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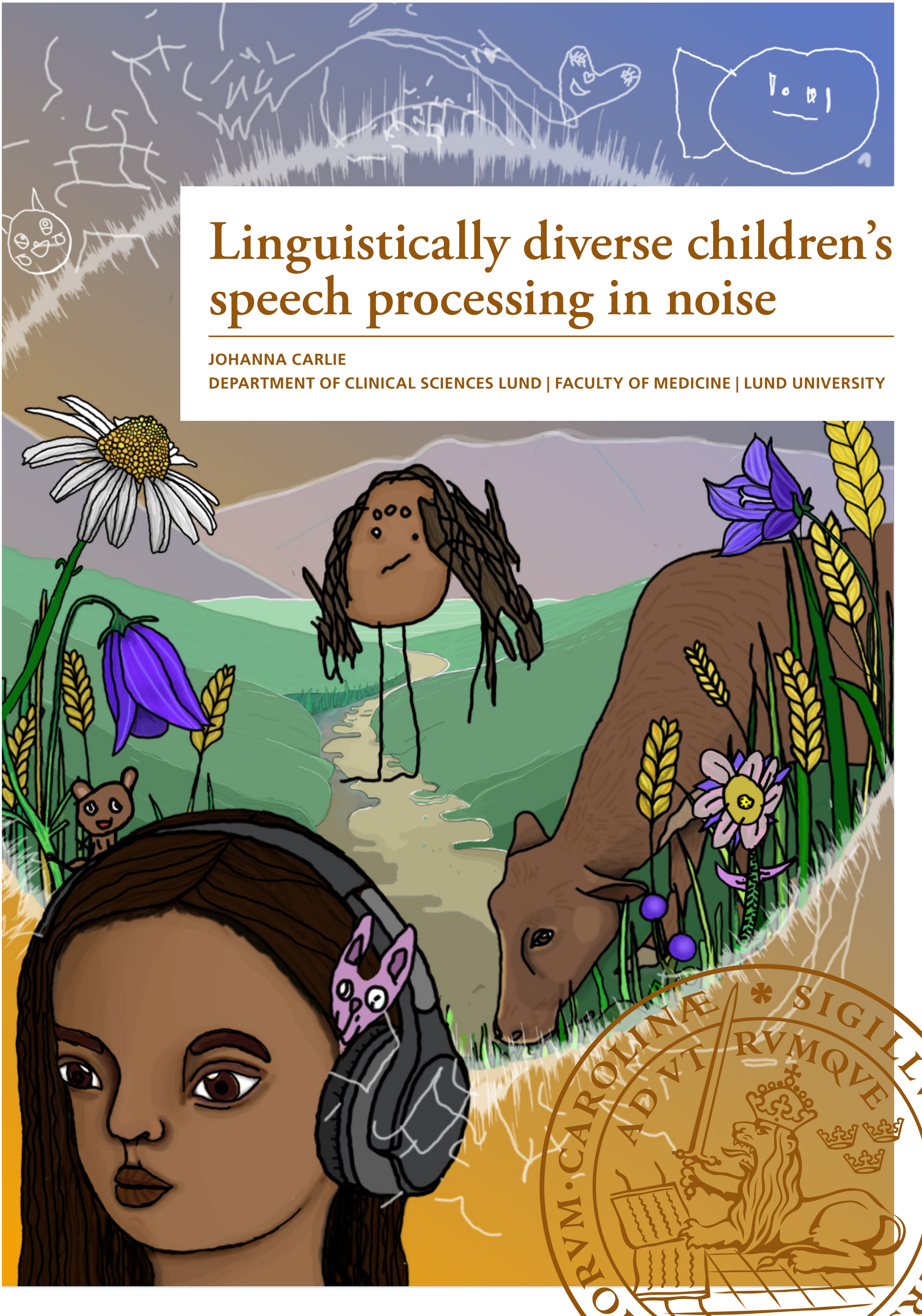

Linguistically diverse children's speech processing in noise

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Johanna Carlie

DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Medicine at Lund University to be publicly defended on 7th of November 2024 at 13:00 in Rune Grubb-salen, Forum Medicum, Sölvegatan 19, 223 62 Lund.

