!" (Dutch versions: "Kijk, een x!", "Wow, het is een X!", "Wow, kijk naar de X?", "Ik zie een X!", and "Wat een mooie X!"). These are Dutch translations of the sentence frames used in Lany (2018), except for the last one, which we exchanged as Lany's sentence frame is more complex in Dutch (Original in Lany, 2018: "I found the X!", Dutch: "Ik heb de X gevonden"). The sentences were recorded by a female native speaker of Dutch in a soundproof booth with Audacity® Version 2.3.3 (Audacity Team, 2019) and edited using Praat Version 6.1.12 (Boersma & Weenink, 2020). Each of these sentence frames was presented twice for each novel label, resulting in 40 training trials, 10 per word. The trial order, side of presentation and object-label match were randomised and counterbalanced over two lists.

Immediately after the training phase, the test phase began. Each trial started again with an attention getter that disappeared if the infant looked at it for 500ms. The infant then was presented with two of the novel objects they had been trained on. After three seconds of silence, they heard the sentence "Find the X!" (Dutch translation: "Zoek de X!"), asking them to look at one of the objects. After four more seconds, both objects disappeared and a new trial began. Each novel object was used as the target six times and paired with all other three objects as distractor, which resulted in 24 test trials. The trial order, side of presentation and object-label mappings were counterbalanced using two different lists.

Visual reaction time (VRT)

During the training phase of the novel word-learning task, we additionally measured infants' visual reaction time (VRT) following the procedure of Lany (2018). We calculated visual reaction time based on how long it took infants to move their eyes from the centre of the screen after the offset of the attention getter to the novel object emerging pseudorandomly on the left or right side of the screen without any auditory cue. This provided us with a baseline processing speed of how long it takes the infants in general to process visual information. We used VRT as an estimation of general (non-linguistic) processing speed, in line with the reasoning of Lany (2018).

Speed of Processing task

After the novel word-learning task, parents could opt to take a short break before the next experiment phase began. Infants were again calibrated using the five-point calibration before the Speed of Processing task. The task was modelled after the gaze-triggered looking-while-listening paradigm introduced in Chapter 2. Each trial began with the attention getter, which was shown until the infant fixated on it for 500ms. The infant was then presented with two pictures on either side of the screen. After two seconds of silent viewing, the infant heard an exclamation (one of the following: “Look!”, “What is this?”, “How nice!”, or “Do you see it?”; Dutch translation: “Kijk!”, “Wat is dat nou?”, “Wat leuk!”, or “Zie je het?”). The target was chosen depending on which item the infant had fixated for 100ms after the offset of the exclamation. The object that had not been looked at was then labelled as the target, forcing the infant to switch from the picture they were looking at to the target and, thus, making it possible to estimate their processing speed for this lexical item. After the onset of the target label, the trial continued for two more seconds.

The objects we used in the speed of processing task were four familiar inanimate objects (car, ball, shoe, bottle) and the four novel objects the infants had been trained on. The objects appeared in yoked pairs and were matched for familiarity (only familiar objects or novel objects were presented together). All the exclamations and labels were recorded by a female native speaker of Dutch, speaking in a child-directed manner.

There were 24 trials per familiarity level (known vs. newly learned), resulting in 48 trials in total. We ensured that each object was the target equally often, as has been done in Chapter 2. Twelve filler trials were randomly inserted during the task. Each filler trial showed two animate familiar items (dog, baby, kitten, or horse), each on one side of the screen, and the infants were asked to look at one of the objects, which was not dependent on the item they were looking at. The prompts for the filler trials were either "Where is the…?" or "Do you see the…?" (Dutch: "Waar is de…?" or "Zie je de…?").

Concurrent vocabulary size

Before coming to the lab, the parents were asked to fill in the Dutch adaptation of the MacArthur Communicative Development Inventories (N-CDI, "Woorden en zinnen"; Zink & Lejaegere, 2002, adapted from Fenson et al., 1993). This questionnaire was used to estimate infants' vocabulary size. Our participants (*n* = 59) had an average concurrent expressive vocabulary of 58 words (*SD* = 70.3; range: 0 – 352) and were reported to know all familiar words. Situating our results within the calculated percentiles of the N-CDI, our participants were roughly between the 80th and 85th percentile, meaning they were above average compared to the norming data. However, it is important to note, that the N-CDI was normed with Belgian children, which is why the percentiles might be different with Dutch infants in the Netherlands. To date, there is no norming N-CDI data available for children growing up in the Netherlands. Additionally, all of our participants were tested after (or in between) spending multiple months in government-ordered lockdown due to the COVID-19 pandemic. A multi-national and -lingual study that included Dutch infants has reported that infants' receptive and expressive vocabulary growth seemed to be steeper during lockdown (Kartushina et al., 2022). Thus, it could be that the above average expressive vocabulary we observed in our sample might be influenced by the lockdown measure.

Parental education

We asked parents to fill in a family questionnaire to find out more about the background and environment the infant was growing up in. For the study, we took the level of education of the mothers as a proxy of socio-economic status, following Lany (2018). On average, the mothers completed 17.51 (range: 12 – 18) years of formal education (*n* = 59). Our measurement was capped at 18 years, since we only asked for "Masters or higher" in our family questionnaire. We thus have a sample of mothers who completed elementary school in the Netherlands and at least one form of secondary education. The majority had completed a Master's degree.

Analyses

For our analyses, we used R (Version 3.5.0; R Core Team, 2018), RStudio (Version 1.3.959; RStudio Team, 2015), and the following R packages: dplyr Version 0.7.5 (Wickham et al., 2018), eyetrackingR Version 0.2.0 (Forbes et al., 2021), janitor Version 2.1.0 (Firke et al., 2021), lme4 Version 1.1-21 (Bates et al., 2015), openxlsx Version 4.1.0 (Walker, 2018), and tidyr Version 0.8.1 (Wickham & Henry, 2018). For visualisation, we used the packages ggplot2 Version 3.1.0 (Wickham, 2016) and GGally Version 2.1.2 (Schloerke et al., 2021). The Bayesian analyses were conducted using JASP Version 0.12.2 (JASP Team, 2020). Our preprocessing and analysis scripts can be found on our OSF website at https://osf.io/b2m8g/.

Preprocessing

All data collected by the eye tracker was first preprocessed as follows: we removed all looking data outside of a trial (i.e. looks off screen, filler trials and attention getters), and coded whether a look was (1) a fixation (defined as at least 100ms stable looking; cf. Casillas & Frank, 2017) and (2) on the target or, if applicable, the distractor (defined by a bounding box with the 200 medial pixels between target regions not being considered).

Our dependent variables were Accuracy (word recognition; defined as average proportion of looking time to the target 300 to 1800 ms after target word onset), Speed of Processing (SoP, for all but the filler trials of the speed of processing task: onset of first fixation to target within a time window of 300 to 1800 ms after target word onset following a fixation on the distractor before or at target word onset) and Visual Reaction Time (VRT, for all novel word learning trials with a single object on screen: the time needed to fixate the displayed object after looking to the centre of the screen within the first 100 ms of the trial). The independent variables were Trial Type (Training, Test & Speed of Processing) and Familiarity (novel or familiar target word). To measure concurrent vocabulary size, we use the reported number of words produced on the NCDI Words and Sentences form (Zink & Lejaegere, 2002).

Exclusions

Trial-level exclusions.

We only included trials in further analyses if infants looked at the screen (either as fixation or free scanning) for at least 100ms in the 2s after target label onset; this held for all trials that involved an object being labelled. This ensured that infants fixated the target object during the learning trials and that we could compute Accuracy and SoP in principle in the test trials. For measuring VRT, we only included trials where infants first looked at the attention getter at the centre of the screen for at least 500ms and then fixated the target within 1800ms of trial onset. This criterion is independent of the above-mentioned exclusion based on looks after target label onset, which means that we could compute VRT for trials that do not count towards the minimum number of learning trials per target word.

Participant-level exclusions.

Infants were excluded for the following trial-based reasons: For the first objective of this study, the replication, they were excluded if they did not have at least 5 (of 10) usable trials per target word in the training phase or if the training phase had to be interrupted due to fussiness or crying (*n* = 30), if we did not obtain at least four trials to calculate their accuracy score (*n* = 23), if we could not compute SoP for at least two familiar words (*n* = 3) and VRT for at least two trials. For the second objective, investigating the nature of SoP, we excluded infants who had not at least two computable VRT trials (*n* = 12) and who did not provide at least two SoP measures for familiar (*n* = 30) or novel words (*n* = 29). All of these exclusion criteria were applied stepwise, meaning we went through the inclusion criteria in the stated order.

Overall, for the first objective, our participants (*n* = 42) provided an average of 10.7 accuracy trials in the Novel-Word Learning task (range: 4 – 24). We opted for a higher minimum number of accuracy trials than Lany (2018) to make sure infants' accuracy scores were not skewed in one direction because they have only learned one or two of the novel items but were not tested on these during the first two trials. For the visual reaction time trials, our infants contributed 34 trials on average (range: 14 – 40). In the Speed of Processing task, the infants included in the analyses for the replication completed an average of 7.5 reaction time trials for familiar words (range: 2 – 16). For the second objective, our participants (*n* = 27) contributed an average of 9.44 trials for speed of processing of familiar words (range: 4 – 16) and 6.48 trials for speed of processing of novel words (range: 4 – 12). Regarding their visual reaction time, they provided 32.26 trials on average (range: 11 – 40).

Results

Goal 1 – Replicating Lany (2018)

The first goal of our study was to replicate the findings by Lany (2018) for 17-month-old Dutch learning infants. Lany (2018) showed that 17-month-old American English learning infants with fast processing speeds for familiar objects performed better in a novel word learning task (i.e. had higher accuracy scores as measured by average proportion of time looking at the target after labelling) than their slower processing peers. In Table 4.1, we present the descriptive statistics of the infants we included for the replication analysis (*n* = 42) with the data from Lany (2018) for comparison (*n* = 35). Overall, the two samples were comparable for all variables included in the analysis.

Using the analyses in Lany (2018) as a guideline, but in order to also be able to quantify evidence for the null hypothesis of no relation, we first conducted Bayesian Pearson correlations between all the factors included in the linear mixed effect model. The results of the correlations can be seen in Table 4.2. Contrary to our prediction, although the correlation between lexical speed of processing of familiar words and the novel word learning accuracy was negative, Bayesian analysis showed that evidence tended towards the null ($r(42) = -.18$, $BF_{10} = 0.35$, visualised in Figure 4.1). In other words, contrary to Lany (2018), there was not good evidence for a relationship in our data.

Table 4.1
Comparison of the Descriptive Statistics for Maternal Education, Expressive Vocabulary, Performance in the Novel Word Learning Task and Reaction Times (VRT, Familiar, Novel Words) Used in the Analyses for Replication of Lany (2018)

	Present Study (*n* = 42)				Lany (2018) (*n* = 35)			
	Mean	*SD*	Min	Max	Mean	*SD*	Min	Max
Maternal Education (years)	17.5	1.07	12	18[a]	16	2.29	12	21
No. Words Produced	60.57	75.48	0	352	69.6	62.2	4	295
Production - Percentile on CDI: W&S	80th - 85th	-	1st	>99th	50th	-	< 5th	90th-95th
VRT (ms)	245.7	68.15	145.74	436.23	276.67	35.02	222	366.5
No. Trials for VRT[b]	33.93	6.02	14	40	4.61	-	2	7
Word Learning Accuracy (Prop.)	.55	.16	.11	.91	.54	.14	.23	.88
No. Trials for Word Learning Accuracy	10.71	5.71	4	24	12	-	2	24
SoP Familiar (ms)	977.82	224.3	436	1457.5	839.8	194.3	490	1273
No. Trials for SoP Familiar [b]	7.47	3.94	2	16	10	-	3	21
SoP Novel (ms)[c]	895.4	240.73	421	1588.5				
No. trials for SoP Novel	5.13	2.85	2	12				

[a] In our questionnaire, the highest education option was “Masters or higher”, which would take a minimum of 18 years in the Netherlands. Our variable is capped at 18 years.

[b] Note that the number of trials regarding the various RTs was different in our study compared to Lany (2018). We had a maximum of 40 VRT trials, 24 SoP Familiar trials and 24 SoP Novel trials. Lany (2018) had 10 VRT trials and 40 SoP Familiar trials.

[c] Only calculated if the infants had at least two Novel SoP trials (*n* = 37 of 42)

Table 4.2

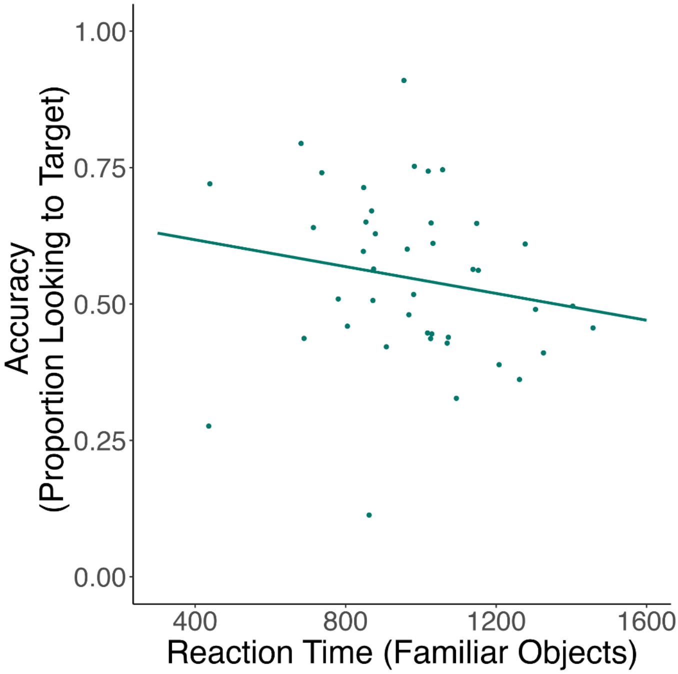
Correlations between maternal education, infants' expressive vocabulary, visual reaction time, novel word learning performance and familiar speed of processing in the present study and Lany (2018)

	Present Study (*n* = 42)				Lany (2018) (*n* = 35)			
	Maternal Education	Words Produced	VRT (ms)	Word Learning Accuracy	Maternal Education	Words Produced	VRT (ms)	Word Learning Accuracy
Words Produced	.22				-.12			
VRT (ms)	-.19	-.07			.27	.02		
Word Learning Accuracy	-.08	.07	-.01		.14	-.12	.02	
SoP Familiar (ms)	-.19	.18	.11	-.18	-.09	.03	.12	**-.45****

Note. ***p* < .01

Figure 4.1

*Scatterplot of Children's Mean Reaction Time to Familiar Objects and Accuracy in the Novel-Word Learning Task (*n *= 42)*



Note. Accuracy is measured by proportion of looking time to the target. The line indicates the linear regression.

It is also noteworthy, that there was no correlation between lexical speed of processing and expressive vocabulary size in both studies, a phenomenon which has been reported in other studies testing infants from 18-months upwards (see Fernald & Marchman, 2012; Fernald, Marchman & Weisleder, 2013; however, Peter et al., 2019, reported a correlation for 19-month-olds but not for 25- and 31-month-olds).

We then conducted a regression to determine whether lexical speed of processing of familiar words explained the accuracy of novel word recognition over and above expressive vocabulary size, maternal education, and visual reaction time, in line with Lany (2018). To this end, we created a control model

$$\textit{Accuracy} \sim \textit{Vocabulary} + \textit{VRT} + \textit{Maternal Education}$$

(R^2 = -.06, $F(3, 38) = 0.21$, $p = .89$), which we compared to a model including the mean reaction time of familiar word recognition (R^2 = -.04, $F(4, 37) = 0.65$, $p = .17$); see Table 4.3 for an overview of both models.

$$\textit{Accuracy} \sim \textit{Vocabulary} + \textit{VRT} + \textit{Maternal Education} + \textit{SoP Familiar}$$

Again, contrary to Lany (2018), we did not find significant evidence that including lexical speed of processing improved the fit of the model (ANOVA R^2 = .92, $F(1,37) = 1.96$, $p = .17$).

