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University of Turku

Faculty of Social Sciences
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Speech-Language Pathology
Doctoral Programme of Social and Behavioural Sciences

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ABSTRACT

Language acquisition requires a child to effectively structure and process sensory input. Language is heavily based on regularities and statistical probabilities in phonemic patterns, syntactic structures, semantics, and pragmatics. Considering the remarkable diversity in the manifestation and characteristics of language, it is nothing short of miraculous that most children effortlessly acquire language. Nevertheless, language acquisition varies among individuals and does not always occur without difficulties. Children typically utter their first words around their first birthdays. Late talkers are children who, for no obvious reason, still produce few or no words by the age of two. In this thesis, I explore domain-general mechanisms (i.e., mechanisms shared across different sensory modalities or areas of cognition) that have been suggested to underlie individual differences in language abilities and examine whether these mechanisms differ across children with and without a history of late talking. In all the studies included in this thesis, the participants were 7–10-year-old children, half of whom had a history of late talking. By investigating the relationship between the suggested mechanisms and early language development, I also aimed to identify potential candidates that could explain language outcomes in late talkers. In Study I, we observed a relationship between the speed of processing and language abilities but no associations between attentional inhibition and language. In Study II, the learning of regularities was found to be associated with language abilities in children with a history of typical early development but not in late talkers. In Study III, we measured electrical brain responses to sounds; the amplitudes of the responses were found to be associated with language abilities, suggesting that differences in language abilities are related to early-level auditory processing. In Study IV, we observed a relationship between the pronounced within-individual variability in response times and language abilities. Based on this finding, I propose the Intra-Individual Variability hypothesis of language, which suggests that instability in processing linguistic inputs may lead to differences in language abilities. In this thesis, I posit that this hypothesis provides a meaningful framework for interpreting the findings of Study I–III as well.

KEYWORDS: Language acquisition, Individual differences, Response times, Electroencephalography, Intra-individual variability

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TIIVISTELMÄ

Kielen oppiminen edellyttää monenlaisia aistitiedon jäsentelyn ja työstämisen valmiuksia. Kieli perustuu säännönmukaisuuksille niin äänteiden yhdistelyssä, kieliopillisissa rakenteissa, merkityssisällöissä kuin käyttötavoissakin. Kielen olemuksen ja ilmentymisen moniulotteisuuden valossa on ihmeellistä, että valtaosa lapsista oppii ympäristön kielen ilman tietoisia ponnisteluita. Kielen omaksumisessa on kuitenkin yksilöllisiä eroja eikä se aina suju ongelmitta. Lapsi alkaa tyypillisesti tuottaa sanoja noin yhden vuoden iässä. Osalla lapsista puheen kehitys on kuitenkin myöhäisempää. Englannin kielellä lapsiin, jotka eivät tuota lainkaan tai juuri lainkaan sanoja kahden vuoden iässä viitataan käsitteellä *late talker*, ”myöhäinen puhuja”, jolle ei ole täsmällistä vakiintunutta vastinetta suomen kielessä. Tässä väitöstyössä tarkastelen kielelliselle ja ei-kielelliselle tiedonkäsittelylle yhteisiä osa-alueita, joiden yksilöllisen vaihtelun on ehdotettu selittävän eroja kielellisissä taidoissa sekä sitä, eroavatko nämä osa-alueet tavanomaisesti ja myöhään puhumaan oppineiden lasten välillä. Kaikissa osatutkimuksissa tutkittavat olivat 7–10 -vuotiaita lapsia, joista puolella oli todettu viivästynyt kielenkehitys (engl. *late talking*) varhaislapsuudessa. Tarkastelemalla yhteyttä varhaisiän kielellisen kehitykseen pyrin myös löytämään mitattavissa olevia mekanismeja kielellisten taitojen kehityksen ennakointiin. Tutkimuksessa I havaitsimme yhteyden tiedonkäsittelyn nopeuden ja kielellisten taitojen välillä, mutta emme yhteyttä tarkkaavuuden ja kielen välillä. Tutkimuksessa II säännönmukaisuuksien oppimisen taidot olivat yhteydessä kielellisiin taitoihin lapsilla, joiden kielen varhaiskehitys oli edennyt tavanomaisesti, mutta vastaavaa yhteyttä ei havaittu myöhään puhumaan oppineilla lapsilla. Tutkimuksessa III mittasimme aivojen sähköisiä vasteita äänille. Vasteiden voimakkuus oli yhteydessä kielellisiin taitoihin, mikä viittaa siihen, että erot kuulotiedon käsittelyssä ovat yhteydessä kielen omaksumiseen. Tutkimuksessa IV havaitsimme reaktioaikojen yksilönsisäisen vaihtelevuuden olevan yhteydessä kielellisiin taitoihin, minkä perusteella esitämme hypoteesin tiedonkäsittelyn epävakaudesta kielellisten taitojen yksilöllisten erojen selittäjänä. Väitöstyössäni esitän, että tämä hypoteesi soveltuu viitekehykseksi myös tutkimusten I–III tulosten tulkintaan.

ASIASANAT: Kielen kehitys, Yksilölliset erot, Reaktioajat, Aivosähkökäyrä, Yksilönsisäinen vaihtelu

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August 2024
Anna Kautto

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List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Anna Kautto, Eira Jansson-Verkasalo & Elina Mainela-Arnold. Generalized slowing rather than inhibition is associated with language outcomes in both late talkers and children with typical early development. *Journal of Speech, Language, and Hearing Research*, 2021; 4: 1222-1234.

II Anna Kautto & Elina Mainela-Arnold. Procedural learning and school-age language outcomes in children with and without a history of late talking. *International Journal of Language & Communication Disorders*, 2022; 6: 1255-1268.

III Anna Kautto, Henry Railo & Elina Mainela-Arnold. Low-level auditory processing correlates with language abilities: An ERP study investigating sequence learning and auditory processing in school-aged children. *Neurobiology of Language*, 2024; 2: 341-359.

IV Anna Kautto, Henry Railo & Elina Mainela-Arnold. Introducing the intra-individual variability hypothesis in explaining individual differences in language development. *Journal of Speech, Language, and Hearing Research*, 2024; 8: 2698-2707.

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1 Introduction and theoretical background

1.1 Language acquisition

Generally, one’s first language is learned through cultural transmission (Yule, 2010). Although a child is not inherently equipped with language at birth, newborns possess an innate predisposition and sensitivity with regard to acquiring the language spoken in their environment (e.g., Kuhl, 2004). A child needs to be exposed to a language to be able to decode the messages carried by the linguistic inputs. This is a demanding task given the complexity of language structures, semantics, and pragmatics. Speech, as a signal, is complex: the acoustic changes occur rapidly and immediately disappear as new information keeps flowing. However, being able to decode the message alone is not enough to become an effective language user, as the information also needs to be remembered and activated quickly and at the right time while interacting with one’s environment. Language acquisition seems to be dependent on sufficient attentional abilities (for review, see Ebert & Kohnert, 2011), cognitive processing speed (for review, see Zapparrata et al., 2023), abilities to learn regularities (e.g., Saffran et al., 1996), movement planning (e.g., Guenther, 1995), and sensory information processing (e.g., Neville et al., 1993). I find it fascinating and somewhat surprising how effortlessly most children acquire language and that we often consider this as self-evident. In this thesis, I studied the aspects of information processing that enable the acquiring of the language of a child’s environment and, more specifically, explain individual differences in language acquisition.

Understanding the nature and prerequisites of typical language acquisition is crucial for comprehending the individual variations seen in this process. Language learning challenges may stem from inefficiencies in one or more of the components essential to language acquisition. While environmental factors can account for variances between individuals, they alone do not provide a comprehensive explanation for all the differences observed (see, e.g., Kidd et al., 2018). In this thesis, I have focused on the individual factors that affect language acquisition.

1.1.1 Late talking

Most children learn the language spoken in their environment easily without any deliberate efforts by their caregivers. Children typically produce their first words around their first birthdays and soon begin to express themselves verbally (for review, see Conti-Ramsden & Durkin, 2012). However, relatively many children—up to 20%, depending on the adopted definition—still produce few or no words by their second birthday even though there is no obvious reason for late language emergence (for review, see Rescorla, 2011). This phenomenon is known as late talking (LT).

LT is often defined based on the expressive vocabulary of a toddler (e.g., Fisher, 2017); this is likely because expressive vocabulary is one of the most easily observable manifestations of language development and is more straightforward to assess than, for example, receptive vocabulary or grammar. What counts as a produced word, however, also depends on the criteria used (see Vihman & McCune, 1994): Is the pronunciation adult-like or at least close to it? Is it produced spontaneously or imitated? Is it understood by the child or the observer? Is it enough if the child produces the word once, or does it have to be part of their active vocabulary to be counted? For a caregiver, it might be difficult to list all the words the child can produce or understand offhand. To this end, curated lists of carefully chosen words, such as those in the MacArthur-Bates Communicative Development Inventories (Fenson et al., 2007), have been proven to be useful and are widely adapted for LT definitions.