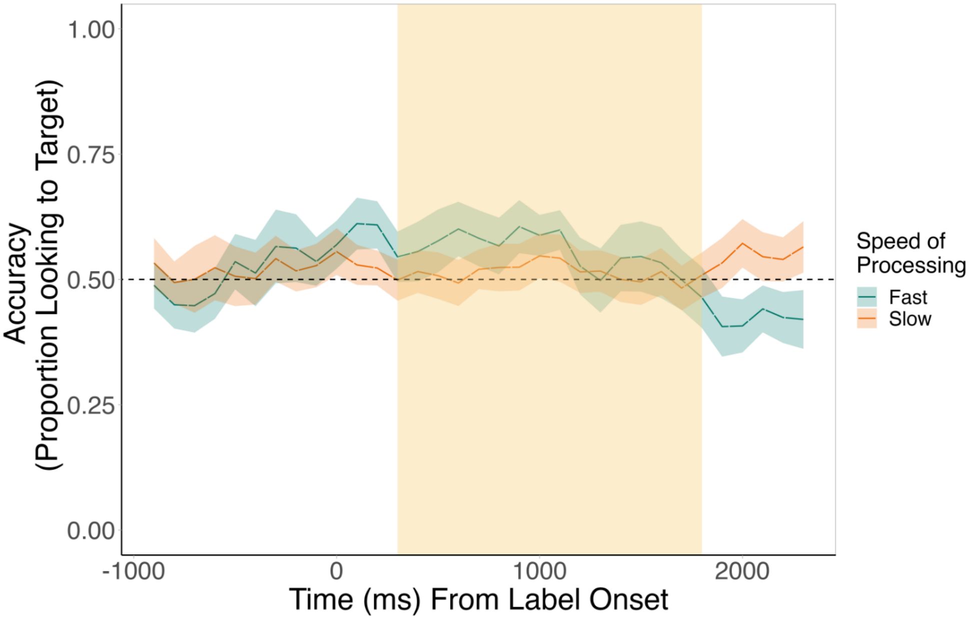
Table 4.3

*Regression Models Predicting Accuracy for Novel Words from Expressive Vocabulary, Visual Reaction Time, Maternal Education and Familiar Speed of Processing as Fixed Effects (*n *= 42)*

Control model	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	0.826	0.451	1.832	.075
Vocabulary	1.948×10^{-4}	3.392×10^{-4}	0.574	.57
VRT	-6.236×10^{-5}	3.738×10^{-4}	-0.167	.87
Maternal Education	-0.016	0.024	-0.645	.52
SoP model	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	1.1	0.486	2.262	.03
Vocabulary	3.069×10^{-4}	3.445×10^{-4}	0.891	.38
VRT	-1.863×10^{-5}	3.705×10^{-4}	-0.05	.96
Maternal Education	-0.023	0.025	-0.944	.35
SoP Familiar	-1.616×10^{-4}	1.155×10^{-4}	-1.4	.17

Figure 4.2

Time Plot Showing the Proportion of Looks to the Target in the Test Phase of the Novel Word-Learning Task Over Time



Note. The two lines show the looking behaviour of the infants split into two groups: fast and slow processors according to the infants' reaction times to familiar words in the Speed of Processing task. The yellow shaded area indicates the time window of our analysis (300-1800ms; *n* = 42).

We then replicated Lany's median split analysis by dividing our infants into groups of fast and slow processors according to a median split (at 981.61ms) and conducting Bayesian one-sample t-tests to compare the novel word learning performance of the infants to chance (.5; see Figure 4.2) For the fast processing infants, the test revealed weak evidence that their mean accuracy for the novel words was greater than chance ($M = .57$, $SE = .04$, $BF_{10} = 1.65$, $n = 21$). For their slower processing peers, the t-test provided weak evidence that their mean accuracy for the novel words was not greater than chance ($M = .52$, $SE = .03$, $BF_{10} = .5$, $n = 21$). In other words, there was some evidence that, as in Lany's analysis, the fast processors were more likely to learn the novel words than the slower processors.

In sum, although we did not replicate Lany (2018) in finding an overall association between familiar word processing speed and the accuracy of novel word learning, we did find some weak evidence that fast processors, but not slow processors, were above chance at novel word learning. However, inspired by the paper by Byers-Heinlein, et al. (2021), proposing different ways to improve reliability in infant research, we decided to explore our dataset further. Following solution four in that paper, collecting more data points per infant, we investigated whether the outcome of the analysis would change if we increased the number of reaction time trials necessary for an infant to be included in the analysis. This change can decrease the impact of measurement error, according to Byers-Heinlein et al. (2021), and thus improve the reliability of results and experimental power. We increased the number of trials required to be included from two, which is the common minimum number of trials across several speed of processing studies, to four.

The stricter criterion meant we excluded eight additional infants, leaving us with a sample with 34 participants (mean age in days = 521.44, *SD* = 8.6, range: 510 – 542; 16 girls). Table 4.4 and Figure 4.3 show that the correlations remain nearly unchanged in the stricter sample. Crucially, although the association between familiar word processing and novel word learning performance was stronger than in the original analysis (*r* = -.25 as compared to -.18 in the original analysis, see Table 4.2), once again, this association was not reliable ($r(27) = -.25$, $BF_{10} = 0.57$ visualised in Figure 4.3).

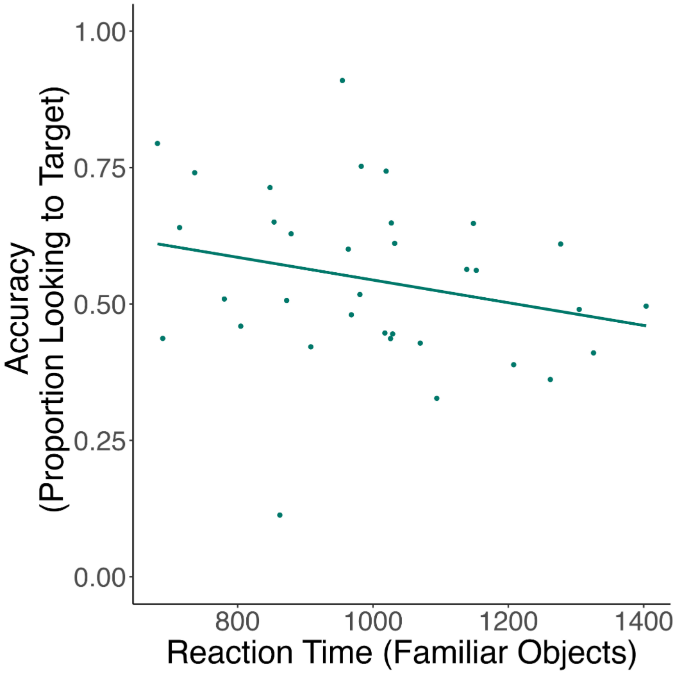
Table 4.4

Correlations Between Maternal Education, Infant's Expressive Vocabulary, Visual Reaction Time, Novel Word Learning Performance and Familiar Speed of Processing with the Stricter Sample (SoP Trial Range: 4 – 16, n *= 34)*

	Present Study (*n* = 34)			
	Maternal Education	Words Produced	VRT (ms)	Word Learning Accuracy
Words Produced	.24			
VRT (ms)	-.28	-.09		
Word Learning Accuracy	-.07	.04	.13	
SoP Familiar (ms)	-.27	.16	.18	-.25

Figure 4.3

*Scatterplot of Children's Mean Reaction Time to Familiar Objects and Accuracy in the Novel-Word Learning Task in the Stricter Sample (*n *= 34)*



Note. Accuracy is measured by proportion of looking time to the target. The line indicates the linear regression.

As with the original analysis, we explored the association further by conducting the same linear regression analysis described above for the stricter sample, to determine whether lexical speed of processing of familiar words explained the accuracy of novel word recognition over and above expressive vocabulary size, maternal education, and visual reaction time (see Table 4.5 for the summary of the models). This time, unlike in the original analysis, the model including lexical processing speed (R^2 = .002, F(4, 29) = 1.02, p = .42) explained more of the variance in the novel word accuracy score than the control model (R^2 = -.08, F(3, 30) = 0.22, p = .88). However, this was significant at .08 only, not at .05 (ANOVA R^2 = .71, F(1,29) = 3.38, p = .08).

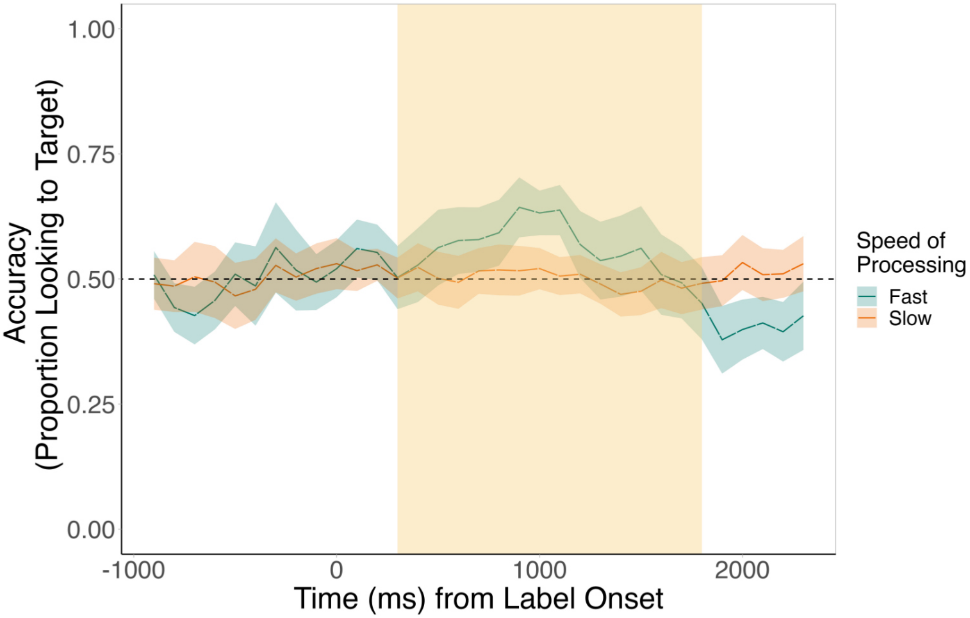
Table 4.5

Regression Models Predicting Accuracy for Novel Words from Expressive Vocabulary, Visual Reaction Time, Maternal Education and Familiar Speed of Processing as Fixed Effects (Stricter Sample, n *= 34)*

Control model	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	0.606	0.488	1.243	.223
Vocabulary	1.243×10^{-4}	3.679×10^{-4}	0.338	.738
VRT	2.63×10^{-4}	4.266×10^{-4}	0.617	.542
Maternal Education	-0.01	0.026	-0.294	.771
SoP model	Estimate	Std. Error	*t* value	Pr (>|t|)
(Intercept)	1.1	0.54	2. 03	.052
Vocabulary	2.863×10^{-4}	3.650×10^{-4}	0.784	.44
VRT	3.532×10^{-4}	4.136×10^{-4}	0.854	.4
Maternal Education	-0.021	0.026	-0.814	.422
SoP Familiar	-2.845×10^{-4}	1.55×10^{-4}	-1.835	.077

Figure 4.4

Time Plot Showing the Proportion of Looks to the Target in the Test Phase of the Novel Word-Learning Task Over Time (Stricter Sample, n *= 34)*



Note. The two lines show the looking behaviour of the infants split into two groups: fast and slow processors according to the infants' reaction times to familiar words in the Speed of Processing task. All of the infants had to have at least four trials for familiar words in the Speed of Processing task. The yellow shaded area indicates the time window of our analysis (300-1800ms; *n* = 42).

Finally in this section, we repeated the Bayesian one-sample t-tests between the fast and slow processors from the original analysis, using the median split of the speed of processing in the stricter sample at 1000.07ms to compare their novel word learning accuracy to chance level (.5). Figure 4.4 illustrates the looking time plot for this analysis, from which it seems like there is a clearer difference in the looking behaviour of the faster and slower processing infants. The faster infants seem to be more accurate in the novel word task during the target window. However, the *t*-test for the fast processors only presented weak, and essentially inconclusive, evidence that the mean word learning accuracy was greater than chance ($M = .58$, $SE = .05$, $BF_{10} = 1.8$, $n = 17$). For the slow processing infants, the test yielded moderate evidence that the novel word learning accuracy was not greater than chance ($M = .51$, $SE = .03$, $BF_{10} = 0.26$, $n = 17$).

Goal 2 – Exploring the nature of lexical speed of processing

The second goal of the present paper was to explore the underlying nature of speed of processing to determine whether it reflects a general cognitive capacity, lexicon-specific processing or item-specific knowledge. In the pre-registration of this study (https://osf.io/b2m8g/) we provided in-depth considerations and differential predictions of the expected patterns of results for each of the three possible scenarios as well as all their possible combinations. In brief, if individual differences in lexical processing speed stem from a *general cognitive capacity*, we predict a strong association between the processing speed of new and familiar words and non-linguistic processing speed; if individual differences stem from *lexicon-specific processing* (i.e. dependent on the size of the lexicon), we would not necessarily expect a relation between linguistic and non-linguistic processing speed, but we would predict a correlation between the processing speed of novel and familiar words; and, finally, if overall performance on the familiar word processing speed task reflects the average over a collection of familiar word-specific capacities (*item-specific hypothesis*), then we would predict novel word, familiar word and visual processing speeds to disassociate.

Deviating from our pre-registered analysis, we decided to only include infants who had at least four visual reaction time trials and four speed of processing trials for both familiar and novel words. Having more trials per individual infants, as suggested by Byers-Heinlein et al. (2021), already provided cleaner data for the analyses for the first goal of this study. This meant that we were only able to include 27 infants, see Table 4.6 for an overview of the descriptive statistics.

Table 4.6
Descriptive Statistics for Expressive Vocabulary, Visual Reaction Time, Speed of Processing of Familiar and Novel Objects for Infants Included in the Analyses for the Nature of Speed of Processing

	Present Study (*n* = 27)			
	Mean	*SD*	Min	Max
Words Produced	74.68	85.78	5	352
Production of Percentiles of CDI: W&S	85th	-	10th	>99th
VRT (ms)	250.5	83.04	153.4	464
Trials for VRT	32.26	8.74	11	40
SoP Familiar (ms)	975.91	176.53	681.5	1325.83
Trials for SoP Familiar	9.44	3.48	4	16
SoP Novel (ms)	901.67	190.38	481.75	1358
Trials for SoP Novel	6.48	2.52	4	12

We ran Bayesian Pearson correlations testing associations between expressive vocabulary, visual reaction time, and speed of processing of familiar and of novel words. We decided against conducting the pre-registered linear mixed effect model, as, due to the low sample size, we might not have enough power to properly assess the variance for the different factors. Moreover, our main goal was to gain insights into the nature of speed of processing by looking at speeds for novel and familiar words and visual reaction time, the relationship of which can be best investigated by correlational tests.

The results of the correlations are presented in Table 4.7 and illustrated in Figure 4.5. For each correlation, there was support for the null hypothesis, suggesting that there are no associations between expressive vocabulary, visual reaction time, and reaction time to familiar and novel words.

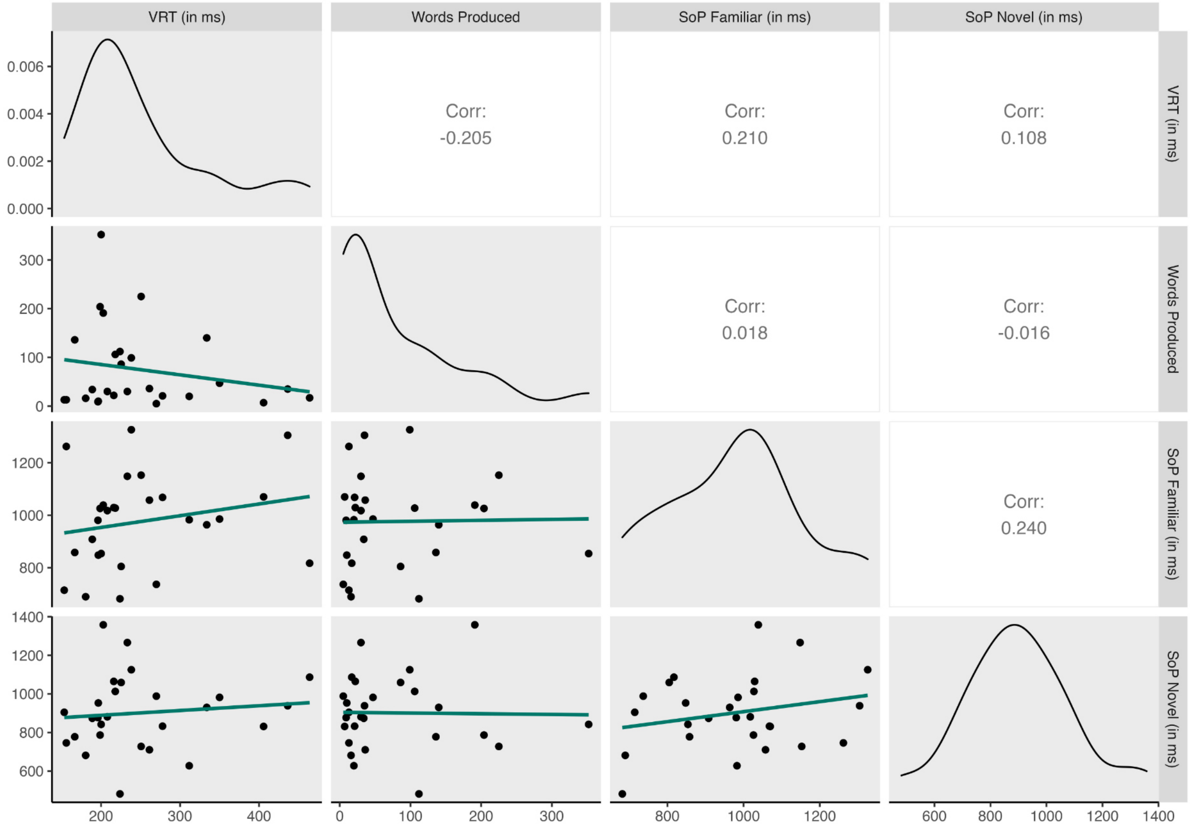
Table 4.7
Correlations Between Expressive Vocabulary, VRT and Speed of Processing of Familiar and Novel Words

	Present Study (*n* = 27)		
	Words Produced	VRT (ms)	SoP Familiar (ms)
VRT (ms)	-.21		
SoP Familiar (ms)	.02	.21	
SoP Novel (ms)	-.02	.11	.24

Since the results suggest that novel word, familiar word and visual processing speeds disassociate, they support the hypothesis that familiar word processing speed task reflect the average over a collection of familiar word-specific capacities (item-specific hypothesis); i.e. that speed of processing stems only from the activation level of the particular words being used in the test. Unfortunately, we do not have enough trials per item to assess these item-specific effects further. In addition, we urge caution in interpreting these null results since our final sample size (*n* = 27) is not big enough to reliably detect small effect sizes in these data.

Figure. 4.5

Correlation Matrix Showing Scatterplots Between Visual Reaction Time, Speed Of Processing Of Familiar And Novel Words And Expressive Vocabulary; As Well As The Density Plot Showing The Distribution Of Each Variable And The Correlation Effect Sizes (n = 27).



Discussion

The aim of the present study was two-fold: First, we aimed to replicate the study of Lany (2018), who found that fast lexical speed of processing of familiar words seemed to facilitate the learning of novel words, as long as the novel word-learning task was challenging for the infants. Secondly, we addressed the uncertainty of the underlying nature of speed of processing and attempted to determine whether it reflects a general cognitive capacity, lexicon-specific, item-specific processing, or a combination of two or three of these. To this end we conducted an eye-tracking study with 17-month-old infants, including a word recognition, a novel word learning, and a speed of processing task. Additionally, we assessed the infants' expressive vocabulary and the education level of their mothers through parental questionnaires.

Our first set of analyses tested whether there was a facilitation effect for fast processors on the novel word-learning task. We first followed the convention of the literature and included all infants who provided at least two trials for which speed of processing of familiar words could be measured. Using our pre-registered sample (*n* = 42) and replicating the analyses of Lany (2018), we could not detect an effect of processing speed, in that fast processing infants did not have a higher novel word accuracy score (measured by proportion of looks to target in our time window). Nor was there a correlation between speed of processing of familiar words and novel word learning performance. We also only found weak evidence that fast infants were more likely to perform above chance level in the test phase of the novel word-learning task.

However, inspired by Byers-Heinlein et al. (2021), we reran the analyses with a stricter criterion, including only participants who had at least four trials speed of processing trials to reduce noise in our data. With this stricter criterion (*n* = 34), we found slightly more reliable evidence for the facilitation effect reported by Lany (2018), in the sense that the correlation was stronger (albeit still non-significant; *r* = -.25 as compared to .18) and that lexical speed of processing explained additional variance over and above expressive vocabulary size, maternal education and visual reaction time in a regression (albeit significant only at *p* = .08). Using the stricter criteria, we also found weak, though still inconclusive, evidence that fast processors were able to learn the new words at levels above chance, while the slow processors did not.

This exploration of the data with two different exclusion criteria demonstrates that the noisiness of the data, which is not uncommon for developmental research with children, can make it difficult to detect meaningful and theoretically highly relevant effects. Thus, not only the participant sample size but also the number of trials, should be kept in mind when planning future studies (for more details and suggestions, see Byers-Heinlein et al., 2021). In the present study, we used a gaze-triggered looking-while-listening paradigm for the speed of processing task (see Chapter 2), which ensured more data points per child could be collected than has been the case in previous research. Interestingly, although the choice of exclusion criteria such as the minimum trial number can have substantial effects on the pattern of the data, the initial choice is often somewhat arbitrary, and is then copied in subsequent studies throughout the literature. Future work on the effect of different trial-level exclusion criteria is needed to investigate how many trials are needed to reliably discover effects of different sizes or whether there are other ways to reduce noise.

In the present study, and following Byers-Heinlein et al. (2021), we suggest that the analyses with the stricter criteria are likely to be more accurate, showing weak evidence for an association between familiar word processing speed and novel word learning. Our data also presented weak evidence that only fast processing infants seem to be able to learn the novel words. However, the question still remains, why do children with faster lexical processing speed for familiar words seem to learn novel label-object mappings better? In Lany (2018), multiple possibilities are discussed, such as the idea that faster processing might free up resources to encode novel words better (see also Fernald & Marchman, 2012) or might help to pick up semantic or grammatical context clues of new words. Nevertheless, for more concrete theory-building about the effect of speed of processing, we must first learn more about what we are actually measuring. Thus, the second goal of the paper was to attempt to shed some light onto the nature of speed of processing, whether it reflects a general cognitive capacity, lexicon-specific or item-specific processing.

To this end, our second set of analyses investigated the relationships between visual reaction time, lexical speed of processing of familiar and novel words and expressive vocabulary size. We reported that there were no reliable correlations between any of our processing measures. The lack of a correlation between lexical processing speed (for familiar and novel words) and visual reaction time provides no robust evidence for the view that lexical processing speed reflects an intrinsic broad *general cognitive capacity*, as measured by visual reaction time (i.e. that some children are slower to respond simply because they tend to move their eyes more slowly, are globally slow to respond to stimuli or are less attentive). The lack of a correlation between familiar and novel word lexical processing speed provides no robust evidence for the view that differences in familiar word processing speed can be attributed to differences in lexicon size (*lexicon-specific processing*) since a larger lexicon would be expected to reliably enable faster processing of both familiar and newly learned words. Instead, the data are most compatible with the idea that speed of familiar word processing is driven by *item-specific* knowledge, such that processing speed depends on the identity of the individual word and is thus free to vary independently of the speed of novel word processing and visual reaction time.

For interpreting the possible outcomes of these analyses, we prepared in-depth predictions of each outcome in the pre-registration of this study (https://osf.io/b2m8g/). While the above conclusion stems from not finding any relationship between the variables, the result should be treated with caution. Our sample size was quite small and thus only powered to find large effects. The effect sizes (Pearson *r* values) between speed of processing of familiar and novel words as well as between familiar speed of processing and visual reaction time were all above .2. Thus, with a bigger sample we might have been able to detect weak or moderate evidence in favour of an association, which might have supported the prediction that speed of processing reflects lexical knowledge or perhaps that all three mechanisms, general cognitive, lexicon-specific and item-specific, together build the foundation for speed of processing. For example, we only used visual processing in this study as a general processing constraint, but we might have obtained stronger evidence for a general cognitive capacity with a different measurement, such as an auditory non-linguistic processing task.

Taking the findings of our two objectives together, it might appear contradictory that we found weak evidence for a facilitating effect of fast processing speed on novel word learning, but no correlation between speed of processing of familiar and novel words. However, it is important to note that, even with stricter inclusion criteria, we only find small, non-significant relationships between novel word learning and speed of processing. Only at *p* =.08, do we appear to see some evidence that processing speed of familiar words adds variance to our regression model on word learning. All in all, we can only conclude that the relationship between speed of processing of familiar words and novel word learning appears to exist, but can only be found in certain experimental circumstances: depending on the items in the speed of processing task (how familiar they are to the infants, see Peter et al., 2019), the experience level of difficulty of the novel word-learning task (see Lany, 2018) and the individual processing speed of the infant (as our results show that only fast processors appear to learn the novel words). Outside of experimental work, this implies that speed of processing can be a factor in learning new words, but it is only one of many. Its effect might be more apparent when the word learning task is particularly difficult, or at certain ages or individual developmental stages.

Interestingly, neither the present study nor Lany (2018) reported a negative correlation between lexical speed of processing of familiar words and the expressive vocabulary size, which has been a comparatively consistent finding in the more recent literature on speed of processing, usually from the age of 18 months upwards (see Fernald & Marchman, 2012; Fernald, Marchman & Weisleder, 2013). However, there are also studies who did not find this relationship at certain ages (Fernald et al., 2006; no correlation for 15, 18 or 21-month-olds; Peter et al., 2019; no correlation for 25 or 31-month-olds). It is difficult to name an explicit reason for the variability of results across studies. It might be due to the noisiness of the measurement or data, which might have affected the result for Lany (2018), but which should be improved in the present study, at least using the stricter inclusion criteria. In addition, as we stated above, the N-CDI vocabulary scores of our participants were reported to be above the norming average and might be higher than expected since the participating families of this study spent a lot of time together at home due to the lockdown as a measurement against the COVID-19 pandemic (which might have affected lexical development; see Kartushina et al., 2022). Finally, our sample was relatively homogenous in terms of socioeconomic status, as measures by maternal education. These factors together may have obscured or minimised individual differences in vocabulary size.

There are, of course, limitations to our current work. Our study aimed to distinguish between different hypotheses about the underlying nature of speed of processing. Our data are not supporting the idea that general cognitive processing is an important factor for lexical speed of processing, but we had only visual reaction time as a non-linguistic measure. In order to get a clearer picture, there are different measures of cognitive abilities that could be used to investigate the nature of speed of processing. Future work, for example, could consider looking into the neural responses of on-line word recognition in infants, which might more closely reflect a domain-general processing ability, or use an auditory processing measure.

It should also be borne in mind that our sample size was much smaller than originally planned; we set a stopping criterion based on the number of infants tested and could with the logistical constraints of infant research not add to our sample. This was partly because the experiment was quite long and difficult for the young participants, and there were several infants who were unable to concentrate for long enough to reach the minimum inclusion criterion. Additionally, we noticed that the infants seemed to grow bored of the novel objects, as they would stop looking to the screen when the novel objects appeared, making it difficult to collect novel word speed of processing data. In addition, the COVID-19 pandemic had a substantial impact on the testing schedule. The extensive cleaning procedures that were required between testing sessions meant that we were able to test fewer children per week. Government regulations governing when children should stay at home (e.g. when they had a temperature, a cough or a snotty nose) meant that parents had to cancel many more visits than in pre-pandemic times. This has a substantial effect on the number of participants we were able to collect in the timeframe allocated to complete this thesis.

Moreover, the fact that testing took place during the COVID-19 pandemic may also have impacted the infants' behaviour and readiness for the study on different levels. So-called 'pandemic babies' are far less familiar than their pre-pandemic peers with the idea of going to other places "to play" and interact with strangers. In addition, all the adults present (usually one experimenter and one adult) had to wear face masks, which made the testing situation strange for the children (note that in the Netherlands, day care personnel did not wear masks at any point in the COVID-19 pandemic), though more so for the participants tested at the beginning, than the participants tested towards the end, of the study, since masks became more commonly used as the pandemic progressed. Furthermore, the common pre-pandemic practice of the babylab was for the researcher to do a "warm-up" with the children; meaning a short period of time spent playing before the study to help the infant getting used to the environment and the researcher (Bergmann et al., 2019). However, this practice was cancelled during the pandemic to limit the possible spread of infection due to increased interaction between the parent, the infant and the researcher. We do not know what effects these adjustments might have had on the infants' level of comfort in the lab and their resulting performance in the tasks.

Conclusion

The present study shows that under certain circumstances (strict inclusion criteria to reduce noise) we can find weak evidence to support the conclusion of Lany (2018) that 17-month-old infants who are fast to recognise familiar words, and thus are fast processors, might be better at learning novel words than their slower processing peers. It furthermore extends these findings by measuring the speed of processing of the novel newly-learned words in an attempt to shed some light onto the underlying nature of lexical speed of processing. The results of our study indicate that rather than general cognitive capacities or lexicon-specific processing it is more likely that speed of lexical processing may be dependent on word-specific features such as frequency and experience with individual words.

Chapter 5

Testing a chunking explanation of the relationship between speed of processing and vocabulary growth (Stage 1 Registered Report)

This chapter is based on Egger, J., Durrant, S., Gay, J., Visaya, A., Jessop, A., Pine, J.M., Bergmann, C., & Rowland, C.F. (n.d.). *Testing a chunking explanation of the relationship between speed of processing and vocabulary growth* [Stage 1 registered report in preparation]. Language Development Department, Max Planck Institute for Psycholinguistics, and University of Liverpool.

Abstract

Children’s vocabulary highly correlates with their ability to process familiar words, yet it is still unclear whether there is a directional relationship between vocabulary development and speed of processing. This study investigates the hypothesis that a larger vocabulary enables children to process familiar words faster, using the CLASSIC model (Jones et al., 2014; Jones & Rowland, 2017). CLASSIC is a computational chunk-based model of non-verbal working memory which mimics the vocabulary learning process in children by receiving naturalistic speech input and saving adjacent phonemes in chunks. As the model continues to process input, it learns to form bigger chunks by joining sub-lexical chunks that frequently occur together to learn word representations. The chunking theory suggests that the time it takes to process a chunk stays the same, regardless of the size of the chunk. We propose that children with larger vocabularies have words and common phrases saved as fewer, bigger chunks and can therefore process speech faster.

To test the hypothesis, we used output of the CLASSIC model and selected highly chunked and minimally chunked words for an eye-tracking study with 24-month-old British learning children. If our hypothesis is correct, our participants will process highly chunked words faster than minimally chunked words. These findings would suggest that the relationship between vocabulary size and processing speed can be explained by the number and type of chunks that children with different vocabulary sizes have stored in long-term memory, a measure directly related to the amount of experience the child has with the language.

Introduction

While it seems that most children acquire language almost effortlessly, the trajectories of their linguistic development can vary extensively and the causes of this developmental variation are still unclear. Various environmental factors can influence this development and cause wide variation in young infants' language abilities. However, the child's own abilities play a significant role in language acquisition as well, such as their ability to process incoming language input efficiently: their speed of processing (Fernald et al., 1998, 2008). Past research has shown that infants' speed of processing correlates with their expressive vocabulary size (cf. Fernald et al., 2006; Fernald & Marchman, 2012), in other words, children who are faster to recognise familiar objects upon naming have larger vocabularies as well. However, while this finding is robustly shown in multiple studies, the important question of *why* this relationship can be observed has not been answered yet.

One possible explanation of the relationship between speed of processing and concurrent vocabulary size might be that children who can process familiar words faster can also learn new words more easily. While not often explicitly stated, on this view, speed of processing is understood as an intrinsic processing ability. By recognising and processing familiar words faster, either more resources can be dedicated to acquisition of new words (Fernald & Marchman, 2012) or new words can be identified more quickly and therefore more easily added to the lexicon (Law & Edwards, 2015). This directional explanation of the correlation, where faster processing causes infants to be better word learners, is supported the results by Fernald and Marchman (2012), who showed that not only the concurrent vocabulary size, but also later vocabulary growth, could be predicted by speed of processing; they assessed processing efficiency at 18 months and showed links to infants' vocabulary at 18, 21, 24 and 30 months. Lany (2018) extended these findings and investigated the relationship between speed of processing and vocabulary in the lab, by assessing the novel word learning performance of 17- and 30-month-olds as a function of their speed of processing ability. Although the study reported a facilitation effect of faster speed of processing on novel word learning for the younger age group, the 30-month-olds show no difference in learning performance related to their processing efficiency. Only in a follow-up experiment, in which the difficulty of the learning task was increased, could the effect be found for the older age group. Lany (2018) proposed, post hoc, that fast processing may help when the learning task is challenging for the child, which is why only the younger age group showed facilitation in the first experiment. In Chapter 4 of this thesis we reported a replication of Lany's (2018) results for 17-month-old Dutch infants, although the effect was detected exclusively with stricter inclusion criteria. Interestingly, however, neither Lany (2018) nor the study in Chapter 4 reported a relationship between vocabulary size and speed of processing in 17-month-old infants. Additionally, Peter et al. (2019), who investigated speed of processing and vocabulary growth across different age points, also did not find a relationship between speed of processing measures at 25 or 31 months and vocabulary size at any age point in their longitudinal study (ranging from 8 to 37 months). These findings do not align with the proposed causal link where faster speed of processing facilitates learning of novel words across language development.