LT has a good prognosis (for review, see Rescorla, 2011). A majority of such children no longer exhibit impaired language abilities at school age. However, some do. To date, there have been no known good predictors for language development for LT children. Further, LT itself can be seen as a risk factor for persistent language difficulties (Bishop et al., 2016), but what causes LT and which children will have persistent language difficulties remain unknown. In this thesis, I aim to identify domain-general abilities—global or broad-level factors common to processing across sensory modalities or different areas of cognition—that may influence LT outcomes.

1.1.2 Persistent language difficulties

Weak language abilities may have long-term impacts on one's academic performance, socioeconomic status, and quality of life (Clegg et al., 2005). Known risk factors for persistent language difficulties include a family history of language disorders, low parental education levels, and being male (Bishop et al., 2017). In this thesis, rather than dividing the participants into "typical" and "disorder" groups based on their language status, I reviewed their language abilities as a continuum and studied whether the theories that are suggested to underly disordered language acquisition could explain individual differences across the board.

In healthcare, one presenting persistent language-learning-related difficulties can be diagnosed with developmental language disorder (DLD). DLD is almost synonymous with the terms *specific language impairment* (SLI) and *developmental dysphasia* and has been widely adopted in recent years after the publication of the CATALISE consortium's terminology consensus panel's articles (Bishop et al., 2016, 2017). Although the terms SLI and DLD are often used almost interchangeably in research literature, SLI is more conservative when it comes to comorbidity with other disorders, and the child's nonverbal IQ is also required to be within, or at least close to, the associated age expectations (see, e.g., Volkers, 2018).

1.1.2.1 The relationship between language difficulties and nonverbal abilities

The CATALISE consensus panel suggests that language impairments without difficulties in other areas of development (such as attention, social interaction, or motor skills) are "the exception, not the rule" (Bishop et al., 2016, p. 8). Accordingly, stringent exclusion criteria based on comorbid conditions may result in poor representative samples in research or the underdiagnosis of language impairments in healthcare, which may restrict the intervention and other services that would benefit an individual. To avoid poor representativeness of children with varying language abilities in Studies I–IV, we only excluded children with obvious motor, behavioral, emotional, or neurological disabilities but not, for instance, children with attention-deficit/hyperactivity disorder (ADHD) or dyslexia.

Many studies have been conducted on individual differences in language acquisition in the context of DLD or SLI, which has also affected the cut-off exclusion criteria for nonverbal reasoning abilities (see, e.g., Volkers, 2018). Although the definition of DLD does not set a specific limit for nonverbal reasoning abilities, many studies with a DLD group still use a cut-off for nonverbal IQ (often >70) because DLD might manifest in a variety of ways in children with differing cognitive abilities (see, e.g., Volkers, 2018). Therefore, we used this exclusion criteria for all the participants in Study I–IV of this thesis.

1.1.3 Language development of late talkers

LT is often considered a risk factor for DLD. Approximately 14–73% of children with a history of LT perform worse than their age-based expectations in language measures at school age (e.g., Feldman et al., 2005; Westerlund et al., 2006). Large variations in these numbers is likely due to the differing age points and criteria used when defining LT and language outcomes. It is also worth noting that not all children with weak language abilities at school age have a history of LT. For example, Armstrong et al. (2017) and Zambrana et al. (2014) report there being a relatively high proportion of children with poor school-age language abilities who have no history of LT.

Categorical accounts of LT consider LT and persistent language difficulties separate phenomena with different etiologies (Rescorla, 2009). Categorical account-based research often focuses on identifying the clinical markers or genetic factors associated with difficulties with learning language. These factors could be useful for categorically predicting whether the language learning difficulties of an LT child will persist. The categorical accounts suggest that the mechanisms underlying late blooming (referring to children with LT who later catch up with their peers in terms of language development) and persistent language difficulties are different, with late blooming and DLD children qualitatively differing from each other, such as by presenting a behavioral marker, feature, or gene that is specific to only one of these categories. According to the *dimensional accounts* of LT (Rescorla, 2009, 2011), the difference between LT and persistent language difficulties is quantitative, and the same mechanisms underlying LT also explain DLD. The differences between LT and DLD would be in terms of the degree and stability of the impairment causing the difficulties in language acquisition—with more severe and persistent difficulties resulting in DLD. According to Rescorla (2009), despite meeting age-based expectations for language abilities at school age, children with typical early development (TED), as a group, still outperform late-blooming children in language measures, which the author interprets as support for the dimensional accounts of language development. In Study I–III (see Section 3.1–3.3), we aimed to investigate whether the attentional inhibition, processing speed, procedural learning, and auditory processing of children with a history of LT (as well as late-blooming children) are similar to those of children with weak language abilities at school age, only varying in degree.

Classification into the categories of typical and atypical (such as in the case of DLD) is not straightforward; language abilities are a continuum and have multiple dimensions (Language and Reading Research Consortium, 2015; Tomblin & Zhang, 2006). In this thesis, I used a continuous measure of language abilities instead of the categories of typical and atypical. This was especially essential to account for variation in language abilities in a meaningful way, as we recruited children with as well as without a history of LT, and many late talkers are known to exhibit language abilities within the typical variation but somewhat lower than the population mean (see Rescorla, 2009). Further, dividing a continuous phenomenon into categories usually leads to a loss of information in further analyses and, thus, is not an optimal choice when not necessitated by certain factors (such as when clinical decision-making is required) (see Fisher et al., 2020).

1.2 Domain-general theories on individual differences of language development

Although it remains unclear why the progress of language acquisition varies between individuals, multiple theories explaining these differences and the nature of atypical language acquisition have been proposed. Some of the best known and most widely used domain-general theories are introduced in this chapter. I use the term *domain-general* to refer to aspects or mechanisms that are shared between different modalities (e.g., auditory and visual) or different cognitive domains (e.g., linguistic and non-linguistic processing within the auditory modality). In addition to understanding disorders associated with language acquisition—the context in which many of these theories have been presented and studied—these theories are also useful for understanding individual variations in the language abilities of children who do not meet the diagnostic criteria, such as for DLD (Kidd et al., 2018). Domain-general theories suggest that the cognitive processes underlying difficulties in language learning are not specific to the auditory modality or speech signals but, rather, are observed across different sensory modalities or domains. Suggested mechanisms include aspects of attention (for review, see Ebert & Kohnert, 2011), statistical learning (Saffran, 2003), processing speed (Kail, 1994), and aspects of auditory processing (Kujala & Leminen, 2017; Tallal & Piercy, 1973). In this thesis, I focus on testing how well the aspects of attentional inhibition (Study I), procedural learning (Study II), generalized slowing (Study I and II), and auditory processing (Study III) can explain individual differences in the language abilities of children with and without a history of LT. It is worth noting that alternative accounts presented in the following chapters are not necessarily contradictory but may represent different mechanisms that contribute to language acquisition or have a shared background (see Kidd et al., 2018). In Sections 1.2.1 and 1.2.2, I introduce the central hypotheses examined in this dissertation.

1.2.1 The declarative/procedural model

According to the declarative/procedural (DP) model, language acquisition depends on brain systems that also subserve other functions (Ullman, 2004). Declarative memory refers to the ability to store and retrieve knowledge related to facts (semantic memory) and events (episodic memory; Riedel & Blokland, 2015), which is responsible for the mental lexicon and word-specific knowledge according to the DP model. In contrast, procedural memory refers to the cognitive and sensorimotor abilities of non-declarative memory that are typically learned through repetition and contain aspects of pattern–response or stimulus–response associations. Procedural memory plays a role in many everyday actions such as typing on a computer keyboard, buttoning up a shirt or walking. The concept of procedural learning is closely related to implicit learning, statistical learning, and sequence learning, and all these concepts might be essentially referring to the same construct. Implicit learning refers to learning without awareness (Batterink et al., 2019), which is often the case in tasks that measure procedural learning. Sequence learning and statistical learning can be seen as two sub-processes of procedural learning (Simor et al., 2019). The term "statistical learning" is defined more broadly as "the ability to extract the statistical properties of sensory input across time or space" (Batterink et al., 2019, p. 2). In turn, sequence learning refers to the "acquisition of probabilistic associations between elements" (Simor et al., 2019, p. 1). The different tasks used to study these constructs may reflect aspects of learning that are partially inseparable (Conway, 2020).

According to the DP model, procedural memory is responsible for the rule-governed aspects of language, such as morphology, phonology, and syntax, and weakness of the procedural system could explain the difficulties related to those aspects of language. In their literature review, Ullman and Pierpont (2005) concluded that a significant proportion of individuals with DLD had abnormalities in the brain structures that support procedural memory and proposed the procedural deficit hypothesis (PDH) to explain individual differences in language development. Subsequently, the DP model and the PDH were supported by findings from several studies, of which many utilized serial-response-time (SRT) tasks as a measure of procedural learning (see Lum et al., 2014). SRT tasks measure visuomotor pattern learning. In a typical SRT task, the participant is presented with stimuli that appear in differing locations. First, the participant is predisposed to a temporal pattern that the stimuli locations follow. They are asked to press a button corresponding to the stimuli locations as quickly as possible. During this phase, their response times (RTs) typically decrease, which is considered to be caused by them having learned the sequence. After this "pattern phase," the participant is presented with a "random phase" that is similar to the pattern phase but with the order of the stimuli locations being randomized. During this random phase, the participant's RTs typically increase. The difference between the RTs in the pattern and random phases, with the latter typically being longer, is thought to reflect the effect of pattern learning as a form of procedural memory.