Another possible explanation for the close relation between speed of processing and vocabulary size might be that children with larger vocabularies are faster at recognising and processing familiar words, which is a reversal of the causal relationship poised above. On this view, processing efficiency would not be an intrinsic ability but rather an experienced-based skill, improved and strengthened by the growing lexicon of the individual child. This explanation fits with the findings of several studies investigating speed of processing in bilingual children (Hurtado et al., 2014; Marchman et al., 2010). They showed that processing speed in one language is only related to the vocabulary size of that particular language, not the learner's other language, which seems to support the idea that individual children's speed of processing is an emergent property of language learning. Furthermore, Peter et al. (2019) have argued for a familiarity/frequency explanation of their failure to find a relationship between speed of processing and vocabulary at 25 and 31 months. They suggest that the words they use in the looking-while-listening paradigm to measure processing speed were so familiar and frequent that even slow processors could recognise them quickly. This then obscured any meaningful between-participant variation in the older age groups. In support of this explanation, they showed that the relationship between processing speed and vocabulary re-emerged in an analysis focussing on a sub-set of the words that were harder to process because they were less frequent.

However, it is difficult to tease apart the two directional hypotheses, given both are to some extent supported by current data and all studies investigating the relationship are essentially correlational. One attempt to do this explicitly was the study by Donnelly and Kidd (2020), who were among the first to investigate these directional hypotheses more closely, using structural equation modelling to test the longitudinal and concurrent relationships of lexicon size and processing speed at 18, 21 and 24 months. Their results show the strongest support for the hypothesis that a larger lexicon leads to faster processing speed, although the authors were unable to rule out a bidirectional relationship in which vocabulary size both affects, and is affected by, individual differences in processing speed.

While there is evidence to support the hypothesis that lexicon size might directly influence speed of processing, the underlying mechanism that drives this relationship is not as clear. Donnelly and Kidd (2020) suggested that early vocabulary growth, specifically across the second year of life, might manifest in a strengthened inner network structures of the lexicon, which would in turn be reflected as increased speed of processing during looking-while-listening tasks. The impact of early vocabulary growth on lexical interconnections, according to Donnelly and Kidd (2020), is indicated by research that showed facilitatory effects of semantic neighbourhood density in young infants (Borovsky et al., 2016; Rämä et al., 2013) comparable to adults, which occurred earlier than inhibitory effects of phonological neighbourhood density. Those, in contrast, were found in 24-month-olds, but not in 18-month-olds (Mani & Plunkett, 2010, 2011), implying that the semantic network structure could come into play earlier during development. It might alternatively be the case that item-level entrenchment plays a role (Mainz et al., 2017), since children who receive a lot of language input can also build deeper lexical representations; if they are exposed to certain words more often, they can process them faster. While both of these accounts have merit and might be plausible, in this chapter, we will investigate a third option: chunk-based learning (see e.g. Gobet et al., 2001) as implemented in the CLASSIC (Chunking lexical and sublexical sequences in children) model (Jones, 2016; Jones et al., 2014; Jones & Rowland, 2017). Within CLASSIC, vocabulary size and lexical processing speed, and thus the relationship between them, are both determined by the number of lexical and sub-lexical chunks of linguistic information the model has acquired from environmental input.

CLASSIC models vocabulary learning as the accumulation of chunked phoneme sequences, with individual differences in the speed of learning determined by differences in amount and type of stored lexical and sublexical material in the lexicon, which is, in turn, determined by the quantity and lexical diversity of the input (Jones & Rowland, 2017). The CLASSIC model works with two important specifications in order to resemble a child's learning process: First, the model learns from incoming input by gradually chunking sequential information into so-called "chunks". Second, the model is only able to fully process a certain number of chunks, in other words only parts of the input. This is similar to young children whose processing abilities are also limited to some extent (Gathercole, 2006).

The model receives naturalistic child-directed utterances from the CHILDES database in the (MacWhinney, 2000) form of sequences of word-delimited phonetic symbols (e.g. /w ɒ t/ /k a t/ for '*what cat?*'). On the first presentation of *what cat*, the model accesses the phonemes that make up these two words, and chunks up adjacent phonemes into new, bigger, two-phoneme chunks (a sub-lexical chunk constituting two adjacent phonemes). On the second parse of the utterance, these two-phoneme chunks are 'chunked' into bigger four-phoneme chunks, and so on (i.e. learned, in this case, *what* and *cat*). With every new pass of the same or similar enough input, the model concatenates chunks until a whole word is represented by one chunk. This means that the more often the model is exposed to the same word, the sooner it will be able to connect the sub-lexical chunks into one chunk resembling the word (/kat/). In other words, as more input is processed by the model, it learns more and more chunks, both sub-lexical and lexical (word representations) chunks, as well as other super-lexical chunks (e.g. /w ɒ t k a t/ as one chunk).

Within the model, existing knowledge at the point of learning, in the form of stored sequences of phonemes (chunks), plays a key role in how the child's input is processed, and subsequently how new knowledge is acquired (Jones et al., 2021). Importantly, these predictions about learning can be extended to explain individual differences in speed of processing. The model predicts that those infants with the biggest vocabulary sizes will have the biggest store of (sublexical and lexical) chunks, which they can call upon to efficiently process and comprehend incoming utterances. If we assume that each chunk takes the same amount of time to be processed no matter its size (a basic assumption of chunking theory itself), models with more, and longer, chunks of stored sub-lexical/lexical knowledge will process the input more quickly. For example, an infant who can parse *where's the cat* with only three chunks of stored knowledge will parse the sentence more quickly than a child who needs six chunks of stored knowledge for the same task. In this way, the model predicts that infants with larger vocabulary will, by way of having longer chunks of stored lexical and sub-lexical knowledge, also process linguistic input more quickly. 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 because they use fewer chunks. In other words, a chunking model explains both why infants with larger vocabularies process familiar words faster and why they learn new words more quickly.

The advantage of the chunk-based explanation of the relationship between vocabulary size and processing speed is that it makes a clear concrete prediction that we can test empirically; that words and sentences that occur frequently in the input and thus infants can represent with only a few (long) chunks will be processed faster than words and sentences that the infant must represented with many (shorter) chunks. For example, *look at the doggie* will be processed faster than *look at the eagle,* if the former can be represented with fewer chunks, even after controlling for length and familiarity of the individual words. There is some indirect evidence for this in the literature from Fernald and Hurtado (2006), who have shown that infants are faster to recognise words embedded in familiar sentence structures than those embedded in less familiar contexts or isolated words (more chunks vs. fewer chunks). In the present paper we test this prediction explicitly.

In summary, the aim of this paper is to test the predictions of a chunk-based learning explanation of the relationship between vocabulary size and processing speed in 24-month-old infants. We used the output of the CLASSIC model, trained on naturalistic speech to children, to identify words and phrases that are likely to be familiar to children but that are, crucially, represented in the model either by a small number of (long) chunks (which we term *highly chunked words/phrases*) or by a large number of (small) chunks (*minimally chunked words/phrases*). We then test infants with these words in a speed of processing task. We predict that highly chunked words/phrases will be processed faster than minimally chunked words/ phrases.

Method

Participants

Stopping rule

We plan to test a minimum of 80 and a maximum of 180 British English-learning 24-month-olds, which includes an anticipated 20% dropout rate. After testing 80 participants, we will check whether we have enough power for the main analyses, for which we need at least 57 included participants with valid data according to our power simulations detailed below. Additionally, we will inspect the descriptive results for a relative importance analysis, which is an analysis that will allow us to isolate which variable is contributing most to the relationship between speed of processing and vocabulary. We will determine whether the effect size looks promising enough for us to continue testing, to power for an inferential relative importance analysis (*N* = 147). Due to restrictions in place to prevent the spread of COVID-19, we cannot present any pilot data.

Inclusion criteria

The infants can participate between 23.5 months and 25 months of age. All participants will be screened for the following inclusion criteria: born after 37 weeks of gestation, had a birth weight of at least 2500g, has no known visual or hearing impairments and their parents do not have dyslexia or a speech or language impairment. Parents will be asked to estimate the amount of non-British English language input the infant might be exposed to and we will exclude any infant that might hear another language for longer than a day per week (corresponding to 87% of input, see Byers-Heinlein, 2015).

Power considerations

For our analyses, we use R (Version 3.5.0; R Core Team, 2018), RStudio (Version 1.3.959; RStudio Team, 2015), and the R packages boot Version 1.3-24 (Canty & Ripley, 2021), doParallel Version 1.0.15 (Daniel et al., 2020), Hmisc Version 4.3-1 (Harrell & Dupont, 2020), knitr Version 1.28 (Xie, 2020), lme4 Version 1.1–21 (Bates et al., 2015), lmerTest Version 3.1-1 (Kuznetsova et al., 2019), relaimpo Version 2.2-3 (Groemping, 2006), stringr Version 1.4.0 (Wickham, 2019), tidyverse Version 1.3.0 (Wickham et al., 2019) and vroom Version 1.2.0 (Hester et al., 2020).

We plan to recruit an initial sample of 80 participants at the age of 24 months (± 6 weeks). This sample size was determined via a series of power analysis simulations based on available data from previous work (Peter et al., 2019). These simulations estimated that a sample size of 57 participants would provide at least an 80% likelihood (the recommended minimum power level; Cohen, 1992) of observing our hypothesised effect (of a difference between highly and minimally chunked phrases) at an alpha level .05. Specifically, the simulation estimated the required sample sizes to observe (1) a group-level effect of item type (highly chunked vs. minimally chunked) on reaction times (required $n = 50$), and (2) the relationship between the reaction times for highly chunked items and concurrent vocabulary size (required $n = 57$). In developmental research, it is typically necessary to recruit a sample size at least 25% larger than these estimates to accommodate for the high likelihood that a considerable proportion of the collected sample will not meet the inclusion criteria and therefore will not be entered in the confirmatory analyses. If necessary, additional families will be recruited until at least 60 children can be included in our analyses.

Materials and Procedure

Stimuli

We first trained CLASSIC on naturalistic input from child directed speech until it had reached the vocabulary 'age' of a 24-month-old child. We defined the 'age of a 24-month-old' as the point at which CLASSIC knew approximately 375 words on the Lincoln Toddler CDI (a parent report instrument of children's vocabulary knowledge, Meints et al., 2017). This is equivalent to the mean number of words known by the Language 0-5 project children at 24 months of age (Rowland et al., unpublished). We then used the Wordbank database (Frank et al., 2017) to identify words that are familiar to 60% to 100% of 24-month-old British English children. We ran these words through the '24-month-old' CLASSIC model and selected eight test items that were highly chunked (meaning they were represented by 1.5 or fewer chunks in the model), and eight items that were minimally chunked (meaning they were represented by 1.8 or more chunks in the model). These sixteen test items were matched into yoked pairs by familiarity level according to the Wordbank database (defined as the percentage of 24-month-olds who knew the word, accessed in March 2020), syllable length and chunkability (in other words, that the model represented the word in a similar number of chunks). When matching the items in the pairs, we also paired animate items with another animate object, as well as making sure that paired items did not share an onset consonant and were phonetically dissimilar.

For each item, we selected four different pictures, so that each picture would appear twice, once as target and once as distractor in the speed of processing task. The images were rated in a prototypicality judgment task beforehand, to ensure they portrayed a familiar, characteristic image of the chosen items. Additionally, for our 12 filler trials we chose 24 filler items that were well known by 24-month-olds. In Table 5.1 we present an overview of all our items in their yoked pairs.

Table 5.1

An Overview of Test and Filler Items, Including Syllable Length, Familiarity Level (Percentage of 24-Month-Olds Who Know the Word According to Wordbank Data) and Number of Chunks CLASSIC Needed to Represent the Word

Pairs_High	Image_1	Syllables	Familiarity level	No. chunks	Image_2	Syllables	Familiarity level	No. chunks
1	Butterfly	3	0.64	2.53	Turtle	2	0.66	2.4
2	Frog	1	0.71	1.8	Bug	1	0.73	1.94
3	Crayon	2	0.65	2.11	Ice-Cream	2	0.72	1.99
4	Fork	1	0.71	1.84	Towel	2	0.63	1.84
			0.69	2.07			0.69	2.04

Pairs_Low	Image_1	Syllables	Familiarity level	No. chunks	Image_2	Syllables	Familiarity level	No. chunks
1	Elephant	3	0.67	1.28	Monkey	2	0.75	1.36
2	Bee	1	0.72	1.01	Lion	2	0.64	1.24
3	Doll	1	0.63	1.32	Bottle	2	0.73	1.36
4	Sock	1	0.72	1.48	Paper	2	0.67	1.24
			0.69	1.27			0.69	1.3

Fillers	Image_1	Syllables	Familiarity level	No. chunks	Image_2	Syllables	Familiarity level	No. chunks
1	ball	1	0.96	1.16	shoe	1	0.94	1.34
2	dog	1	0.93	1.12	bird	1	0.88	1.33
3	cat	1	0.85	1.06	duck	1	0.87	1.16
4	apple	2	0.87	1.13	book	1	0.91	1.04
5	hat	1	0.86	1.07	bed	1	0.81	1.05
6	tree	1	0.8	1.16	balloon	1	0.87	1.46
7	cow	1	0.79	1.07	bear	1	0.79	1.05
8	banana	3	0.87	1.61	spoon	1	0.78	1.38
9	cake	1	0.76	1.08	bus	1	0.76	1.13
10	boat	1	0.76	1.17	flower	2	0.76	1.56
11	train	1	0.79	1.04	juice	1	0.87	1.15
12	biscuit	2	0[a]	0[a]	house	1	0[a]	0[a]
			0.77	1.06			0.77	1.14

[a] The words “biscuit” and “house” did not appear in the Lincoln CDI and Wordbank datasets and were therefore not included in the model. However, they were identified by using Wordbank data as words which are known by over 60% of two-year-olds and so were included as filler items.

For the auditory stimuli, we asked a female British native speaker to record several audio fragments using child-directed speech. We asked her to record “Look” in eight different variations, each target item as one token, and four different exclamations (“Do you like it?, Can you find it?, Can you see it?, How cool is that?”). For the filler trials, we recorded six exclamations with different intonations (“Watch!, What is this?, How nice!, Do you see it?, Wow!, How nice!”) as well as each filler word once. Additionally, she recorded the exclamation “Look at the pictures!”, which were used for test trials where infants repeatedly did not look at the screen. All recordings were normalised for pitch and volume.

Equipment

We will use eye-tracking (Eyelink 1000 Plus; SR Research: Ottawa, Ontario, Canada), which allows for the tracking and coding of eye-movements online. The experiment will take place inside a U-shaped booth in the Liverpool Language lab, created by two sound attenuated boards and a dark curtain. Use of these boards to the left and right of the child minimises distractions, external noise, and light - all of which serve to direct the child’s attention to the screen. The curtain is located behind the monitor, and minimises distractions by ensuring that any wires associated with the equipment are not visible.

Participants sit in a car seat (or chair) in front of a 17” LCD monitor mounted on a hydraulic arm. Located just below the monitor and attached to the arm mount is the EyeLink camera. Behind the monitor and the curtain, are two speakers (one located to the left of the monitor and one to the right) through which all sound is played.

Procedure

At the beginning of the experiment, the researcher instructs the caregiver to place their child in a car seat or directly on their lap, in case the child might refuse to sit in the car seat. After ensuring that the child is seated comfortably, the experimenter places a small high-contrast target sticker on the child’s forehead. This sticker allows the eye-tracker to be used in “Remote head free-to-move mode” - a setting ideal for use with infants because it does not require the use of a head or chin rest, and quickly resolves eye location even when there is movement of the head. The experimenter then leaves the booth and seats themselves on the other side of screen to the right of the child where the host eye-tracker laptop (which processes the looking data), a desktop computer (which runs the experiment) and a laptop (which is connected to the webcam) are located. From this position, the experimenter is able to view the child's face, adjust the eye-tracker's settings, and control the settings related to calibrating, launching and running the experiment. Before the experiment starts, a short child-friendly cartoon is played, with the intention to draw the child's eyes towards the screen in order to adjust the settings for the participant. During this time, the experimenter assesses the child's distance in relation to the camera using the information given by the host eye-tracker laptop. If the position is unsatisfactory, adjustments are made to the camera using the flexible arm mount so that the distance from the camera lens to the child's eye is between 580mm and 650mm. The experimenter also ensures that the eye is in focus, and that the corneal and pupil resolution meet the necessary criteria for accurate detection of pupil location.