Recently, the use of SRT tasks for studying procedural learning has received some valid criticism because of the low reliability and sensitivity of these tasks (Krishnan & Watkins, 2019; West et al., 2018, 2021). In Study II, we aim to avoid the common pitfalls in such study designs by analyzing language abilities as a continuum instead of extreme groups (see Section 2.3.2) and considering trial-level data instead of mean aggregates (see Section 2.6). In addition to SRT tasks, other tasks, such as artificial grammar learning (Evans et al., 2009) and probabilistic categorization (Kemény & Lukács, 2010), have been used to study procedural learning in relation to language disorders.

Motor planning can also be seen as a component of procedural memory (see Sanjeevan et al., 2015). Based on earlier experiences of motor activities, and sensory feedback during the movements, the motor sequence is planned beforehand and monitored during the movement. Performing motor activities, such as verbal utterances, reaching for objects, or walking, requires successfully coordinating the timing, movement range, and tension of many different muscles (on motor control, see e.g., Rosenbaum, 2009). Motor planning, as a procedural memory ability, is learned through repetition. An interesting example of motor planning development, known as the “end-state comfort” (ESC) phenomenon (Rosenbaum et al., 1990), is observed when handling objects. If your task is to turn over a mug that is placed upside down on a table, you typically grasp it with a relatively awkward initial grasp with your thumb facing down, which allows you to end the movement with a comfortable “thumb up” grasp. The initial awkward grasp would typically not be used if the aim was just to move the mug and not turn it over. This is considered to reflect the planning of the whole movement sequence before starting, thus minimizing the time spent in the awkward positions. Young children tend to start with a comfortable grasp, which is considered to reflect the stage of motor planning development in which the child is not yet able to plan the whole movement series beforehand. This phenomenon has been studied in the dowel task, which is also known as an ESC task (Rosenbaum et al., 1990), in which the participant is asked to move a dowel from one cup to another. In the task, the target trials require the dowel to be turned over, while the control trials do not require this; the participant is to simply move the dowel from one cup to another. In their study, Sanjeevan et al. (2018) reported that children with DLD were more likely to perseverate in the dowel tasks; although their use of uncomfortable initial positions was comparable to their typically developing peers, children with DLD were more likely to continue using uncomfortable initial grasps in the trials that did not require the dowel to be turned over. The authors interpreted this as evidence of motor-planning difficulties in children with DLD. In Study II, we measured procedural learning in both learning visuomotor sequences (using an SRT task) and motor planning (ESC task). In Study III, we used a sequence predictability manipulation to investigate the procedural learning effect on auditory brain responses.

1.2.2 Capacity theories

Rather than a single theory, capacity theories is an umbrella term for multiple theories that assume language learning is constrained by some form of cognitive capacity. The nature of this capacity varies across these theories. For example, it has been suggested that this capacity could be working memory (e.g., Just & Carpenter, 1992), attention (e.g., Finneran et al., 2009; Larson et al., 2020), general processing speed (Kail, 1994), or auditory processing (e.g., Corriveau et al., 2007; McArthur & Bishop, 2004). While the DP model is based on the distinction between procedural and declarative memory, which include both short- and long-term memory (Ullman, 2004), the capacity theories often use the computer metaphor and distinguish between information processing and storage. Restrictions in different forms of "short-term" processing capacity are thought to regulate the learning of "long-term" abilities, such as language.

1.2.2.1 Attention and inhibition

As a type of capacity, limitations in attention are suggested to degrade language acquisition by making it more demanding to stay focused on language input and ignore distracting information in the environment. Children with weak language abilities have been reported to have difficulties associated with attentional inhibition (the ability to suppress distracting information while focusing on a task; Larson et al., 2020; Marton et al., 2007; Pauls & Archibald, 2016). In Study I, we investigated the participants' ability to suppress distracting stimuli in a visuomotor flanker task (described in Section 3.1). In addition, in Study III, we used a noise manipulation to investigate the effect of this kind of capacity load on low-level auditory brain responses.

1.2.2.2 Auditory processing difficulties

Efficient processing of auditory input is crucial for spoken language acquisition. Some theories on individual differences in language acquisition have suggested that difficulties in learning a language arise from processing-capacity limitations, especially in the auditory modality (for review, see Miller, 2011). Despite having normal peripheral hearing, some children with weak language abilities have been reported to perform worse than their typically developing peers in tasks that require simple decoding of the physical aspects of sounds (see Kujala & Leminen, 2017), to determine the temporal order of rapid auditory stimuli (Tallal & Piercy, 1973), or to engage in dichotic listening, which refers to a binaural test used to measure auditory attention (Asbjørnsen & Helland, 2006). Specifically, difficulties in processing brief, sequential stimuli are suggested to be a possible cause for language disorders, as such quick acoustic transitions are a characteristic of phonemes in speech (Tallal & Piercy, 1975). Certain studies suggest that difficulties associated with auditory processing are only observed in a subgroup of children with DLD (Bishop & McArthur, 2005). Further, as many tasks used for studying auditory processing contain elements of other cognitive abilities, such as attention, processing speed, or working memory, it remains unclear whether the difficulties are specific to auditory processing or can also be observed in other sensory modalities. In Study III, we examined low-level involuntary brain responses to auditory stimuli, allowing us to investigate the relationship between auditory processing and language abilities.

1.2.2.3 Generalized slowing

According to Kail (1994), language-learning difficulties could be explained by domain-general slowness in processing, which could degrade language acquisition. Slowness in performance related to weak language abilities has been reported in a range of tasks—both linguistic and non-linguistic (for a meta-analysis, see Zapparrata et al., 2023)—and atypically long latencies in auditory brain responses have also been observed in children with DLD (see Kujala & Leminen, 2017). Spoken language as a signal is rapidly changing, and, therefore, language acquisition is suggested to be especially vulnerable to slowness in processing. Children with DLD have been reported to perform worse than their typically developing peers in tasks that require rapid auditory processing (Tallal & Piercy, 1975). Kail (1994) suggests that the processing slowness in participants with weak language abilities is observed across a range of varying tasks and, thus, reflects a general slowness in cognitive processing across modalities. Such slowness in processing language inputs results in slower rates of language learning and restrictions in language abilities. The RT data from Studies I and II enabled the investigation of language abilities in relation to visuomotor processing speeds.

1.2.2.4 Intra-individual variability

Studies I–III were designed to measure aspects of procedural learning and forms of capacity (attentional inhibition, auditory processing, and processing speed) in relation to language abilities. Similar to almost all RT studies on language abilities, Studies I and II focused on RT length when measuring the aforementioned dimensions of processing. However, in addition to distribution location (the length of the RTs), distribution shape can also reveal individual differences in cognitive processes (Balota & Yap, 2011; Kofler et al., 2013; Marmolejo-Ramos et al., 2023).

An ex-gaussian distribution is commonly used in studies on the intra-individual variability (IIV) in RTs. This distribution can be defined by three parameters: mu (location), sigma (dispersion), and tau (right skew). The distribution mean can be calculated as the sum of the parameters mu and tau. The ex-gaussian parameters mu and sigma are typically correlated. Mu is often associated with manipulations of task complexity (Matzke & Wagenmakers, 2009): increases in task demands increasing RTs overall. Hence, in studies on population-level effects, mu alone might be informative, as the between-participant differences in these studies are a nuisance and not a phenomenon of interest. However, sometimes, the effects of interest, such as differences in RTs between conditions, can be greatest in the fastest (e.g., the Simon task) or slowest (e.g., the Stroop task) responses (Castel et al., 2007; Pratte et al., 2010).

In studies that focus on individual differences instead of the effect of a task itself, the distribution dispersion and shape become more interesting. While mu is strongly associated with task demands, tau is thought to reflect individual differences and is relatively stable for an individual during different tasks (Balota & Yap, 2011). Pronounced right skews in RT distributions, which are reflected by an exponentially modified gaussian parameter tau, or overall increased IIV in RTs, such as standard deviations (*SD*s), have been linked to working memory and intelligence (Schmiedek et al., 2007), ADHD (for review, see Kofler et al., 2013), cognitive decline, neuropathology, and even mortality (for review, see Haynes et al., 2017). In Study IV, we studied IIV in RTs in relation to language abilities to investigate whether RT inconsistencies, in addition to processing speeds (see Section 1.2.2.3), were associated with individual differences in language abilities.

2 Research questions, data, and methodological considerations

2.1 Aims of the study

In this thesis, I aimed to enhance our understanding of the mechanisms that govern individual differences in language acquisition and to seek potential predictors for language development in children with and without a history of LT. By compiling the findings from Studies I–IV (summarized in Section 3), I attempted to draw conclusions regarding the interactions and commonalities between the various factors that have been suggested to contribute to language development (see Section 1.2).

2.2 Participants

The participants for all four studies included in this thesis were the same and were recruited from the Southwestern Birth Cohort Study (Lagström et al., 2012). The cohort included 9,936 children, 1,827 of whom participated in follow-up studies. Studies I–IV of this thesis were a part of the cohort study ("NeuroTalk" project). Both NeuroTalk and the cohort study were approved by the ethics committee of the Hospital District of Southwest Finland.

All NeuroTalk participants (*n* = 79) completed at least three behavioral-data-collection sessions, and most also participated in a fourth visit to provide electroencephalography (EEG) data. In addition to the study visits for the data collection for NeuroTalk, the participants had also completed at least one of the following early-language measures at an earlier stage of the cohort study: the MacArthur-Bates Communicative Development Inventories (Fenson et al., 2007; 24 months), the Fox Language Inventory (Korpilahti & Eilomaa, 2002; 36 months), the Renfrew Word Finding Vocabulary Test (Renfrew, 1995; 36 months), and the Reynell Developmental Language Scales III (Edwards et al., 2001). Two children were recruited from outside the cohort study and, thus, the aforementioned early-language measures were not available for them. However, their history of LT was confirmed through an assessment by a speech-language pathologist at the age of two or three

All participants were required to come from a household where Finnish was spoken, normal hearing according to a pure-tone audiometry screening and parent reporting, no obvious motor, behavioral, emotional, or neurological disabilities, and a performance reasoning index (PRI) of over 70, measured by the Wechsler Intelligence Scale for Children (WISC; Wechsler, 2003). Data of two children were excluded based on the PRI criterion.

2.3 Direct language measures

2.3.1 History of late talking

The participants' history of LT was defined by one or more of the following criteria: a performance of below -1.25 SD from the population mean in (1) the MacArthur-Bates Communicative Develop Inventories (Fenson et al., 2007) expressive vocabulary at 24 months; (2) the Fox Language Inventory (Korpilahti & Eilomaa, 2002), which is a screening instrument executed by a clinical nurse at 36 months; (3) the Renfrew Word Finding Vocabulary test (Renfrew, 1995) at 36 months, or (4) speech-language service delivery before the age of four and confirmation of LT status by a speech-language pathologist. The children with TED performed in line with the relevant age expectations in measures 1–3, the data for which were available from the earlier stages of the study, and had no history of LT or speech-language intervention according to their parents. A comparison of the demographic measures and standardized tests of LT and TED children is presented in Table 1.

2.3.2 School-age language abilities

The participants' school-age language status was measured using standardized tests. In order to obtain a versatile but brief measure of their overall language abilities, we formulated a language index that was a mean of three standardized subtests: WISC-IV Vocabulary (Wechsler, 2003), NEPSY-II Comprehension of Instructions, and NEPSY-II Narrative Memory (Korkman et al., 2007). Since we were interested in determining how overall language performance was related to different aspects of cognition, this was a suitable outcome variable to be modelled at the group level. The tasks themselves were validated and standardized for assessing the participants' performance in terms of language and verbal memory.

Table 1. Participants' demographic information and performance on standardized tests, *p*-values from two sample *t*-tests between the groups (chi-square goodness of fit test for SES). Participants wit PRI <70 (n = 2) excluded.

	HISTORY OF LATE TALKING (N = 41)	**TYPICAL EARLY DEVELOPMENT (N = 36)**	***P*-VALUE**
AGE (MONTHS)			.099
MEAN (*SD*)	109.73 (10.18)	106.31 (7.35)	
RANGE	89 - 125	93 - 122	
PRI[1]			.099
MEAN (*SD*)	100.39 (16.70)	107.11 (18.59)	
RANGE	71 - 131	71 - 140	
SES[2]			.080
1 LOW	11 (26.8%)	9 (25.0%)	
2 MEDIUM	20 (48.8%)	10 (27.8%)	
3 HIGH	10 (24.4%)	17 (47.2%)	
LANGUAGE INDEX[3]			.003
MEAN (*SD*)	8.19 (2.70)	10.06 (2.71)	
BELOW -1.25 *SD* (DLD)	n = 11 (26.8%)	n = 4 (11.1%)	
RANGE	3.67 - 13.67	5.00 - 14.67	
COMPREHENSION OF INSTRUCTIONS[4]			.011
MEAN (*SD*)	9.32 (2.85)	11.19 (3.50)	
RANGE	3 - 15	1 - 15	
NARRATIVE MEMORY[5]			.025
MEAN (*SD*)	6.46 (4.35)	8.67 (4.07)	
RANGE	1 - 15	1 - 15	
VOCABULARY[6]			.075
MEAN (*SD*)	8.78 (3.92)	10.31 (3.41)	
RANGE	1 - 16	1 - 18	

[1] Performance Reasoning Index measured by WISC-IV
[2] Socio-economic status, measured by maternal education level on scale 1–3
[3] Mean of three subtests (vocabulary, comprehension of instructions, and narrative memory)
[4] NEPSY-II Comprehension of instructions subtest
[5] NEPSY-II Narrative memory subtest
[6] WISC-IV Vocabulary subtest

2.4 Response times

Response time (RT) can be a valuable metric for discerning components of behavioral performance, especially when it is implemented within rigorous experimental designs. It can uncover performance differences both within and between individuals as well as across trials of successfully completed tasks. This approach is practical because differences in language abilities could be attributed more to differences in processing efficiency than those in language knowledge, particularly after early childhood (McMurray et al., 2022); hence, it may be possible to observe these differences using the length of the RTs (which reflect processing efficiency) when the proportion of correct answers (which denote knowledge) between the participants are similar. The shape of the RT distribution is typically right-skewed (e.g., Ratcliff, 1979) and can be effectively captured by an exponentially modified gaussian (ex-gaussian) or inverse gaussian distribution (Figure 1). Log transformations are also widely used to normalize RT distributions, as distribution normality is an assumption for many statistical models. Measuring a reliable RT requires the collection of data from a sufficient number of trials. Usually, this is not a problem since measuring RTs is a relatively straightforward process using a computer, and the presenting stimuli rarely take a long time or a large amount of effort.

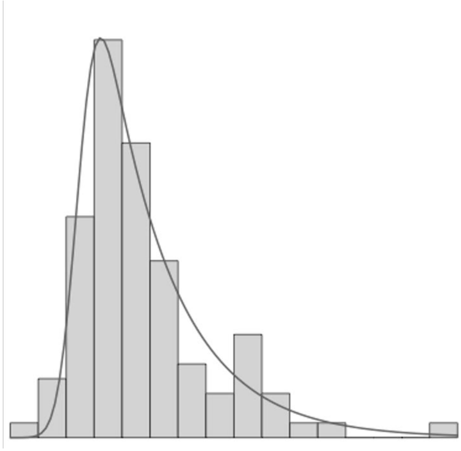

Figure 1. Example of the typical shape of an RT distribution with a fitted exponentially modified gaussian distribution (red curve)

In experimental studies, the RTs of participants across different conditions can be compared to measure the targeted effect of interest. The magnitude of the effect of interest in these tasks varies, for instance, based on the stimulus properties, vigilance, and task complexity (see Kosinski, 2008, for review). Individual differences in skills, expertise, age, and motivation, among other factors, may also affect RTs (see Kosinski, 2008, for review). Thus, RTs have been utilized in studies on individual differences. The magnitude of individual RTs in many tasks is measured in hundreds of milliseconds, while the effects of interest are measured in tens of milliseconds (Rouder et al., 2023). Within-participant variation is typically greater than the effect of interest, which emphasizes the importance of the reliability of RT measures.

Studies that utilize RT measures often focus on the means or other estimates of the central tendency (see, e.g., Balota & Yap, 2011). Studies I and II were structured according to traditional RT-difference designs, but instead of individual RT means, all the measured RTs for each participant were used for fitting the statistical models. However, even generalized linear mixed models that account for differences between individuals in RT estimates and can fit distributions other than the normal distribution (such as inverse gaussian or exponentially modified gaussian) in RTs (e.g., Bates et al., 2015) calculate estimates of central tendency. Although methods for calculating the parameters of individual distribution shapes have been known for decades (e.g., Ratcliff, 1979), these measures are still often ignored in studies on individual differences. One possible reason for this might be that fitting RT distributions has been thought to be methodologically challenging. However, well-documented existing software libraries (e.g., fitdistrpus for R, Delignette-Muller & Dutang, 2015) actually make the distribution fitting rather simple and quick to perform. In Study IV, we utilized the distribution fitting methodology to investigate the IIV of RTs in relation to language abilities.