Once the researcher is satisfied with the set-up, the child completes a five-point calibration. Once the calibration is successful, the experimenter starts the experiment. In the beginning of each trial, a central smiley face (location: 352, 224) is used as an attention getter to draw the child's attention to the middle of the screen. Once the child looks to the face for at least 800ms, it disappears, ensuring that trials will only start when the child is attending to the screen.

The eye-tracking experiment uses an adaptation of the gaze-triggered paradigm, which maximises the number of valid speed of processing trials (see Chapter 2). In each test trial, two images are presented to the participant, one of them has been predetermined as the target, one as the distractor (location left image: 0, 262; location right image: 704, 262). The dimensions of both images are 320mm x 240mm. The child views the picture in 2000ms of silence, after which the infant hears "*Look*!" Then, as soon as the child looks at the predetermined distractor image for 100ms, the target noun is labelled, followed by an exclamation. In the test trials, one of the displayed items, the predetermined target, is named after 100ms silence. The trial continues for an additional two seconds after the onset of the target label. The two images are shown for the entirety of the trial, which for all trials (including filler trials) is 7000ms. The images then disappear and the central attention getter (smiley face) is displayed. Once the child has fixated on the face for 800ms the following trial begins. The experiment consists of a total of 64 test trials, meaning that each pair of test item images is presented eight times over the course of the experiment. Each item is presented as both the target and the distractor four times. Additionally, there are 24 filler trials inserted randomly between the test trials. The filler trials are the same as the test trials, with the distinction that the target label is played when the child has looked to the target image for 100ms, to verify that the child does not learn to always switch their gaze when hearing the audio recordings.

If, during a test trial, the child does not look at the predetermined target during the 1000ms time window after the onset of "*Look!*", the target noun is not named, but a filler sentence is used instead (e.g. *look at the pictures*). This trial is the repeated (once only) at the end of the experiment, in order to maximise the number of valid trials.

During the experiment, the experimenter uses the webcam to monitor the child, intervening if necessary to adjust the child's position or to direct attention towards the central attention getter. The experimenter also notes, on a trial-by-trial basis, any audible noises (e.g. crying, talking) that occur at the onset of the target word. Because of the large number of trials in this task, we anticipate that children may become bored as the task progresses. For this reason, keyboard button presses are programmed into the experiment that allow the experimenter to play an attention getting sound or brief looming animation to recover the child's attention. It is programmed so that this function is only possible in between trials, when the central smiley face attention getter is on the screen. The caregivers are asked especially not to name the items shown during the task and to not interact with the child during the experiment, unless to comfort them. If the child appeared to be fussy, the caregiver could give them a pacifier or a snack during the experiment. After the eye-tracking task is completed, the experimenter asks the caregivers fill out a checklist, indicating which of the target words used in the task the child could understand.

Parental questionnaire

Before the study in the lab, we ask the parents to fill in the online UK-CDI Words and Sentences, in order to get an estimation of the expressive and receptive vocabulary score of their children. This is a newly developed parent report checklist that contains a vocabulary scale of the most common vocabulary items in UK children's vocabulary between 18 and 30 months of age and sections that measure different aspects of morphosyntactic knowledge. Information about CDI construction, validity and reliability can be found in Fenson et al. (2007). We will report only on the results of the vocabulary scale in this study. If the parents give their permission, the obtained data from the questionnaire will also be made available for the norming study of the UK-CDI.

Planned analysis

While testing is ongoing we will create a code pipeline using dummy data from adults. This will contain mixed effects models and regression analyses, carried out in R (R Development Core Team, 2008). If maximal models do not converge, we will remove random slopes by removing the highest order term that explains the lowest variance, in turn, until the model converges. Table 5.2. provides an overview over the research questions in this chapter, including our hypotheses, the planned analyses and a short summary of the interpretation of the possible outcomes.

In sum, the goal of the planned study is to test the predictions of a chunk-based learning explanation of the relationship between vocabulary size and processing speed in 24-month-old infants. We predict that highly chunked words/phrases will be processed faster than minimally chunked words/phrases. This result will support the idea that the relationship between lexical processing speed and vocabulary can be explained as emerging from differences in the amount and type of knowledge (lexical and sub-lexical knowledge) stored in the mental lexicon.

Table 5.2

Study Design and Research Questions

Question	Stated hypothesis	Alternative hypothesis	Analysis plan	Interpretation of the outcomes
1. Do children process highly chunked words faster than minimally chunked words? (Chunks are defined by the CLASSIC output that approximates that of a two-year-old, see Materials and Procedure)	On a group-level, the participants show a faster reaction time for words that are highly chunked (fewer chunks according to the CLASSIC output) compared to words that are minimally chunked.	There is no significant effect of item type on the reaction times of highly or minimally chunked words.	Mixed effect model of reaction times, item type (highly chunked vs. minimally chunked), Random effects: item and participant	If item type shows a significant effect on reaction time, we will claim support for our stated hypothesis.

Question	Stated hypothesis	Alternative hypothesis	Analysis plan	Interpretation of the outcomes
2. Do children with a larger vocabulary process familiar words faster?	There will be a negative correlation between vocabulary size and reaction times for all words, meaning that children with larger vocabularies are faster at processing familiar words	There is no correlation between vocabulary size and reaction times for all words.	Linear regression model with expressive vocabulary size and reaction times	If the regression yields a negative correlation between vocabulary size and reaction times, we will claim support for our stated hypothesis. If there is no correlation, there is no evidence for our hypothesis. A positive correlation (larger vocabularies related to slower processing) will be considered equivalent to the null hypothesis
3. Exploratory question: Does the individual vocabulary size of the child only influence the processing speed of minimally chunked words?	Interaction. Faster reaction times for minimally chunked words when children have bigger vocabularies, effect for highly chunked words smaller/non-existent		Mixed effect model reaction time, item type (highly vs. minimally chunked) & vocabulary. Random effects: item and participant	

Chapter 6

General Discussion

There is wide variation among children regarding their lexical development, for example how quickly they expand their vocabulary knowledge. Past research has identified environmental influences that might cause these individual differences in lexical development, such as different aspects of parental speech input. Recent studies have also shed light onto the importance of the child's own vocabulary knowledge and individual abilities. One of these abilities, the time it takes an infant to process language input, for example in a word recognition task, is called speed of processing. The present dissertation investigated the role of speed of processing in early lexical development and its possible interplay with parental language input and role in novel word learning, with the aim of further explaining the observed individual differences and offer a path towards causal accounts.

Overall, there were three main objectives within this thesis: Our first objective was to improve the robustness and reliability of the speed of processing measurement, since one of the recurring problems in studies investigating processing speed in infants was the low number of trials per participant, causing noise and making it difficult to draw robust conclusions in general. For several studies in particular, this low number of usable trials has made it difficult or impossible to conduct certain analyses (Thorpe & Fernald, 2006; Zangl & Fernald, 2007) or may have concealed meaningful effects in the data (Fernald et al., 2006; see discussion in Fernald & Marchman, 2012).

Our second objective was to investigate the interaction between parental language input, infants' vocabulary and processing speed; going beyond the quantity of input and considering qualitative aspects as well. While Hurtado et al. (2008) have reported that quantity and quality of speech input correlated with vocabulary size and speed of processing at a later age, they only tested the effect of the amount of speech input, leaving the role of input quality uncertain.

Our third objective was to examine the relationship between speed of processing and vocabulary in more detail. While many studies report a relationship (e.g. Fernald et al. 2006; see Chapter 1 for a summary), the cause of the relationship is still unknown. Specifically, there are multiple hypotheses about the directionality of the relationship, such as that faster processing speed leads to larger vocabularies or that having a bigger lexicon enables faster familiar word recognition. However, while some speculate, only few studies test the hypotheses on the driving aspect of the relationship.

In this chapter, I summarise the findings of the preceding chapters and discuss their implications for our understanding of early lexical development and infants' speed of processing. Moreover, I outline open and newly emerging questions and propose future research directions that can further deepen our understanding and knowledge of these crucial early stages in language acquisition.

Summary of findings

In **Chapter 1**, I described the motivation for this thesis and discuss, how speed of processing was discovered and gained importance in language acquisition research. Against this background, the following empirical chapters investigate the three objectives described above.

In **Chapter 2**, I focused on the first objective of the thesis, namely the robustness of measuring speed of processing in infants. Speed of processing is measured in looking-while-listening paradigms in which children are usually presented with two pictures of familiar objects (Fernald et al., 2008). After a short silent period during which the infants can look at both pictures, one of the objects is then named. The time it takes the infant to shift their gaze from the distractor picture to the target is then assessed and defined as the infant's processing speed. An important limitation of this measure is that only trials in which the infant is looking at the distractor object when the target is named can be included in the analysis. Trials in which the infant is already looking at the target by chance or not looking at the screen at all have to be discarded, since it is impossible to determine how long it takes the infants to process the target label. This meant that many studies have included only a few trials, both at the individual and the group level (see Table 2.1 in Chapter 2), making it difficult to detect meaningful effects or even conduct certain analyses (see Fernald & Marchman, 2012; Zangl & Fernald, 2007).

In Chapter 2 we introduced an adapted version of the looking-while-listening that was designed to increase the number of trials we would be able to obtain. The new paradigm (*Gaze-triggered paradigm*) automatically identifies the object the infant is looking at and then plays the label of the other object, requiring the infant to disengage from the picture they had fixated and to look to the other object. Our primary goal was to increase the number of trials available for measuring processing speed. We conducted an eye-tracking study with Dutch learning 18-month-old infants and tested them using both paradigms in a within-subject design, comparing the speed of processing measures obtained. As predicted, the new Gaze-triggered paradigm indeed yielded substantially more speed of processing trials compared to the original paradigm. However, the individual performances of the infants were comparable across paradigms, confirming that the manipulated paradigm measured the same concept of processing speed as the original one (i.e. yielded a valid processing speed measure). As the second goal of the study, we aimed to replicate the relationship between expressive vocabulary size and speed of processing reported in previous literature. As predicted, we observed a negative correlation between processing speed and concurrent expressive vocabulary size, comparable in size to effects reported in past research (see Fernald et al., 2013).

In the study presented in **Chapter 3** we addressed the second objective of the thesis, and investigated if and how different aspects of parental speech input could account for emerging individual differences in infants' vocabulary size and processing speed. The data for this chapter was collected with the same participants in the same lab visit as the data presented in Chapter 2. After the eye-tracking session, we conducted a free play session at the lab in which we asked parents to play with their 18-month-old as if they were at home. These play sessions were recorded and later transcribed and analysed for quantity and quality of parental speech input; in particular, for number of word tokens, lexical diversity and mean length of utterance (MLU). Additionally, the parents were asked to fill in the N-CDI *Words and Sentences* (a standardised vocabulary checklist; Zink & Lejaegere, 2002) before the lab visit, and then invited to complete further N-CDIs when their children were 24 and 30 months old. We tested three hypotheses: First, we hypothesised that the amount of parental speech input (input quantity) would correlate with both vocabulary size and processing speed. We argued that repeated exposure would both help integrate new words in the infants' lexicon and strengthen existing lexical representations, leading to faster processing of these words. Second, we predicted that lexical diversity would correlate with vocabulary, as the more different type of words an infant is exposed to, the more words they can learn. However, we did not expect a direct effect on speed of processing. That said, we suggested that there might be an effect of lexical diversity on speed of processing that was moderated by the infants' vocabulary size, given that a larger vocabulary seems to lead to faster processing. Third, for parental MLU, which can be seen as an index of morphosyntactic complexity, we hypothesised that there would be an interaction between parental MLU and speed of processing. We suggested that, on one hand, that faster processors would be better able to process longer, more complex sentences in their input, and thus would be able to use this input to expand their vocabulary. On the other hand, for slower processors, we expected that long sentences in the input might be too difficult to process, hindering their ability to take in all of the linguistic information and thus slowing their vocabulary growth. In order to test these hypotheses with a larger sample we also analysed a comparable, pre-existing dataset of British English learning infants.

For neither the Dutch nor the British English data were there significant correlations between any of the parental speech input aspects and infants' processing speed. For the Dutch infants, we observed correlations between their vocabulary size at 18 months and parental lexical diversity and MLU, but not for the amount of speech input measure. This suggested that our participants benefitted from more lexically diverse and morphosyntactically complex input, but not from increased amounts of input. Regarding our hypotheses on the interplay between different measures of input and infants' processing speed and vocabulary, we found no significant evidence for our predictions. There were no significant correlations between number of word tokens and any infant measurements. There was also no indirect effect of lexical diversity on speed of processing via vocabulary size and no interaction between speed of processing and MLU influencing the vocabulary growth. However, visual inspections of the interplay between MLU, speed of processing and vocabulary growth between 18 and 24 months revealed that the effects were in the predicted direction in both the Dutch and the British English data. It would thus be useful to investigate these trends in future studies with more statistical power.

Chapter 4 and Chapter 5 were focused on addressing our third objective of further investigating the relationship between speed of processing and vocabulary size. In Chapter 4 we tested the hypothesis that faster processing children will be better at learning new words and therefore have a larger vocabulary, while in Chapter 5 we present a stage 1 registered report to test whether children with larger vocabularies can process familiar words faster, rather than vice versa. The Covid-19 pandemic prevented us from collecting data for the study in Chapter 5.

Chapter 4 followed and extended the work of Lany (2018), who tested the processing speed and novel word learning performance of 17- and 30-month-olds. Her results indicated that, as predicted, children who were faster processors of familiar words performed better in the novel word-learning task. However, unexpectedly this was only the case if the task was, to some degree, challenging for the children. We aimed to replicate this study with Dutch-learning 17-month-old infants in an eye-tracking experiment, using the new Gaze-triggered looking-while-listening-paradigm (introduced in Chapter 2) to measure processing speed. The infants first participated in a novel word-learning task in which they were shown four novel objects and heard the Dutch-like pseudoword labels in training trials and then were tested on these novel words. Following Lany (2018), we also measured the non-linguistic visual reaction time of the infants during the training trials. Infants' accuracy in the word learning task was assessed by measuring the proportion of looking time to the target versus another novel object after hearing its label, thereby showing that they correctly linked label and object. Afterwards we measured their speed of processing of familiar words, and in an extension of Lany (2018), also tested their processing speed for the novel words.

Our results were in the same direction as those of Lany (2018) but not as clear cut. Even when we set stricter inclusion criteria to reduce noise in the data (as suggested by Byers-Heinlein et al., 2021), the evidence to support a correlation between novel word accuracy and speed of processing of familiar words was still weak, though the effect size was stronger than with more lenient inclusion criteria. The results with the stricter criteria showed that familiar processing speed could explain additional variance of the performance in the novel word-learning task, though this was not significant at $p < .05$ (but at $p = .08$, two-sided). Additionally, there was weak evidence that only those infants who were fast at processing familiar words performed above chance-level in the novel word-learning task, meaning that only fast processors were able to learn the labels for the new objects. In a secondary aim and to shed more light on the nature and origin of speed of processing, we assessed the relationship between processing speed for familiar and novel words and visual reaction time. The results of this investigation yield no reliable correlations between processing speeds of familiar or novel words or visual reaction time. We argued that our results are most compatible with the conclusion that speed of processing is driven by item-specific knowledge (i.e. that processing speed depends very much on how well children know individual words). However, it is important to point out that the interpretation of the data stems from finding no significant correlations and that the effect sizes for each relation were, in fact, above .2. Given that the small sample size in our study was not sufficiently powered to detect small effects, a more well powered study might lead to a different result and view on the nature speed of processing.

In **Chapter 5** we presented a Stage 1 Registered Report designed to investigate whether having a larger vocabulary leads to faster processing of familiar words, rather than vice versa. This expectation builds on the results of Chapter 4 and additionally was inspired by previous bilingual studies on processing speed, where no cross-linguistics effects have been observed. These studies suggest that the processing speed of familiar words in one language is tied to their vocabulary size in that language (Hurtado et al., 2014; Marchman et al., 2010). It was also inspired by the suggestion by

Peter et al. (2019) that the relationship between vocabulary size and processing speed depends very much on the words used in the processing task. They observed significant correlations between processing speed and vocabulary at 19, but not at 25 and 30 months, and proposed that the words used in the speed of processing task might have been well known at the later ages, so that even slower processers could recognise them quickly. This would have obscured meaningful individual differences between the participants.