2.5 Electroencephalography and event-related potentials

Electroencephalography (EEG) is a technique used to monitor brain activity. Owing to its high temporal accuracy and relatively low demands with respect to participants' co-operation, EEG is a widely used method for studying language-related phenomena even in children. The event-related-potential (ERP) technique allows the measurement of brain responses to specific events or stimuli. ERPs are characterized by a series of voltage fluctuations (ERP components) that occur in response to specific sensory, cognitive, or motor events. Analyzing these components provides a tool to investigate the processes and mechanisms underlying functions such as perception, attention, and language processing (Swaab et al., 2012). The names of the ERP components include information about their polarity (positive or negative) and either their order (e.g., P1 and N2) or timing (e.g., P300 and N400). The latency, amplitude, and polarity of these components change during childhood, which is thought to denote brain maturation (e.g., Kihara et al., 2010). ERP study designs allow researchers to study brain processes for various sensory modalities, of which we studied procedural learning and the aspects of capacity load in the auditory modality (Study III) to investigate whether the phenomena observed during visuomotor tasks (such as those used in Studies I and II), which require participants to actively focus on stimuli and responses, would also be observed in passive, auditory contexts.

Mismatch negativity (MMN; Näätänen, 1992) is an ERP component that reflects the processing of a change or "mismatch" in a sequence of sensory stimuli. MMN reflects the difference in ERPs in relation to regularly occurring standard stimuli and unexpected deviant stimuli. It is an automatic response, meaning that it does not require conscious effort to be elicited, which makes it a valuable measure for studying young children or other special populations that might face challenges associated with collaboration. It occurs at approximately 100–250 milliseconds from the onset of the deviance and is considered to reflect the pre-attentive processing of the physical features of a stimulus. MMN studies have reported differences in low-level auditory processing between children who have language-related difficulties and their typically developing peers, including smaller response amplitudes or longer latencies (for review, see Kujala & Leminen, 2017). Study III involved the investigation of MMN responses to frequency contrasts in relation to language abilities.

2.6 Statistical methods

The variables of school-age language abilities and LT were the same in all studies included in this thesis. The school-age language abilities were measured as a continuous variable instead of being divided into categories of typical and atypical (see Section 2.3.2). LT was used as a categorical variable because of its binary nature in participant recruiting, targeting children with a history of LT or TED (see Section 2.3.1). These participant-related variables were used as predictors in statistical models in Studies I–III, as we wanted to account for the nested nature of the multiple observations per participant in the experimental tasks and ERP recordings with random structures. Our measurements of RTs and ERPs included hundreds of observations per participant and task. We did not aggregate these measures for participant means because we wanted our models to account for the information on within-individual variation obtainable from these measures. This approach results in more accurate estimates and confidence intervals compared to the commonly used approach of aggregating data to measures of central tendencies (see Rouder & Haaf, 2019).

3 Overview of the studies

3.1 Study I

Several studies have reported associations between aspects of attention and language abilities (see Section 1.2.2.1). Most of the earlier studies have been conducted by comparing groups of children with and without DLD. In Study I, our objective was to examine the relationship of attentional inhibition with school-age language outcomes for children with and without a history of LT. We also sought to investigate the support for two opposing accounts of LT—dimensional and categorical (see Section 1.1.3)—and examine whether our findings would be affected by our choice of IQ exclusion criteria based either on the SLI definition (stringent cut-off criteria; PRI of less than 85) or the DLD definition (loose cut-off criteria; PRI of less than 70).

The participants consisted of 73 children from the NeuroTalk project (LT *n* = 38; see Section 2.3.1 for LT definition). They completed a flanker task designed to measure attentional inhibition (Rueda et al., 2004). The task was a part of the Attentional networks test (ANT) which has been designed to measure three different aspects of attention: orienting, alerting, and inhibition (which is also referred to as conflict resolving or executive attention). It involved five fish stimuli, and each child was instructed to focus on the middle fish. Once the stimuli appeared on the computer screen, they were required to press the button that corresponded with the direction in which the middle fish was swimming. Half of the trials were congruent, meaning that all five fish were swimming in the same direction, and half were incongruent, where the middle fish was swimming in a direction opposite to that of the other four fish. The difference between the RTs for the congruent and incongruent trials was used as a measure of inhibition. Typically, the RTs in this task are longer in the incongruent trials, which is thought to reflect the effect of inhibition. This effect was studied in relation to the language abilities measured using standardized tests (see Section 2.3.2). The RT, as a response variable, was log-transformed to allow the fitting of a linear mixed-effects model with an assumption of response variable distribution normality. We also fitted random effects to account for within-participant variation in RTs across trial types.

We hypothesized that the effect of inhibition would be greater the weaker the child's language abilities were. In line with the dimensional accounts of LT, we also hypothesized that children with TED would have stronger inhibition skills (smaller flanker effect) compared to the LT group. This was not the case, as the inhibition measured by the flanker effect was found to not be associated with school-age language abilities or LT. However, we observed a primary effect of school-age language abilities on RTs in general, which suggested that children with stronger language abilities had shorter overall RTs. No significant differences were observed in the RTs of children with and without a history of LT. This suggested that different mechanisms may govern persistent language difficulties and LT. All results were essentially the same despite the choice of the IQ exclusion criteria (stringent vs. loose). Based on our findings, we concluded that slow processing was associated with weak language abilities to support the capacity theory of generalized slowing, with processing speed possibly explaining individual differences in language development.

3.2 Study II

In Study I, we investigated one suggested mechanism that could explain individual differences in language development: attentional inhibition. In Study II, we focused on another suggested mechanism, namely procedural learning (see Section 1.2.1), in relation to school-age language abilities and a history of LT. The participants were the same as those in Study I: 79 children, 43 of whom had a history of LT. Further details about the LT definition, demographic information, and standardized measures for school-age language abilities have been described in Section 2.3.1 and 2.3.2.

The participants completed two tasks that reflect the different forms of procedural learning: a visuomotor SRT task (see Section 1.2.1), designed to measure pattern learning, and an ESC task (see Section 1.2.1), designed to measure motor planning (see Rosenbaum et al., 1990). These effects of procedural learning were studied in relation to language abilities. The language abilities were measured using standardized tests (see Section 2.3.2). We utilized a linear mixed-effects model with log-transformed RTs as a dependent variable and a generalized linear mixed-effects model with binomial distribution to fit a model with a binary response variable (the ESC task). In both models, the within-participant variation between the task trials was measured by a random effects term.

For our SRT task, each participant was presented with four adjacent empty boxes. During the task, a small creature would appear in one of the boxes. The participant was asked to press a button corresponding to the creature location as soon as possible after its appearance. The task consisted of three phases with 100 stimuli each. The first two phases were the so-called pattern phases, in which the location where the creature appeared followed a certain pattern that the participant was unaware of. In the third phase, the location at which the creature appeared was randomized and did not follow any pattern. The pattern learning was measured by two effects: first, the decrease in RTs during the first two phases and, second, the increase in RTs in the third phase when the stimulus location no longer followed a pattern.

The materials used for the ESC task consisted of three cups, labelled “1,” “home,” and “2” from left to right, and a dowel (23 cm long, 5 cm in diameter, with one end colored black and the other green). During the task, the participant was asked to move the dowel from one cup to another. At the beginning of each trial, the dowel was placed in the “home” cup in the middle. The instructions for the task were simple: “Move the black/green end of the dowel to cup one/two.” The task consisted of 16 trials; half of these were the so-called target trials, wherein the participant was required to turn the dowel over, while the other half were the control trials, where the dowel did not have to be turned over. The participants’ grasps during the target trials—specifically, the proportion of initial awkward grasps (“thumb down”), which resulted in a comfortable (“thumb up”) grasp at the end of the movement sequence—were studied. The use of these awkward initial grasps was considered to reflect motor planning, implying that the participant had already planned the entire movement series before beginning the motor action. Previous studies have suggested that the level of motor planning is reflected by the proportion of these initial awkward grasps (Rosenbaum et al., 1990).

In line with the DP model and PDH (see Section 1.2.1), we hypothesized that there was a relationship between better language abilities and (1) a higher proportion of initial awkward grasps in the ESC task and (2) larger effects of pattern learning in SRT, which were calculated based on the RT decrease during the pattern phases and the RT increase during the random phase. We also hypothesized that TED children would outperform LT children in these measures. Contrary to our hypothesis, the participants’ performance in the ESC task was not related to the measures of language. However, as expected, the children with better language abilities had larger effects of pattern learning in the SRT task. Children with and without a history of LT did not differ from each other in the way we expected: children with a history of LT even had slightly greater RT increases from the end of the pattern phases to the beginning of the random phase than those with TED. Interestingly, the relationship between school-age language abilities and the measures of pattern learning was found to be modulated by the history of LT such that this relationship was observed in children with TED but not in the LT group. Based on our findings, we concluded that procedural learning is a promising predictor of language abilities in children with TED but not in those with a history of LT.

3.3 Study III

In Study III, we investigated the relationship of auditory processing and procedural learning with language abilities using an EEG paradigm. We chose to use a passive auditory paradigm as an alternative method for studying pattern learning (as a form of procedural learning) to shed light on the role of the visual, attentional, and motor aspects that likely affected the results obtained in Study II and other studies that have used similar methods for measuring procedural learning. The paradigm was designed such that we could also measure the effect of noise on auditory processing. We hypothesized that this manipulation would reflect the effect of an increased capacity load on auditory processing. The participants of this study were the same as those in Studies I and II. We aimed to investigate whether procedural learning in the auditory modality, without a component of motor response, could be associated with language abilities or a history of LT. Furthermore, we aimed to investigate the effect of noise on low-level auditory processing.

We used a passive auditory ERP paradigm to measure MMN to sine tone contrasts (see Section 2.5 for a description of the ERP and MMN methodology). To measure procedural learning, we manipulated the predictability of the deviant stimuli while keeping the probability constant using a paradigm by Lecaignard et al. (2015). In this paradigm, the occurrence of the deviant stimuli was either unpredictable (pseudorandom) or predictable in a way that the order of the stimuli followed a repeating pattern, with an increasing number of standard stimuli in between the deviants (1–8 standard stimuli between the deviants). We also manipulated the demands in terms of auditory processing by adding noise to half of the experimental blocks. We investigated whether the effects of procedural learning and the increased auditory-processing demands (noise) on MMN would be associated with language abilities or a history of LT.

We modelled ERP amplitudes on a single trial level (i.e., 1,712–2,606 trials per participant) as a function of experimental manipulations (MMN, noise, and predictability) and individual factors (history of LT and language abilities) using a linear mixed-effect model with the individual effects of ERP magnitude and MMN as the random factors. Contrary to our expectations, the effect of predictability on MMN was not observed in our sample. Consequently, we were not able to investigate the relationship between language abilities or LT and the effect of predictability. The noise decreased the overall ERP amplitudes, but its effect was not found to be related to the stimulus type (standard vs. deviant, i.e., MMN), language abilities, or a history of LT. However, the ERP amplitudes in the MMN-based time window (150–250 ms after stimulus onset) and a post hoc P1 time window (75–175 ms) were found to be associated with language abilities, in that children with stronger language abilities presented a smaller positive P1 amplitude and a larger negative amplitude in the MMN-based time window compared to their peers with weaker language abilities.

A post hoc model that used the participant's age as a predictor suggested that the P1 amplitude was associated with the participant's age in a similar manner as their language abilities.

Smaller P1 amplitudes for children with better language abilities or a higher age might indicate the automatization of the processing of the physical properties of the stimuli, thus enabling effective auditory processing in the following stages, which was reflected by stronger ERP responses in the MMN-based time window. Based on our findings, we concluded that individual differences in language abilities were associated with low-level auditory processing, which could possibly be related to more mature auditory processing in children with stronger language abilities compared to those with weaker ones.

3.4 Study IV

Despite their obvious advantages, RT studies, such as Studies I and II, also have some limitations (see Section 1.1.2.4. and 2.4). The IIV in RTs is relatively large, and it is important to understand that increasing the number of trials per participant decreases RT variation only to a certain point, after which the distribution becomes rather stabile for a participant and task. Individual variations in within-participant RTs have often been disregarded in research by calculating individual mean RTs. In addition to processing speed (see Section 1.2.2.3 on the generalized slowing hypothesis), the inconsistency in timing, which is measured using the IIV of RTs (Section 1.2.2.4), is likely important for perceiving spoken language and could potentially be related to individual differences in language abilities.

In this fourth study, we examined the relationship between the within-individual variation in RTs and language abilities. We reanalyzed the RT data from Studies I (ANT task) and II (SRT task), in which we had found longer RTs to be associated with language abilities, and we sought to investigate whether increased IIV in cognitive performance, as reflected by RT fluctuations (see Section 1.2.2.4), would be associated with weak language abilities. Comparisons between the LT and TED groups were omitted from this study, as we did not observe any meaningful effects related to the presenting of a history of LT in the original studies (summarized in Section 3.1 and 3.2) and wanted to keep the statistical models in this brief research-note-type article as simple as possible.

We first modelled language abilities as a function of RT *SD*s with a linear regression model. High RT *SD*s were associated with low language abilities, as expected, especially in the SRT task. As both dispersion and skewness can be denoted by increased RT *SD*s, we continued to investigate whether the observed relationship is associated with the dispersion or skewness of the RT distributions. To compare distribution shapes across participants, we fitted an exponentially modified gaussian (ex-gaussian) distribution for each participant's data from separate subtasks (ANT congruent and incongruent trials and the three phases of the SRT task). This resulted in the individual measures of mu (location), sigma (dispersion), and tau (right skew). The linear mixed-effects models indicated an association between the pronounced proportion of exceptionally long RTs (ex-gaussian tau) in the SRT task and weak language abilities. However, the association between tau and language abilities was found to be insignificant in the ANT task, which could potentially be due to the lower reliability of the parameter estimates given the small number of trials in the ANT compared to the SRT task. We employed random forest models to further compare the relative variable importance of the ex-gaussian parameters for predicting language abilities. For the ANT data, the random forest model failed to accurately predict language abilities from the RT parameters; this could be due to the aforementioned low trial counts resulting in the lower reliability of the parameter estimates in the ANT compared to the SRT data. The random forest model for the SRT data revealed that tau was a more important predictor for language abilities than the other ex-gaussian parameters; this suggests that IIV may predict language abilities better than response slowness, which has been associated with language abilities in studies that support the generalized slowing hypothesis (Kail, 1994).

Based on our findings, we proposed an IIV hypothesis to explain individual differences in language development. We suggested that the observed IIV in RTs reflects inconsistency in processing linguistic inputs, which degrades language acquisition and underlies the individual differences in language abilities. The more instable the processing is, the more exposure to language is needed to construct a mental model of its regularities. A somewhat similar hypothesis in the context of dyslexia proposes that neural noise originating from increased neural excitability in cortical networks contributes to reading difficulties (Hancock et al., 2017). I posit that this mechanism might also underlie certain observations that are interpreted as evidence for other theories regarding individual differences in language (see Section 1.2), which I further discuss in Section 4.1.2.

4 Discussion and conclusions

4.1 Domain-general mechanisms underlying individual differences in language abilities

The four articles of this thesis investigated aspects of domain-general, non-linguistic processing in relation to language abilities. While the origins of individual differences remain unknown, evidence of phenomena related to language sheds light on the possible mechanisms that govern these differences. In the subsequent chapters, I summarize the findings of these studies and aim to integrate the seemingly divergent research findings and proposed theories to explain individual differences in language acquisition. Finally, I provide some suggestions for researchers trying to address unanswered questions regarding language development and try to outline some practical implications of my work for people living and working with children with varying language abilities.

4.1.1 Explaining school-age language abilities

4.1.1.1 The declarative/procedural model

Studies II and III were designed to analyze aspects of procedural learning in relation to language abilities. In Study II, participants with weaker language abilities showed smaller SRT task effects, indicating poorer procedural learning than children with better language abilities. However, this effect was only significant in children with a history of TED, not LT. One possible explanation for this, according to the DP model (Ullman, 2004), is that the definition of LT relies more on the language abilities related to the declarative memory system (the lexicon) and measures of school-age language abilities for procedural memory (structural aspects of language), which results in overlapping effects in the LT group. This is because, for some of the participants, the possible difficulties related to language abilities may be more related to the declarative aspects of language, thus partly masking the possible relationship between pattern learning and school-age language abilities. In Study IV, the effect of pattern learning on ERPs was not observed on the sample level, indicating that the study design was not suitable for studying individual differences in procedural learning. Hence, it was not surprising that we did not observe any differences in pattern learning in relation to language abilities.

With regard to the findings of the SRT task effects from Study II (see Section 1.2.1 and 3.2), I would like to offer up a small self-critical remark: observing the SRT effect on the sample level required using sustained attention correction (described in Study II; technical details reported in the supplementary material of the article) that was based on an assumption about the nature of the RT increase during task phases (suggested to reflect a decrease in sustained attention during the task and corrected accordingly on the sample level), which could not be explicitly tested using our data. However, the individual differences we observed were not affected by this correction, as it was performed similarly for all participants. That being said, the SRT task is generally not optimal for studying individual differences and has been suggested to lack both reliability and sensitivity (Krishnan & Watkins, 2019; West et al., 2018, 2021; also see Section 4.3), and, overall, statistical learning and language abilities have been suggested to only be weakly correlated (Boeve et al., 2023). In conclusion, we found some evidence supporting the DP model and PDH, but the differences in procedural memory can only explain a small part of the between-individual variance in language abilities.

4.1.1.2 Capacity theories

Studies I–IV investigated forms of processing capacity in relation to language abilities. *Attentional inhibition*, measured by the congruency effect in the flanker task (Study I), was observed at the group level but, contrary to our hypothesis, was not associated with language abilities. Similarly, the noise manipulation (Study III), which can also be seen as a type of capacity load for attentional inhibition, was not found to be related to language abilities.