We proposed that chunk-based learning (see e.g. Gobet et al., 2001) as implemented in the CLASSIC model (Chunking lexical and sublexical sequences in children; Jones, 2016; Jones et al., 2014; Jones & Rowland, 2017) makes it possible to examine the direction of the relationship between processing speed and vocabulary. CLASSIC is a computational chunk-based model of non-verbal working memory which mimics the vocabulary learning process in children. The model receives naturalistic child-directed speech input and saves the adjacent phonemes of the words in chunks. As more input is processed by the model, it learns more and more chunks as word representations, as well as other super-lexical chunks (e.g. a common phrase as one chunk). We suggested that, assuming it takes the same amount of time to process one chunk, no matter its size (an assumption of chunking theory itself), children who have words and phrases stored as bigger chunks will be faster processors. In other words, if children have stored phrases like “look at the” as one super-lexical chunk, they will process it faster than children who have the words saved as separate chunks in their lexical knowledge. Importantly, chunks build up as a result of linguistic experience, thus children with bigger vocabularies are predicted to have more, and bigger, chunks stored in long-term memory, and thus will be able to process the input faster.

To test this hypothesis, we designed an eye-tracking study with 24-month-old British English learning children, using an adapted version of the gaze-triggered paradigm presented in Chapter 2. For the stimuli in the study, we first checked with the data available on Wordbank (Frank et al., 2017) to determine which words are produced by at least 60% of 24-month-olds, and thus are likely to be familiar to our participants. Then we used the CLASSIC model, trained with speech input from the CHILDES database (MacWhinney, 2000) of parental speech to children to a vocabulary size representative of a 24-month-old child, to determine the number of chunks that CLASSIC used to represent these familiar words. We then selected eight highly chunked (i.e. represented by the model by fewer chunks) and eight minimally chunked (i.e. represented by the model as many chunks) words for the eye-tracking study. If our hypothesis is correct, highly chunked words will be processed faster than the minimally chunked words, suggesting that the relationship between vocabulary size and processing speed can be explained in terms of the number and type of chunks that children with different vocabulary sizes store in long-term memory, a measure directly related to the amount of experience the child has with the language.

Objective 1: Reliability of speed of processing

The first objective of the present thesis was to improve the reliability of the speed of processing measure. As outlined in the General Introduction (Chapter 1), the most consistently reported finding, the negative correlation between speed of processing and vocabulary size, is, at the same time, not as robust as has sometimes been claimed. The reports of the relationship vary in the strength of the effect size, the ages it can be found with and whether it is connected to preceding, concurrent and subsequent vocabulary size and/or the speed of vocabulary growth.

One of the reasons for this inconsistency is the noisiness of the data, unfortunately a common by-product when conducting infant studies. In Chapter 2, we presented a new Gaze-triggered looking-while-listening paradigm which increased the number of trials for the individual infants and in doing so also allowed us to include more data. In this chapter we also replicated the correlation between speed of processing and vocabulary size at 18 months, a common age for these speed of processing studies. Chapter 3 provides further evidence that more data points per individual participant can increase the robustness of the measurement. When replicating the analyses of Lany (2018), we saw clearer and more defined effects when we had more trials per individual infants, even when we used the stricter inclusion criteria that reduced noise but also reduced sample size (c.f. Byers-Heinlein et al., 2021). Additionally, studies like the one proposed in Chapter 5 are only possible with an in-built gaze-contingent paradigm, since, for the analyses proposed, we will need to collect at least some data for each of the sixteen words selected as stimuli. Put differently, only if we can measure infants' speed of processing for all items, and not just on average, and possibly based on only one or two items, can we begin to examine which role the words presented themselves play.

Our modification will allow researchers to collect more trials with bigger sample sizes in future studies (for further explanation why this is necessary see also Byers-Heinlein et al., 2021). In particular, studies such as that presented in Chapter 3, and Ronfard et al. (2022), which both yielded inconclusive patterns of data, will benefit from having more data available for analyses. We also predict that the new paradigm will prove useful for testing infants younger than 18 months, where studies tend to yield less reliable results due to noisy data, as a result of younger children's shorter attention span and thus less data being collected altogether. To illustrate the problem, consider that looking-while-listening data is being collected and interpreted from children as young as six months old (e.g. Bergelson & Swingley, 2012; Tincoff & Jusczyk, 2012), but processing speed is not reported before 12 months (see Table 2.1 in Chapter 2).

Overall, the present thesis provides evidence that speed of processing measure presented here can indeed be reliable and real measure of infants' processing capabilities, though it is important to account for the noisiness of the measurement. In order to ensure that the measurement is robust and properly powered for in-depth analyses of infants' lexical and cognitive development, experiments need to plan for not only adequate overall sample sizes but also for sufficient trials per individual participant. The more trials that can be used to compute speed of processing, the more robust the individual measures will be.

Speed of processing and processing accuracy

While the present thesis focused on processing speed (usually considered a form of reaction time analogous to the adult literature), the majority of the research on infants' processing efficiency also includes an accuracy measure (proportion of looking time at the target). One disadvantage of the Gaze-triggered looking-while-listening paradigm is that, while it improves the robustness and reliability of measuring speed of processing as the reaction time of word recognition, it changes the baseline for the infants' looking behaviour considerably. This complicates the assessment of the accuracy measure. In studies using the traditional design, we can assume, and actually observe, that, before the onset of target naming, children will look, on average 50% of the time at the target compared to an equally interesting distractor (chance level). In the Gaze-triggered paradigm, this baseline moves down towards, ideally, 0%, since the target audio is triggered by the infant looking at the distractor object. If future studies wish to include accuracy as a processing measurement, we recommend that they calculate the difference in fixation proportions to the same object as target and as distractor after naming (see Bergelson and Swingley; 2013), and/or include a baseline in analyses of the time-course (e.g. growth curve models).

We question, however, the value of adding an accuracy measure. Since reaction time is a more direct measure of processing speed than accuracy (Donnelly & Kidd, 2020), the only benefit of adding accuracy is to increase the number of trials included, since accuracy measures are not reliant on the child looking at the distractor at the onset of the target word. However, this is no longer an issue with the new Gaze-triggered design. In addition, including all trials no matter what the child was looking at when the target was named may obscure important relationships. Ronfard et al. (2022) investigated lexical processing via reaction time and accuracy, referring to the former as the speed and the latter as correctness of lexical processing efficiency. In their study, they split the analyses for the accuracy into three different measures: only target-initial trials, only distractor-initial trials and all trials combined; explaining that the former two trial types require to children to carry out different looking tasks; staying on the target or shifting their gaze from the distractor to the target. They reported that only accuracy from distractor-initial trials were linked to cognitive and social skills, similar to speed of processing. Thus, we suggest that our Gaze-triggered paradigm may even be superior to the original design for accuracy measures, if the goal is to investigate links to other capabilities.

Objective 2: Sources of individual differences in processing speed

Above we argue that our gaze-triggered paradigm delivers a reliable measure of infants' lexical processing capacity. Our next step in this thesis was to investigate *why* we observe individual differences in processing speed. In other words, what factors influence the individual speed of processing of each child measured in a study? The results of Chapter 3 (the impact of structural aspects of parental speech input on speed of processing and vocabulary) and Chapter 4 (do faster processors find it easier to learn new words) were inconclusive, and the data for the study in Chapter 5 is yet to be collected.

However, our tentative conclusion, given the direction of the effects in our studies, combined with results from the previous literature, is that it is more likely to be the size of the individual lexicon of the children that is the driving factor of individual differences in speed of processing, rather than vice versa. In other words, children with big vocabularies are able to process familiar words faster than children with small vocabularies. Of course, the specific processing speed will also vary for individual words, as well as being influenced by other factors such as the identity of the embedding sentence (Fernald & Hurtado, 2006) and preceding identifiers (Lew-Williams & Fernald, 2007). However, taking this thesis' results as a whole, it seems most plausible that the underlying individual processing ability is directly influenced by the child's vocabulary knowledge, although some variations might be observed due to specific word features (e.g. an individual infant's familiarity with the word, word frequency, chunking) or task design.

It still remains unclear how the relationship between speed of processing and vocabulary size exactly comes about, however, since the results in Lany (2018) and in Chapter 3 indicate that faster processing goes hand in hand with better novel word learning performance, even when taking individual lexicon size into account, at least in difficult word learning situations or at certain ages. The results of Chapter 5 and future research will help us characterise the relationship further by exploring possible different directions.

Objective 3: What is speed of processing?

Not only the is the relationship between speed of processing and vocabulary not quite clear, after almost 25 years of research it is still not completely established, what speed of processing actually is or in other words, what exactly is measured when these studies are conducted. The processing speed measured in looking-while-listening paradigms might reflect the general processing capacity of the infants', as suggested by Marchman and Fernald (2008) or Marchman et al. (2022). However, it might also reflect lexicon or linguistic specific processing or, as suggested above, item-specific processing. In Chapter 4, we aimed to gain more insights into the underlying nature of processing speed but our results were mostly inconclusive. Interpreting the results of Chapter 4 generously, we might be tempted to assume that speed of processing simply measures the ability of the children to process the individual items in the task (averaged over items), rather than reflecting a more global language processing ability, but we cannot exclude a linguistic processing hypothesis completely.

In addition, even though neither Fernald et al. (2006), Lany (2018), nor Chapter 4 show a correlation between purely visual reaction time and speed of processing, there is other evidence that speed of processing may be related to later non-verbal performances, such as non-verbal IQ (Marchman et al., 2022). Thus, speed of processing might reflect, to some extent, general cognitive processing abilities or could at least partially predict the development of such.

Fully articulated theoretical and computational models and more highly powered studies that make item-level analyses possible are needed to investigate this fundamental further. However, this thesis shows that knowing more about what speed of processing is actually measuring is crucial to our understanding of how it is related to vocabulary size and other factors, and importantly whether we can ascribe a causal role to processing speed in the mechanisms of vocabulary development.

Recommendations for future work

As might have become clear after reading this thesis, much more work is required to understand the relationship between speed of processing, vocabulary size, and language experience, and their contribution to later vocabulary development. Our first step is to conduct the experiment described in Chapter 5 and use the outcomes of the study to stimulate further research. Ideally, the results of Chapter 5 will help us to better understand the relationship between processing speed and vocabulary size, since we are directly testing the hypothesis that larger vocabularies lead to faster processing. However, even if we find evidence for this direction of the relationship, it is still important to keep in mind that according to Lany (2018) and Chapter 4, faster processing is also related to better novel word learning. Thus, we need to also develop, and compare, more explicit models and theories based on other assumptions, for example that the relationship of speed of processing and vocabulary size is bi-directional, or even that the direction of the relationship depends on the infant's individual developmental stage.

In addition, the underlying nature of processing speed needs to be investigated further to make, and test, explicit claims of its impact on early lexical development. Past research (Fernald et al., 2006; Lany, 2018) and Chapter 4 have used purely visual reaction time as a proxy of general cognitive processes at the same age, and have reported no correlation. However, one could argue that it is unlikely that a measure in one domain (visual) will correlate with a measure in another (auditory). Other measures of general cognitive processing speed may be more appropriate; such as executive function tasks (see Anderson, 2002; Diamond, 2013) that test inhibitory skills, complex attention and working memory. For example, Ronfard et al. (2022) used a "hide-the-pot" task to measure working memory together with inhibition control and reported a correlation between the performance in the task and the accuracy scores of distractor-initial trials in the speed of processing task (although not with the reaction time scores). Future work should investigate the relationship between speed of processing and other tasks assessing executive functions (for examples, see Bernier et al., 2010).

Expanding the research to use neurophysiological methods might be another useful avenue to assess the relationship between infants' cognitive development (Bell, 2001, 2002; Morasch & Bell, 2011) and lexical processing speed. It might be possible, for example, to record neural correlates during a looking-while-listening paradigm to gain a better understanding of ongoing brain activity during language processing. Previous work has for example shown a link between neurocognitive correlates of word segmentation in the first year and later language development (Junge et al., 2012; Kooijman et al., 2013). Using electroencephalography to measure neural correlates in infants used to be quite challenging given that this method is sensitive to movement. However, newly developed pipelines to detect and correct such motion artifacts (Fló et al., 2022; Marriott Haresign et al., 2021) allow for better data quality, and we expect future developments to further improve the signal-to-noise ratio in infant EEG studies.

We also suggest that future research should investigate lexical speed of processing in other languages. The majority of studies so far have been conducted with American and British English or Mexican Spanish learning infants. The study in Chapter 2 is one of the first to measure speed of processing in infants learning another language (Dutch; see also Suttora et al., 2017, for Italian, though they did not investigate the correlation between speed of processing and vocabulary). A first step to broaden the diversity of speed of processing research has been taken by MacDonald et al. (2018), who designed a visual language processing task to observe online looking patterns of children learning American Sign Language (ASL). Their results revealed individual speed of processing differences: 30-month-olds whose first language is ASL varied in how fast they oriented their attention to the target after perceiving the sign, and speed was correlated with age as well as vocabulary size (how many signs the children could produce). This finding further provides evidence that the size of the children's lexicon might be a key source of individual differences in processing, even when tested in a language that utilises the visual modality. Future research should investigate whether other findings from spoken language also hold in sign languages. For example, it might be that visual reaction time correlates with speed of processing of sign languages, since both are based in the visual domain, contrary to the results we reported in Chapter 4.

Finally, it is important to note that some of the data presented in this thesis was collected after the first government administered lockdown in response to the COVID 19 pandemic, and everyday life for families with young children was seriously disrupted as a result of the regulations. Thus, our results may have been affected by the effects of lockdown on children's lexical development. For example, a recent study has suggested that young children's vocabulary growth during the pandemic was faster than before (Kartushina et al., 2022). This dovetails with our own results, since the expressive vocabulary scores of the 17-month-old infants reported in Chapter 4 were above average compared to the norming data. In contrast, the vocabulary sizes reported in Chapter 2 and 3 were collected before the pandemic and are in line with the norming data. Thus, while it is important to note that the norming data for the N-CDI was collected with Dutch learning infants in the Dutch speaking regions of Belgium (and may not accurately reflect the vocabulary of Dutch infants in the Netherlands), it might be that the effects of lockdown affected the vocabulary scores reported in Chapter 4. Future research should investigate how the lockdowns and restrictions might have impacted children's overall development as well as individual differences.

Conclusion

A key question in language development research is why children differ in how quickly they acquire their first language and, in particular, in how fast they grow their lexicon. This question is relevant both for our fundamental understanding of human cognition and learning, and has practical relevance by allowing us to identify developmental trajectories that would benefit from targeted intervention. In this dissertation I investigated the role of speed of processing, a reaction time measure of familiar word recognition, in early lexical development. I presented a gaze-triggered looking-while-listening paradigm to measure speed of processing more robustly and replicate the commonly reported negative correlation between processing speed and concurrent vocabulary size for 18-month-olds in a new language (Dutch). Regarding the relationship between children's language development and parental speech input, the results of the thesis are inconclusive but indicate possibly interesting patterns of interaction between speed of processing and morphosyntactic complexity in parental speech input, and their impact on vocabulary growth. Furthermore, the thesis explores possible explanations for the correlation between speed of processing and vocabulary, investigating both the hypothesis that faster processing infants are better at learning new words and the hypothesis that the larger their vocabulary is, the faster the infants can process familiar words. Finally, the dissertation takes further steps to uncover the underlying nature of speed of processing. While the results of this thesis are often inconclusive, they provide insightful information for future work to explore the development of infants' lexicon and its relationship with infants' processing ability.

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Research Data Management

Personal data

I collected the following personal data for this thesis:

- birthdays (Chapter 2 to 4),
- gender, language background, as well as information about language, speech, or hearing disorders (Chapters 2 to 4),
- video recordings (Chapters 2 to 3)

It was necessary to collect these personal data to achieve the research objectives of my project. The background information (language background as well as information about disorders) were used to exclude participants from analyses if they did not meet our studies' inclusion criteria. I ensured that I did not collect more personal data than necessary for achieving the objectives of this project.

Privacy

Personal data was anonymised where possible. Participant numbers were matched in a password-protected file with the participants' birthdays (Chapter 2 to 4) and their IDs in the database of the Baby and Child Research Center; meaning that birthdays and participants' IDs were kept separate from the research data. The birthdays were used to calculate the age of the participants at the time of testing or the completion of the questionnaire but have not been saved further. The date of testing was also deleted after calculating the age, as to not be able to deduce the identity of the participating families.

Since it is not possible to anonymise video recordings, these will not be shared with anyone outside of the project. They will be securely stored in the MPI Archive. The transcriptions of the recordings are anonymised and stored in the MPI Archive under the access level “Restricted”, meaning that access can be requested.

Ethical approval and informed consent

There was a blanket ethical approval for the studies in Chapters 2 to 4 granted to the Language Development Department by the Ethics Committee of the Faculty of Social Sciences at Radboud University (ECSW2017-3001-474 Manko-Rowland;Language Development). For the study in Chapter 5, which is currently running (status October 2023) in the UK, ethical approval was granted on 29th May 2020 (valid for five years) by the Central University Research Ethics Committee at the University of Liverpool.