However, we observed differences in *auditory processing* in relation to language abilities in the form of low-level auditory ERPs to sine tones in the P1 time window (75–175 ms from stimulus onset). These effects were related to processing simple tones in general. The processing of auditory contrasts (differences between the responses to frequent vs. novel stimuli, which are reflected by the MMN) was not found to be related to language abilities. However, weaker P1 responses and stronger overall negative responses in the MMN-based time window (150–250 ms) were found to be associated with stronger language abilities. Further, weaker P1 responses were also observed to older age within the sample, which we considered to possibly reflect the maturation and automatization of early auditory processing. These findings could be interpreted as evidence for auditory processing accounts on language (see Section 1.2.2.2) and suggest that the differences in processing even the low-level physical features of auditory inputs may explain individual differences in language acquisition. Our findings are in line with those of Bishop and McArthur (2005), who reported that ERP amplitudes to sine tones in a subgroup of children with DLD resembled those of younger typically developing participants.

RT length as a measure of *generalized slowing* was analyzed in Studies I and II, in which longer overall RTs were associated with weaker language abilities, as hypothesized. However, further examination of the RT data from these studies (Study IV) suggested that RT IIV was an even stronger predictor for language abilities than RT length. Accordingly, we presented *the IIV hypothesis* of individual differences in language acquisition, suggesting that differences in the stability of processing could underlie individual differences in language abilities. According to the IIV hypothesis, children with instable processing need more repetitions to learn different aspects of language. While our hypothesis remains to be verified, it provides a suggestion for a framework that could integrate findings that are seemingly independent of each other, which is further discussed in the next chapter.

4.1.2 One mechanism or many factors?

Leo Tolstoy's novel *Anna Karenina* begins with the following well-known words: "All happy families are alike; each unhappy family is unhappy in its own way" (Tolstoy, 1875–1877/1998). The so-called Anna Karenina principle, which implies that success in something favorable requires certain attributes and that lacking any of these attributes can cause failure, has been applied to several fields of research—from economics to microbiology (e.g., Baur, 2022; Bornmann & Marx, 2012; Zaneveld et al., 2017). This principle also effectively characterizes how I would summarize the origins of individual differences in language acquisition both in light of the studies included in this dissertation and earlier research in the field: there are many prerequisites for successful and effortless language development (see Section 1.1). Failure in relation to any of these prerequisites can result in degraded language acquisition. As mentioned in the previous chapter, the findings from Studies I–IV support the different theories used to explain individual differences in language acquisition (see Section 1.2), and these theories do not rule each other out. However, some of these observations might share a common background, as the factors suggested to account for between-individual variation in language development do not develop in isolation from each other. In the following sections, I review our findings from the perspective of IIV as a candidate for a shared mechanism that explains the findings from many earlier studies, including Studies I–III of this thesis.

At least two possible mechanisms could explain the generalized slowing and IIV hypotheses being different manifestations of the same phenomenon. First, the methods used for studying RTs, especially the aggregating measures of RTs to individual means (see Section 3.4), may have resulted in interpreting the IIV in RTs as evidence for longer RTs. Although trial-level statistical modelling allows us to account for the within-individual variation in RTs, these models still focus on the measures of central tendencies (RT length), as IIV is not explicitly examined but rather controlled for as some sort of measurement error, including noise. Interpreting the IIV in RTs as slowness could occur, especially for participants with a pronounced "tail" component in their RT distributions, which is often the case for those with weak language abilities. Figure 2 visualizes two distributions with the same mean and *SD* but different shapes. It is also worth noting that RT length and dispersion (central tendency measure and the *SD* or exponentially modified gaussian parameter sigma) are typically somewhat correlated and, thus, partly include the same information. However, different relationships of the two with various abilities suggest that distinguishing between the two can reveal different aspects of information processing (e.g., Balota & Yap, 2011). While most previous studies have focused on RT length and examined the central tendency measures, Study IV suggests that measures of IIV may carry even more information about the underlying processes and, therefore, serve as a better predictor. In Studies I and II, we found slower RTs to be associated with weaker language abilities. However, in Study IV, further analysis of the same data using the variable importance comparison of a

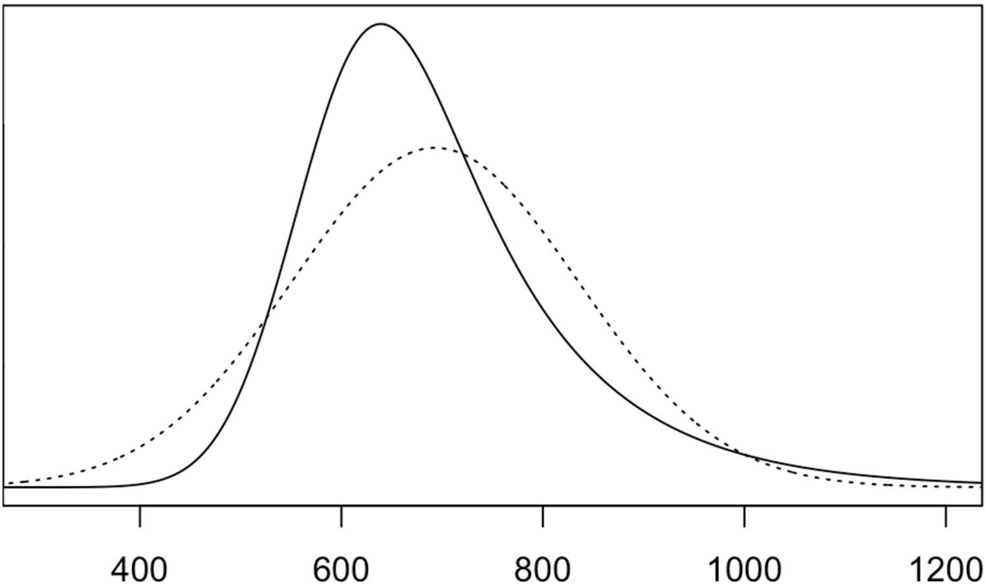

Figure 2: Exponentially modified gaussian (solid line) and normal (dotted line) distributions with the same mean and standard deviation. Note that the normal distribution is a special case of the exponentially modified gaussian distribution with tau = 0.

random forest model suggested that RT dispersion, especially for the exponentially modified gaussian parameter tau that reflects the proportion of unusually slow responses, is an even stronger predictor for language abilities than RT length.

According to the DP model and PDH, children with weak language abilities have deficits with regard to learning regularities. As language is heavily based on statistical probabilities (see Section 1.2.1), it would not be surprising to see difficulties in this form of learning if the input becomes "noisy" because of the neural processes themselves. Our observations of weaker pattern learning in participants with weaker (as opposed to stronger) language abilities (Study II) may stem from pronounced IIV in processing, which could hinder the learning of the sequence in an SRT task. If the processing of the statistical regularities varies considerably within the task, more exposure to the sequences is needed to identify the embedded patterns. Findings from SRT studies suggest that children with DLD perform worse than their typically developing peers in tasks with brief exposures to pattern sequences, but the differences between the groups decrease if the exposure to stimuli is increased (Lum et al., 2014). This makes sense in light of the IIV hypothesis, according to which individuals with large IIV need many repetitions to learn the statistical probabilities of the environment.

Auditory processing deficits might also not be specific to the auditory modality. In Study III, we investigated the ERP amplitudes in relation to language abilities; but in the context of the IIV hypothesis, it would also be important to investigate whether trial-level response latencies have high IIV in relation to weak language abilities. This kind of a finding would support our hypothesis regarding the IIV in RTs reflecting instability in terms of processing. While we do not suggest a specific locus for processing inconsistency, early ERP responses, which are thought to reflect the processing of the physical features of sound stimuli, could help verify whether the IIV in relation to language is observed at the sensory processing level. For example, differences in brain oscillations have been reported to be related to language abilities (Stanojević et al., 2023). This may also affect the observed differences in ERPs that are caused by differences in, for instance, the alpha phase reset (Hanslmayr et al., 2006).

The origins of the IIV in RTs has been theorized to be caused by variability either in information processing or response caution (van Maanen et al., 2011). Response caution refers to the amount of information required to make a decision. The lower the response caution is, the lesser the amount of information that is needed for decision-making (i.e., giving a response, such as a button press in a task such as the ANT or SRT). Increased IIV has been linked to lower neural integrity (Haynes et al., 2017; Lin et al., 2014); yet, it remains unknown whether this would be a cause, correlate, or consequence of IIV. Abnormalities in the brain's default-mode network have been linked to ADHD (Kelly et al., 2008), which is a condition associated with increased IIV (Kofler et al., 2013). The default-mode network is typically activated during wakeful rest, when the person is not focused on a task (Raichle, 2015). Sonuga-Barke and Castellanos (2007) have presented a hypothesis suggesting that performance variability in ADHD stems from default-mode network interference during a task. The proportion of exceptionally long RTs (reflected by the ex-gaussian parameter tau) has also been suggested to reflect attentional lapses during task performance (Hervey et al., 2006). Based on the findings from a study on the simultaneous registration of motor RTs and single-trial visual ERPs, Ribeiro et al. (2016) suggest that fluctuations in sensory processing seem to underlie RT variability. I suggest that the IIV hypothesis provides future studies with a fruitful starting point to investigate the links between brain-level phenomena and behavior.