In the Netherlands, all participating families were registered in the database of the Baby and Child Research Center for possible participation studies. They were personally contacted by phone or email to inform them about the study opportunity and to inquire if they were interested in participating in the studies. Before the study, the parents were provided with an informed consent sheet and asked to sign it. Additionally, the questionnaires which were conducted online also included an informed consent confirmation at the beginning. Parents could withdraw from either the study or the Baby and Child Research Center database at any time.

Data storage

The research data and analysis scripts of Chapters 2 to 4 are stored at the MPI archive with varying access levels, depending on the sensitivity of the data. Anonymised data and analysis scripts are additionally shared on the Open Science Framework. All the relevant links can be found below.

The whole project on the MPI Archive:
https://hdl.handle.net/1839/4f7e0384-af1e-4c22-b216-45c156a8257d
Chapter 2: https://osf.io/8fwrb/
Chapter 3: https://osf.io/pjdbz/ (Dutch dataset)
https://hdl.handle.net/1839/6fc23cc9-b789-40ba-9184-80fe0e7992fb
(English dataset on the MPI Archive)
Chapter 4: https://osf.io/b2m8g/

Summaries

English Summary

Most children acquire their mother tongue seemingly without any effort, but there are differences in how fast they acquire it. For example, while some children may already say their first words when they are one year old, others might not speak until they are one and a half years old, or even older. These differences can be caused by variations in the environment of the child, for example, the way the parents speak to their child, but also the child's own abilities, for example, how many words they understand already or how fast they can recognise familiar words, can play a role in causing differences. The latter is called speed of processing in the literature.

Past research has shown that how many words infants know is related to how fast they process words. However, we do not know why these two aspects are connected. There are two suggestions: On the one hand, it might be that if an infant can recognise familiar words quickly, they might also be better at learning new words. On the other hand, it could be that if an infant knows a lot of words already, they are also faster in processing incoming words. Additionally, past research has shown that the way parents talk to their child impacts their linguistic development and the number of words parents use has shown to influence the infant's speed of processing. But what other aspects of parental speech might have an effect on an infant's individual abilities? For example, is the range of different words from parents or the length of the sentences might be related to the speed of word recognition in infants? In this thesis, I investigated the relationship between the words infants know and how fast they process words as well as how different aspects of parental speech might affect infants' individual processing abilities.

In Chapter 2 of this thesis, I focused on creating a more robust way to measure the speed of word recognition in children. When conducting studies with infants, one of the biggest problems is that we do not always get as many experimental trials as we need. For example, when we want to measure how fast infants recognise words, we show them two pictures and name one of them. Children (and adults) will look at a picture if it has been named quite quickly and unconsciously. Unfortunately, if they are already looking at the picture that is named, we cannot measure when the infants process what they heard. We need them to look at the other picture first, so we can see how long it takes them after hearing the name to look at the correct picture. (As a note, for adults we could ask them to do something, e.g. press a button, when they understood the word to measure their processing speed, which cannot be done with young children)

This is why we created a new experimental design, which will automatically select the object that the infants are not looking at as the one being named. Then the infants always have to move their eyes to the other picture, if and when they understand the word and we can measure how fast they are able to do so. In Chapter 2, we studied whether our new design measured similar results for 18-month-olds as the original design. To this end, we invited 18-month-olds and one of their parents to the babylab and measured the infants' speed of processing using the new and the original experimental design in an eye-tracking experiment. We checked whether the speed of word recognition for each infant is comparable in both designs, and if we were able to get more usable experimental trials per infant with the new design. We also asked the parents to fill in a standardised vocabulary questionnaire for their children, to estimate how many words the children know.

We found that we were indeed able to collect more trials per infant with the new design and that the speed of processing was similar for each infant in both designs. Additionally, we were able to demonstrate the relationship between the number of words the infants knew and their processing abilities with our Dutch participants, in line with past literature.

In Chapter 3, I looked at how the way parents speak to their children might impact the infants' processing abilities and how many words they know. This study was conducted jointly with the study in Chapter 2. After the eye-tracking experiment, we asked the parent to play with their child as if they were at home using toys we gave them. These play sessions were recorded and afterwards transcribed and analysed for different aspects of parental speech: number of words used, range of different words, and length of sentences. For each of these aspects, we had different predictions: First, we wanted to see whether we find a relationship between the number of words the parents use and infants’ vocabulary knowledge or their speed of processing. Our prediction was that the more words infants hear, the more they would be able to learn, and it would strengthen their knowledge of words they already know and thus help them process familiar words faster. Second, we wanted to see whether the range of different words parents use would affect the infants’ vocabulary knowledge. We assumed that a larger variety of words would help the infants learn new words. This might then indirectly help them process words faster. Third, we wanted to see how the length of sentences from parents might influence infants’ language development. Here, the prediction was that if infants processed familiar words quickly, they could also process longer sentences more easily and learn more words from their parents' input, therefore developing a larger vocabulary. On the contrary, we assumed that if infants are slow to process familiar words, longer sentences might actually be difficult to process, and the infants might not be able to learn as much from the parents’ input. We also wanted to test these predictions with a larger group of infants, so we analysed a comparable dataset which collected speed of processing, infants’ vocabulary sizes at different ages and parental speech in the United Kingdom (Language0-5 project) additionally to our Dutch data.

We did not find relationships between the infants’ processing speed and any aspects of parental speech for either the Dutch or the British English participants. For the Dutch infants, we could show that the range of words the parents used and the length of sentences was related with the infants’ vocabulary knowledge at 18 months. Our other predictions for both datasets did not pan out. When presenting the data in graphs, we could see tendencies of the interacting relationship between infants’ speed of processing and sentence lengths in parental speech, but could not find a statistically significant result. Thus, it might be interesting to look at this in future studies with more statistical power.

Chapter 4 and 5 of the present thesis looked at the relationship between speed of processing and vocabulary knowledge, trying to tease apart why these two measures are related.

In Chapter 4, I replicated a study that has been done with American English learning infants. The original study showed that in difficult word learning tasks, fast processing infants were better at learning new words than their slower processing peers. In addition to replicating the study with Dutch 17-month-olds, we also measured the speed of word recognition of the new words the children had just been taught, to find out more about what is determining the speed of word recognition. We wanted to see whether it is related to general cognitive abilities, only language abilities or if it is specific to the words.

We found that only fast processing infants were able to learn any new words in our study. Our results showed the same direction as the original study, but our results did not reach statistical significance. For the second goal, trying to see what is influencing speed of processing, we did not have a lot of data we could include, but it seems that speed of word recognition is mostly driven by the individual words. Future studies are needed to investigate these relationships in more detail.

The study presented in Chapter 5 is still running at the moment of writing this thesis, since it was delayed due to the COVID-19 pandemic. The goal of this study is to see whether the relationship between speed of processing and vocabulary knowledge is the other way around, meaning that knowing more words leads to faster processing of known words. We used a computational model (CLASSIC) to select words that, according to the model, are frequently heard by children and faster learned and words that are also frequently heard but not as quickly learned. We are conducting an eye-tracking experiment with 24-month-old British English children to measure speed of word recognition for these selected words and aim to compare the speeds of both groups of words.

To summarise the work of my doctoral thesis: I have introduced a new experimental design to measure the speed of word recognition more robustly and I have shown that speed of processing is related to vocabulary knowledge of Dutch infants. I have provided some information on the interplay between children’s language development and parental speech input. I have shown that fast processing infants are better at learning new words. While some results of this thesis are inconclusive, they provide insightful information for future studies on speed of processing and language development.

Nederlandse Samenvatting

De meeste kinderen verwerven hun moedertaal schijnbaar zonder enige moeite, maar er zijn verschillen in hoe snel ze hun taal leren. Sommige kinderen kunnen bijvoorbeeld hun eerste woordjes al zeggen als ze een jaar oud zijn, terwijl anderen pas praten als ze anderhalf jaar oud zijn, of zelfs nog ouder. Deze verschillen kunnen worden veroorzaakt door variaties in de omgeving van het kind, bijvoorbeeld de manier waarop de ouders tegen hun kind praten. Maar ook de eigen vaardigheden van het kind, bijvoorbeeld hoeveel woorden ze al begrijpen of hoe snel ze bekende woorden kunnen herkennen, kunnen een rol spelen bij het veroorzaken van verschillen. De snelheid van het herkennen van bekende woorden wordt in de literatuur snelheid van verwerking genoemd.

Eerder onderzoek heeft aangetoond dat de hoeveelheid woorden die kinderen kennen, samenhangt met de snelheid waarmee ze woorden verwerken. We weten echter niet waarom deze twee aspecten met elkaar samenhangen. Er zijn twee suggesties: Aan de ene kant zou een kind dat bekende woorden snel kan herkennen, ook beter kunnen zijn in het leren van nieuwe woorden. Aan de andere kant is het mogelijk dat een kind dat al veel woorden kent, ook sneller is in het verwerken van binnenkomende woorden. Daarnaast heeft onderzoek aangetoond dat de manier waarop ouders tegen hun kind praten invloed heeft op hun taalontwikkeling, en het aantal woorden dat ouders gebruiken blijkt de verwerkingssnelheid van kinderen te beïnvloeden. Maar welke andere aspecten van ouderlijke spraak zouden een effect kunnen hebben op de individuele vaardigheden van een kind? Bijvoorbeeld, is de variëteit van woorden die ouders gebruiken of de lengte van hun zinnen gerelateerd aan de snelheid van woordherkenning bij kinderen? In dit proefschrift heb ik onderzocht wat de relatie is tussen de woorden die kinderen al kennen en hoe snel ze nieuwe woorden verwerken. Verder heb ik bekeken hoe verschillende aspecten van ouderlijke spraak de individuele verwerkingsvaardigheden van kinderen kunnen beïnvloeden.

In hoofdstuk 2 van dit proefschrift heb ik me eerst gericht op het ontwikkelen van een robuustere manier om de snelheid van woordherkenning bij kinderen te meten. Bij het uitvoeren van studies met kinderen is een van de grootste problemen dat we niet altijd zoveel datapunten krijgen als we nodig hebben. Als we bijvoorbeeld willen meten hoe snel kinderen woorden herkennen, laten we ze twee plaatjes zien. Vervolgens noemen we van één plaatje wat erop staat. Kinderen (en volwassenen) zullen vrij snel en onbewust naar het plaatje kijken wat benoemd is. Helaas kunnen we niet meten wanneer de kinderen verwerken wat ze gehoord hebben, als ze al naar het plaatje kijken dat genoemd is. We moeten ze eerst naar het andere plaatje laten kijken, zodat we kunnen zien hoe lang ze erover doen om naar het juiste plaatje te kijken nadat ze de naam hebben gehoord. (Als opmerking: voor volwassenen kunnen we hen vragen iets te doen, bijvoorbeeld op een knop drukken, wanneer ze het woord begrijpen, om hun verwerkingssnelheid te meten, wat bij jonge kinderen niet mogelijk is.)

Daarom hebben we een nieuwe proefopzet ontwikkeld, die automatisch het object waar de kinderen niet naar kijken, selecteert als het object dat benoemd wordt. De kinderen moeten dan altijd hun ogen naar het andere plaatje bewegen, als en wanneer ze het woord begrijpen. Zo kunnen we meten hoe snel ze dat kunnen. In hoofdstuk 2 onderzochten we of de nieuwe proefopzet voor 18-maanden-oude kinderen vergelijkbare resultaten opleverde als het oorspronkelijke ontwerp. Daartoe nodigden we kinderen van 18 maanden en één van hun ouders uit in het babylab en maten we de verwerkingssnelheid van de kinderen met behulp van het nieuwe en het oorspronkelijke experimentele ontwerp in een eye-tracking experiment. Vervolgens controleerden we of de snelheid van woordherkenning voor elk kind vergelijkbaar is in beide ontwerpen en of we in staat waren om meer bruikbare datapunten per kind te krijgen met het nieuwe ontwerp. We vroegen de ouders ook om een gestandaardiseerde woordenschatvragenlijst in te vullen voor hun kinderen, om in te schatten hoeveel woorden de kinderen kennen.

We ontdekten dat we met het nieuwe ontwerp inderdaad meer datapuntrn per kind konden verzamelen en dat de verwerkingssnelheid voor elk kind in beide experimentele opzetten vergelijkbaar was. Bovendien konden we de relatie aantonen tussen het aantal woorden dat de kinderen kenden en hun verwerkingssnelheid bij onze Nederlandse deelnemers, zoals aangetoond in eerdere literatuur.

In hoofdstuk 3 heb ik onderzocht hoe de manier waarop ouders met hun kinderen praten van invloed zou kunnen zijn op de verwerkingsvaardigheden van de kinderen en het aantal woorden dat ze kennen. Dit onderzoek werd gezamenlijk met het onderzoek in hoofdstuk 2 uitgevoerd. Na het eye-tracking experiment vroegen we de ouders om met hun kind te spelen alsof ze thuis waren met speelgoed dat we hen gaven. Deze speelsessies werden opgenomen en daarna getranscribeerd en geanalyseerd op verschillende aspecten van ouderlijke spraak: aantal gebruikte woorden, variëteit van woorden en lengte van zinnen. Voor elk van deze aspecten hadden we verschillende voorspellingen: Ten eerste wilden we zien of we een verband zouden vinden tussen het aantal woorden dat de ouders gebruiken en de woordenschatkennis van kinderen, of hun verwerkingssnelheid. Onze voorspelling was dat hoe meer woorden kinderen horen, hoe meer ze zouden kunnen leren. Het aantal aan woorden, die kinderen horen, zou hun kennis van woorden die ze al kennen versterken en hen dus helpen om bekende woorden sneller te verwerken. Ten tweede wilden we zien of de variëteit van woorden die ouders gebruiken, invloed zou hebben op de woordenschatkennis van de kinderen. We veronderstelden dat een grotere verscheidenheid aan woorden de kinderen zou helpen om nieuwe woorden te leren. Dit zou hen dan indirect kunnen helpen om woorden sneller te verwerken. Ten derde wilden we zien hoe de lengte van de zinnen van ouders de taalontwikkeling van kinderen zou kunnen beïnvloeden. Hier was de voorspelling dat als kinderen bekende woorden snel verwerken, ze ook gemakkelijker langere zinnen kunnen verwerken en meer woorden kunnen leren van de input van hun ouders, waardoor ze een grotere woordenschat ontwikkelen. Daarentegen veronderstelden we dat als kinderen bekende woorden langzaam verwerken, langere zinnen moeilijker te verwerken zouden kunnen zijn en de kinderen minder zouden kunnen leren van de input van de ouders. We wilden deze voorspellingen ook testen met een grotere groep kinderen, dus analyseerden we naast onze Nederlandse data een vergelijkbare dataset die verwerkingssnelheid en de woordenschat van kinderen op verschillende leeftijden en ouderlijke spraak verzamelde in het Verenigd Koninkrijk (Language0-5 project).

We vonden geen relatie tussen de verwerkingssnelheid van de kinderen en aspecten van ouderlijke spraak, noch voor de Nederlandse noch voor de Brits-Engelse deelnemers. Voor de Nederlandse kinderen konden we aantonen dat het aantal woorden dat de ouders gebruikten en de lengte van de zinnen gerelateerd was aan de woordenschatkennis van de kinderen op 18 maanden. Onze andere voorspellingen voor beide datasets kwamen niet uit. Bij het presenteren van de gegevens in grafieken konden we tendensen zien van een interactief verband tussen de verwerkingssnelheid van kinderen en de zinslengte in ouderlijke spraak, maar hadden geen statistisch significant resultaat. Het zou dus interessant kunnen zijn om hiernaar te kijken in toekomstige onderzoeken met meer statistische kracht.

In hoofdstuk 4 en 5 van dit proefschrift heb ik gekeken naar de relatie tussen verwerkingssnelheid en woordenschatkennis en geprobeerd uit te zoeken waarom deze twee maten samenhangen.

In hoofdstuk 4 heb ik een onderzoek herhaald dat is uitgevoerd met Amerikaans-Engels kinderen. Het oorspronkelijke onderzoek toonde aan dat bij moeilijke woordleertaken, kinderen met een snelle verwerkingssnelheid beter waren in het leren van nieuwe woorden dan hun leeftijdsgenoten met een langzamere verwerkingssnelheid. Naast het repliceren van het onderzoek met Nederlandse kinderen van 17 maanden, hebben we ook de snelheid van woordherkenning gemeten van de nieuwe woorden die de kinderen net hadden geleerd, om meer te weten te komen over wat de snelheid van woordherkenning bepaalt. We wilden zien of het gerelateerd is aan algemene cognitieve vaardigheden, alleen aan taalvaardigheden of dat het specifiek is voor de woorden.