Language acquisition requires the effective functioning of different areas of the sensory systems and cognition as well as favorable environmental conditions (such as exposure to language input). Difficulties related to different independent components of language acquisition may accumulate, resulting in restrictions in language abilities. I suggest that the observations interpreted as evidence for alternative theories on individual differences in language acquisition (see Section 1.2), including our findings from Studies I–III, could share a common background of instability in processing, which is reflected by the IIV in RTs (Study IV) and could themselves be interpreted as symptoms of the mechanism that underlies individual differences in language acquisition. However, I do not yet have evidence to prove this based on our studies or existing literature. To investigate this, I suggest some future directions for research in Section 4.3.

4.2 Cognitive processes in children with and without a history of late talking

One of the aims in Studies I–III was to investigate whether we could find attention, procedural learning, or aspects of auditory processing to be associated with a history of LT. We did not observe any hypothesized or other clearly interpretable differences between LT and TED children in the areas of information processing considered in Studies I–III. Children with a history of LT even performed a bit better than the TED children in the SRT task, indicated by a slightly larger task effect and shorter overall RTs (Study II), and had marginally larger MMNs to sine tone contrasts (Study III). However, this could be due to the children in the LT group being slightly older than those in the TED group (see Table 1). The relationship between the school-age speed of processing (Study I) and procedural learning (Study II) was observed more clearly in children with a history of TED than LT. Explaining the language outcomes of children with a history of TED seems to be more straightforward than explaining those of children with a history of LT, with the relationship between the studied abilities and language being stronger in the TED group than the LT group for processing speed (Study I) and procedural learning (Study II).

Overall, we did not observe interactions between having a history of LT and school-age language abilities that would support our original hypotheses or otherwise be clearly interpretable. As the participants in all the studies were the same, it is possible that our sample of children with a history of LT happened to not be representative of LT children. Language difficulties at school age were more common in participants with a history of LT (approximately 27% of the children), and the group means in the language test scores were significantly lower in the LT group (Table 1). However, approximately 11% of the TED children also failed to meet the relevant age-based expectations in language tests at school age.

Multiple factors likely contribute to successful language development, which could explain why we did not find a clear candidate for predicting LT outcomes from our separate measurement candidates. Machine learning methods have provided some promising results for relatively accurately predicting language outcomes from preschool measures (Gasparini et al., 2023). Nonetheless, it is worth noting that, to date, the best-known predictors for language development are factors associated with the environment, genetics, or the child's demographic information rather than aspects of information processing. We are still unaware of *how*, for example, hereditary factors relate to language abilities. LT itself has also been seen as a risk factor for persistent language difficulties. It could perhaps result in persistent language difficulties through the "talking to talkers" mechanism (Dailey & Bergelson, 2023), according to which adults are more likely to talk to children who can already talk.

4.3 The future of studying individual differences in language acquisition and abilities

Using paradigms that compare the differences in various conditions have become increasingly popular in studies on individual differences in language abilities. These studies include both behavioral (such as RT) and neural-level (such as ERP) data, as seen in Studies I–III of this thesis. To date, a majority of these studies have used values aggregated over multiple observations from a participant (e.g., RT means or mean amplitudes) and treated IIV as noise and nuisance (e.g., Whelan, 2008). Mostly related to within-participant variation, RT studies on individual differences have been criticized for their low reliability (Draheim et al., 2019). Not accounting for individual variation when calculating RT estimates based on aggregated measures (i.e., participant means) can lead to confidence in false results (Rouder & Haaf, 2019). With modern devices (computers, keyboards, touchscreens, and button-press response boxes), the technical limitations associated with measurement resolution (i.e. the ability to detect small changes) are rarely a source of unreliability, as the devices' precision is typically just a couple of milliseconds, and the variation in this across trials and participants is random; thus, the studied effects are not affected systematically. This means that the unreliability mostly stems from the task design. The simplest way to improve reliability is to increase the number of trials per participant and appropriately model the within-participant variation in RT measures. I believe that the inconsistent results of studies on PDH (see West et al., 2021) could be partly explained by the fact that a majority of these studies ignore the IIV in RTs in a way that yields overconfidence in potentially false results (as described by Rouder & Haaf, 2019).

Studies I–III employed the effects of experimental manipulations on RTs to examine individual differences. We aimed to avoid the common pitfalls associated with these approaches (i.e., overly high confidence in individual-level observations and the ignoring of confidence intervals, see Rouder & Haaf, 2019) by analyzing trial-level data and collecting data for a relatively high number of trials per participant. However, the statistical models used in Studies I–III still treated the within-individual variation in these measures as noise instead of an effect of interest. Based on the findings of Study IV, I suggest that this "noise" is neither random nor unwanted (as noise should be by definition, see Scales & Snieder, 1998 for discussion on the nature of noise) and carries systematic information about individual features that we still do not properly understand. It is worth noting that the central findings from Studies I–III are mostly related to overall responses (main effects in the statistical analyses, e.g., language abilities related to slower response times in Study I and overall ERPs in Study III) or relatively simple manipulations (two-way interactions, such as SRT task effects, in relation to language in Study II) and not to complex "comparisons of comparisons" between multiple study manipulations and individual differences. One advantage of using the measures of IIV in RTs is that these are not based on the difference scores that have been suggested to be problematic when studying individual differences (Rouder et al., 2023).

The within-individual variation in RTs also has the potential to link neural-level phenomena to observations related to behavior (see Sonuga-Barke & Castellanos, 2007; van Maanen et al., 2011), and, with this information, it might help explain the biological mechanisms that govern the development of neural systems. The IIV hypothesis also provides a new framework to integrate seemingly contradictory findings interpreted as evidence from competing theories on individual differences in language acquisition (see Section 4.1.2). Further studies can be conducted by reanalyzing the existing datasets of RTs, eye-tracking, and ERPs produced with participants whose information regarding language abilities is available. The IIV, which has largely been treated as noise, seems to carry a signal that is relevant in the context of language abilities, the observation of which raises many clear questions that can be operationalized and studied explicitly using approaches such as the distribution fitting methodology. IIV analyses also possess the potential to shed light on the similarities and differences between DLD and ADHD, as attentional deficits are common in children with language learning difficulties (see Section 1.1.2.1), and increased IIV in RTs has been associated with ADHD (Kofler et al., 2013).

Future studies should seek to test our hypothesis and try to formulate a measure that would reflect the hypothesized instability in its purest possible form. Although the IIV in RTs was associated with language abilities (Study IV), the explanatory power of the IIV in visuomotor RTs for language abilities is modest—similar to many other predictors in the field. Further, we could critically examine our approaches to measuring language abilities, as the associated tests or other measures typically do not take into account potential IIV in linguistic performance, which seems to be a relevant phenomenon as well (see Van Geert & Van Dijk, 2002 for an example of the mean length of utterance). Addressing this potential issue is not straightforward, as many language measures require time and knowledge to administer and cannot be repeated many times because of the practice effects jeopardizing the results (Calamia et al., 2012). In group-level studies, this has perhaps not been considered an issue because of the "averaging out" that occurs when there are a sufficient number of participants. However, the magnitude of the IIV in measures of language abilities can potentially vary between individuals, which, to my knowledge, has yet to be systematically studied.

4.4 Clinical implications

Based on the results of Studies I–IV, certain recommendations can be provided for the prevention of and interventions for developmental language disorders. LT should not be the only risk factor considered when identifying at-risk children for persistent language disorders, as many children who are not identified as late talkers also exhibit language learning difficulties. In children with TED, measures of processing speed or IIV in RTs could potentially help recognize risk factors that could be detected early on using, for instance, saccadic RT measures of eye-tracking—a method that would also be suitable for small children who are not yet capable of performing a button-press RT task. However, at this point, the predictive value of these measures has not been proven to be so large that they could be useful at the individual level, at least when used as a single measure. In future studies, known risk factors, such as LT, poor use of gestures, or a family history of language impairments (Bishop et al., 2016), and neurocognitive measures could potentially be combined to increase the predictive accuracy for persistent difficulties.

If the IIV hypothesis we have presented in Study IV gains support in future studies, it would indicate that at-risk children should be exposed to enriched language environments, especially ones which include enhanced repetitions of the words and structures they do not yet know or use, to overcome the restrictions produced by the pronounced IIV states for language acquisition. The professional expertise of speech-language pathologists could be utilized to design these enriched daily environments for at-risk children so that those who need more than the average amount of exposure to language inputs to learn would have sufficient inputs to acquire language. Understanding the diversity in cognition, in association with language abilities, could also help better understand the world from the perspective of a child whose language abilities do not meet the expectations of their environment.

Abbreviations

ADHD	Attention-deficit/hyperactivity disorder
ANT	Attentional networks test
DLD	Developmental language disorder
DP	Declarative/procedural (model)
EEG	Electroencephalography
ERP	Event-related potential
ESC	End-state comfort (task)
IIV	Intra-individual variability
LT	Late talking
MMN	Mismatch negativity
PDH	Procedural deficit hypothesis
PRI	Performance reasoning index
RT	Response time
SRT	Serial response time (task)
TED	Typical early development

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