In onze studie waren alleen kinderen met een snelle verwerking in staat om nieuwe woorden te leren. Onze resultaten wezen in dezelfde richting als het oorspronkelijke onderzoek, maar onze resultaten bereikten geen statistische significantie. Voor het tweede doel, het proberen te achterhalen wat de verwerkingssnelheid beïnvloedt, hadden we niet veel gegevens die we konden opnemen, maar het lijkt erop dat de snelheid van woordherkenning vooral wordt bepaald door de individuele woorden. Toekomstige studies zijn nodig om deze bevinding beter te onderzoeken.

Het onderzoek dat in hoofdstuk 5 wordt gepresenteerd, loopt nog op het moment dat deze proefschrift wordt geschreven, omdat het is uitgesteld vanwege de COVID-19 pandemie. Het doel van dit onderzoek is om te kijken of de relatie tussen verwerkingssnelheid en woordenschatkennis andersom ook bestaat, wat betekent dat het kennen van meer woorden leidt tot snellere verwerking van bekende woorden. We gebruikten een computationeel model (CLASSIC) om woorden te selecteren die volgens het model vaak gehoord worden door kinderen en sneller geleerd worden, en woorden die ook vaak gehoord worden maar minder snel geleerd worden. We voeren een eye-tracking experiment uit met Brits-Engelse kinderen van 24 maanden oud om de snelheid van woordherkenning voor deze geselecteerde woorden te meten en we willen de verwerkingssnelheden van beide woordgroepen vergelijken.

Om het werk van mijn proefschrift samen te vatten: ik heb een nieuwe, experimentele proefopzet geïntroduceerd om de snelheid van woordherkenning robuuster te meten en ik heb aangetoond dat snelheid van verwerking gerelateerd is aan woordenschatkennis van Nederlandse kinderen. Ik heb informatie gegeven over de wisselwerking tussen de taalontwikkeling van kinderen en de spraakinput van ouders. Ik heb aangetoond dat kinderen met een snelle verwerkingssnelheid beter zijn in het leren van nieuwe woorden. Hoewel sommige resultaten van dit proefschrift niet eenduidig zijn, bieden ze inzichtelijke informatie voor toekomstige studies naar verwerkingssnelheid en taalontwikkeling.

Deutsche Zusammenfassung

Die meisten Kinder erwerben ihre Muttersprache scheinbar mühelos, aber es gibt Unterschiede darin, wie schnell sie ihre Sprache lernen. Während manche Kinder zum Beispiel schon mit einem Jahr ihre ersten Worte sagen, sprechen andere vielleicht erst mit eineinhalb Jahren oder sogar noch später. Diese Unterschiede können durch Variation in der Umgebung des Kindes verursacht werden, zum Beispiel durch die Art und Weise, wie Eltern mit ihrem Kind sprechen. Jedoch auch die eigenen Fähigkeiten des Kindes, z. B. wie viele Wörter es bereits versteht oder wie schnell es bekannte Wörter erkennen kann, können eine Rolle bei der Entstehung von Unterschieden spielen. Letzteres wird in der Literatur als Verarbeitungsgeschwindigkeit bezeichnet.

Frühere Studien haben gezeigt, dass die Anzahl der Wörter, die Kleinkinder kennen, damit zusammenhängt, wie schnell sie Wörter verarbeiten. Wir wissen jedoch nicht, warum diese beiden Aspekte miteinander verbunden sind. Es gibt zwei Vermutungen: Einerseits könnte es sein, dass ein junges Kind, das bekannte Wörter schnell erkennen kann, auch besser imstande ist, neue Wörter zu lernen. Andererseits wäre es aber auch möglich, dass ein Kind, das bereits viele Wörter kennt, auch schneller in der Lage ist, neue Wörter zu verarbeiten. Frühere Studien haben außerdem gezeigt, dass die Art und Weise, wie Eltern mit ihren Kindern sprechen, deren sprachliche Entwicklung beeinflusst und die Anzahl der von den Eltern verwendeten Wörter sich auf die Verarbeitungsgeschwindigkeit der Kleinkinder auswirkt. Welche anderen Aspekte der elterlichen Sprache könnten sich auf die individuellen Fähigkeiten eines Kindes auswirken? Könnte zum Beispiel die Vielfalt an Wörtern der Eltern oder die Länge der Sätze mit der Geschwindigkeit der Worterkennung bei Kleinkindern zusammenhängen? In dieser Arbeit untersuchte ich die Beziehung zwischen den Wörtern, die junge Kinder kennen, und der Geschwindigkeit, mit der sie Wörter verarbeiten. Außerdem beschäftige ich mich mit der Frage, wie sich verschiedene Aspekte der elterlichen Sprache auf die individuellen Verarbeitungsfähigkeiten von Kleinkindern auswirken könnten.

In Kapitel 2 dieser Arbeit habe ich mich darauf konzentriert, eine robustere Methode zur Messung der Geschwindigkeit der Worterkennung bei Kleinkindern zu entwickeln. Bei der Durchführung von Studien mit Kindern besteht eines der größten Probleme darin, dass wir nicht immer so viele Versuchsreihen bekommen, wie man eigentlich bräuchte. Wenn wir zum Beispiel messen wollen, wie schnell Kinder Wörter erkennen, zeigen wir ihnen zwei Bilder und nennen eines davon. Kinder (und Erwachsene) schauen recht schnell und unbewusst zu dem Bild, das benannt wurde. Wenn sie bereits auf das genannte Bild schauen, können wir leider nicht messen, wann die Kinder das Gehörte verarbeitet haben. Wir müssen sie zuerst auf das andere Bild schauen lassen, damit wir sehen können, wie lange sie nach dem Hören des Namens brauchen, um zum richtigen Bild zu schauen. (Als Hinweis: Erwachsene könnten wir bitten, etwas zu tun, z.B. einen Knopf zu drücken, wenn sie das Wort verstanden haben, um ihre Verarbeitungsgeschwindigkeit zu messen, was bei kleinen Kindern nicht möglich ist.)

Deshalb haben wir ein neues Versuchsdesign entwickelt, bei dem automatisch das Objekt, auf das die Kinder nicht schauen, als das zu benennende ausgewählt wird. Dadurch müssen die Kinder ihre Augen immer dann auf das andere Bild richten, wenn sie das Wort verstehen, und wir können messen, wie schnell sie dazu in der Lage sind. In Kapitel 2 untersuchten wir, ob unser neues Design bei Eineinhalbjährigen zu ähnlichen Ergebnissen führte wie das ursprüngliche Design. Zu diesem Zweck luden wir 18 Monate alte Kinder und ein Elternteil ins Babylab ein und maßen die Verarbeitungsgeschwindigkeit der Kinder mit dem neuen und dem ursprünglichen experimentellen Design in einem Eye-Tracking-Experiment. Anschließend überprüften wir, ob die Geschwindigkeit der Worterkennung für die Kleinkinder in beiden Versuchsplänen vergleichbar ist und ob wir mit dem neuen Design mehr verwertbare Versuche pro Kind erzielen konnten. Außerdem baten wir die Eltern, einen standardisierten Wortschatzfragebogen für ihre Kinder auszufüllen, um zu schätzen, wie viele Wörter die Kinder kennen.

Wir fanden heraus, dass wir mit dem neuen Design tatsächlich mehr Versuche pro Kind sammeln konnten und dass die Verarbeitungsgeschwindigkeit für jedes Kind in beiden experimentellen Designs ähnlich war. Darüber hinaus konnten wir bei unseren niederländischen Teilnehmer: innen einen Zusammenhang zwischen der Anzahl der Wörter, die die Kinder kannten und ihren Verarbeitungsfähigkeiten nachweisen. Dies stimmt mit der bisherigen Literatur überein.

In Kapitel 3 habe ich untersucht, wie sich die Art und Weise, wie Eltern mit ihren Kleinkindern sprechen, auf die Verarbeitungsfähigkeiten der jungen Kinder und die Anzahl der Wörter, die sie kennen, auswirken könnte. Diese Studie wurde gemeinsam mit der Studie in Kapitel 2 durchgeführt. Nach dem Eye-Tracking-Experiment baten wir die Eltern, mit ihrem Kind so zu spielen wie zu Hause. Dabei benutzten sie Spielzeug, das wir ihnen zur Verfügung stellten. Diese Spielsitzungen wurden aufgezeichnet und anschließend transkribiert und auf verschiedene Aspekte der elterlichen Sprache hin analysiert: Anzahl der verwendeten Wörter, Vielfalt an verschiedenen Wörtern und Länge der Sätze. Bei jedem dieser Aspekte gingen wir von unterschiedlichen Prognosen aus: Erstens wollten wir herausfinden, ob es einen Zusammenhang zwischen der Anzahl der von den Eltern verwendeten Wörter und den Wortschatzkenntnissen der jungen Kinder oder ihrer Verarbeitungsgeschwindigkeit gibt. Wir gingen davon aus, dass Kinder umso mehr lernen können, je mehr Wörter sie hören, und dass dies ihr Wissen über bereits bekannte Wörter stärkt und ihnen somit hilft, bekannte Wörter schneller zu verarbeiten.

Zweitens wollten wir herausfinden, ob sich die Vielfalt der von den Eltern verwendeten Wörter die Wortschatzkenntnisse der Kleinkinder beeinflussen würde. Wir nahmen an, dass eine größere Vielfalt an Wörtern den Kindern helfen würde, neue Wörter zu erlernen. Dies könnte ihnen dann indirekt helfen, Wörter schneller zu verarbeiten. Drittens wollten wir sehen, wie die Länge der Sätze der Eltern die Sprachentwicklung der Kinder beeinflussen könnte. Dabei wurde davon ausgegangen, dass Kinder, die bekannte Wörter schnell verarbeiten, auch längere Sätze leichter verarbeiten und mehr Wörter aus dem Input ihrer Eltern lernen und somit einen größeren Wortschatz entwickeln können. Im Gegensatz dazu gingen wir davon aus, dass Kinder, die vertraute Wörter nur langsam verarbeiten, auch längere Sätze nur schwer verarbeiten können und daher nicht so viel aus dem

Input der Eltern lernen können. Wir wollten diese Prognosen auch mit einer größeren Gruppe von Kindern testen und analysierten daher zusätzlich zu unseren niederländischen Daten einen vergleichbaren Datensatz, der die Verarbeitungsgeschwindigkeit, die Wortschatzgröße der Kinder in verschiedenen Altersstufen und die elterliche Sprache im Vereinigten Königreich (Language0-5 project) erfasste.

Weder bei den niederländischen noch bei den britischen Teilnehmer: innen fanden wir einen Zusammenhang zwischen der Verarbeitungsgeschwindigkeit der Kinder und irgendwelchen Aspekten der elterlichen Sprache. Für die niederländischen Kinder konnten wir zeigen, dass die Bandbreite der von den Eltern verwendeten Wörter und die Länge der Sätze mit dem Wortschatzwissen der Kinder im Alter von 18 Monaten zusammenhing. Unsere anderen Prognosen für beide Datensätze haben sich nicht bewahrheitet. Bei der grafischen Darstellung der Daten in Diagrammen konnten wir Tendenzen der Wechselbeziehung zwischen der Verarbeitungsgeschwindigkeit der Kinder und der Satzlänge in der elterlichen Rede erkennen, hatten aber kein statistisch signifikantes Resultat. Es wäre interessant, dies in zukünftigen Studien mit mehr statistischer Aussagekraft zu untersuchen.

In den Kapiteln 4 und 5 der vorliegenden Arbeit wurde die Beziehung zwischen Verarbeitungsgeschwindigkeit und Wortschatzwissen untersucht, um herauszufinden, warum diese beiden Maße zusammenhängen.

In Kapitel 4 habe ich eine Studie wiederholt, die mit amerikanischen Englisch lernenden Kleinkindern durchgeführt wurde. Die ursprüngliche Studie zeigte, dass bei schwierigen Wortlernaufgaben schnell verarbeitende Kleinkinder neue Wörter besser lernten als ihre langsamer verarbeitenden Altersgenossen. Zusätzlich zur Wiederholung der Studie mit 17 Monate alten niederländischen Kindern haben wir auch die Geschwindigkeit der Worterkennung der neuen Wörter gemessen, die die Kinder gerade gelernt hatten, um mehr darüber herauszufinden, was die Geschwindigkeit der Worterkennung bestimmt. Wir wollten herausfinden, ob diese Geschwindigkeit mit allgemeinen kognitiven Fähigkeiten oder nur mit sprachlichen Fähigkeiten zusammenhängt oder ob sie spezifisch nur für Wörter ist.

Wir stellten fest, dass in unserer Studie nur schnell lernende Kinder in der Lage waren, neue Wörter zu lernen. Unsere Ergebnisse gingen in die gleiche Richtung wie die der ursprünglichen Studie, erreichten aber keine statistische Signifikanz. Für das zweite Ziel, nämlich herauszufinden, was die Verarbeitungsgeschwindigkeit beeinflusst, hatten wir nicht viele Daten, die wir einbeziehen konnten, aber es wirkt, als ob die Geschwindigkeit der Worterkennung hauptsächlich von den einzelnen Wörtern abhängt. Künftige Studien sind jedoch erforderlich, um diese Zusammenhänge genauer zu untersuchen.

Die in Kapitel 5 vorgestellte Studie ist zum Zeitpunkt der Verfassung dieser Arbeit noch nicht abgeschlossen, da sie aufgrund der COVID-19-Pandemie verschoben wurde. Ziel dieser Studie ist es, herauszufinden, ob die Beziehung zwischen Verarbeitungsgeschwindigkeit und Wortschatzwissen umgekehrt ist, d. h., dass die Kenntnis von mehr Wörtern zu einer schnelleren Verarbeitung der bekannten Wörter führt. Wir haben ein Computermodell (CLASSIC) verwendet, um Wörter auszuwählen, die dem Modell zufolge von Kindern häufig gehört und schneller gelernt werden und Wörter, die ebenfalls häufig gehört, aber nicht so schnell gelernt werden. Wir führen aktuell ein Eye-Tracking-Experiment mit 24 Monate alten britischen Kindern durch, um die Geschwindigkeit der Worterkennung für diese ausgewählten Wörter zu messen und wollen die Geschwindigkeiten der beiden Wortgruppen anschließend vergleichen.

Um die Arbeit meiner Dissertation zusammenzufassen: Ich habe ein neues experimentelles Design entwickelt, um die Geschwindigkeit der Worterkennung robuster zu messen, und ich habe gezeigt, dass die Geschwindigkeit der Verarbeitung mit dem Wortschatzwissen niederländischer Kleinkinder zusammenhängt. Ich habe einige Informationen über das Zusammenspiel zwischen der Sprachentwicklung von Kindern und dem elterlichen Sprachinput geliefert. Des Weiteren habe ich gezeigt, dass schnell verarbeitende Kleinkinder neue Wörter besser lernen. Obwohl einige Ergebnisse dieser Arbeit uneindeutig sind, liefern sie aufschlussreiche Informationen für zukünftige Studien über Verarbeitungsgeschwindigkeit und Sprachentwicklung.

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About the Author

Julia Egger was born on March 31st 1994 in Vienna, Austria. She obtained a bachelor’s degree in Romance philology (main language: Spanish) from the University of Vienna. As part of her bachelor studies, she also spent seven months in Barcelona, Spain, for an ERASMUS exchange at the University Pompeu Fabra. She received a research master’s degree in Language and Communication at the Radboud University. In her master’s thesis, Julia used EEG to investigate the neural correlates of incidental L2 auditory word learning under the supervision of Dr. Kristin M. Lemhöfer. In November 2017, Julia joined the newly founded Language Development Department (LaDD) and conducted the research presented in this doctoral thesis under the supervision of Prof. dr. Caroline F. Rowland and Dr. Christina Bergmann. In addition to her studies, Julia coordinated and taught courses on Open Science & Key Practices, supported the Baby and Child Research Center PR Team and organised scientific and social events within the IMPRS and the LaDD. She was also actively involved in several science communication projects, such as participating in various science festivals (Kletskoppen Kindertaalfestival, InScience Festival, Expeditie NEXT), writing guest blogs for Donders Wonders and editing articles for the MPITalkling Blog. In June 2023, she started working as a postdoctoral project manager for the RESONATE project funded by Horizon Europe and headed by Dr. Mathew P. White at the Vienna Cognitive Science Hub at the University of Vienna.

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Egger, J., Rowland, C.F., & Bergmann, C. (2020). Improving the robustness of infant lexical processing speed measures. *Behavioral Research Methods*, 52(5), 2188–2201.

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