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Abstract: Many children in primary school listen and learn through their second language, often under noisy listening conditions. This thesis is based on assessments of 7 to 9-year-old primary school children (N=98) attending Swedish schools in areas of low socio-economic status where most students had immigration background. The overall aim of this thesis was to increase knowledge on how multitalker babble noise affects speech processing in primary school children of cultural and linguistic diversity. The first objective was to develop and evaluate a listening comprehension task to increase reliability in assessments of young primary school children of cultural and linguistic diversity. The developed task, called Lyssna, Förstå och Minnas (English: Listen, Comprehend, and Remember; LFM) was evaluated and considered suitable for investigating effects of adverse listening conditions in young primary school children of cultural and linguistic diversity. The second objective was to Investigate how multitalker babble noise affects speech processing, memory retention, listening effort and fatigue in these children. In summary, the findings indicate that short-term exposure to multitalker babble noise impairs children's immediate comprehension and recall of spoken information. However, this adverse effect on comprehension and recall may be temporary and it can potentially be normalized with memory consolidation and the process of recall. The third objective was to investigate the role of school language (Swedish) exposure on speech processing, memory retention, listening effort and fatigue under different listening conditions. The findings showed that increasing school language exposure was associated with increasing comprehension and memory for spoken Swedish narratives. However, the results were inconclusive as to the effect of multitalker babble noise, suggesting that children with little exposure to and knowledge in the school language may be more susceptible to the negative effects of multitalker babble noise on tasks which rely highly on adequate speech perception and fast processing and switching between tasks, but not on longer narrative tasks such as the LFM task. Using pupillometry, a physiological measure of listening effort and fatigue,the results pointed to increased listening effort and listening imposed fatigue in more challenging listening conditions, an effect which was driven by children with less experience in the school language.The last objetive was to identify within-listener factors important for speech processing in quiet and in multitalker babble noise. The importance of working memory capacity was a key finding. Implicit working memory processing, as measured by nonword reptition, was a strong predictor for speech processing in both quiet and in noise. Further, age differences in working memory processing was found, suggesting that younger children may have a more difficult time to use explicit working memory processing for comprehension in noise, as compared to their older peers.

Key words: Bilingualism; Listening comprehension; Cognitive development; Multitalker babble noise; Adverse listening conditions; Working memory; Learning; Classroom acoustics

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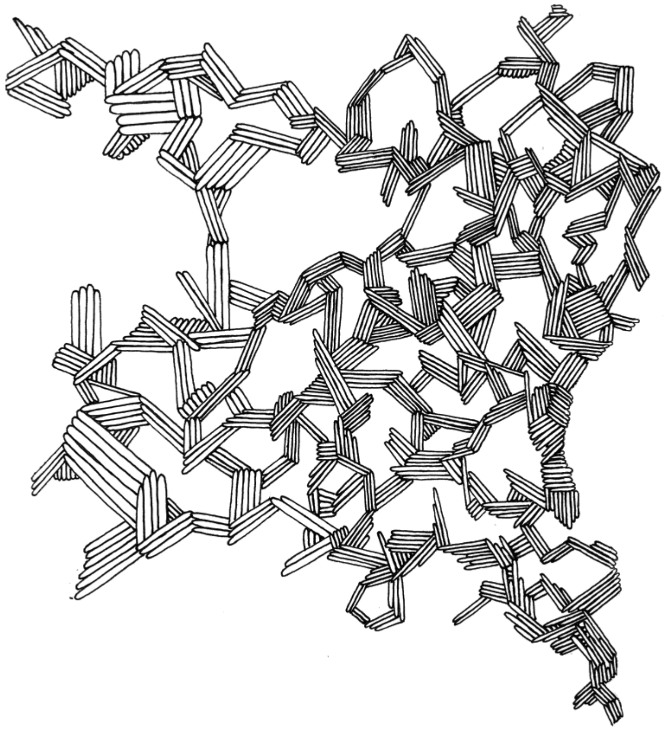

In dedication to the noise.

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Preface and Acknowledgements

As an undergraduate speech-language pathology student I came across the possibility to do a small research project about audio-visual integration of speech in noisy listening conditions as a summer job. I travelled to collect data for weeks, heavily pregnant, presented the project and went on parental leave. The next spring, I was still on parental leave, and would some months later start writing my master's thesis. I got the summer research scholarship again, and this time Birgitta (my supervisor then and co-supervisor now) asked me to develop a narrative comprehension test that could be used in their studies of children's speech processing in noise. I was starting to get a little cognitively under stimulated being on parental leave and took on the project wholeheartedly. Many people – family, friends, and later-to-be colleagues were involved in my thorough searches to design a perfect task. My daughter, Tanja (a good sleeper may I add), was with me – on park benches writing on my phone, at friends' houses evaluating the task, at meetings with Birgitta, crawling around in her office. The final pilot testing of the task showed that the efforts seemed to pay off. So, I continued evaluating the task as a master's thesis together with my co-author and friend, Anouk. I am still proud of our thesis, which came to be when we both were raising one-year-olds, driving back and forth to preschools, writing at all places except something resembling an office, calming stressed-out dogs, and creating an intricate world of inside jokes (including alter-egos and citing Flashback users APA-style). And so I continued the work as a PhD student, starting with a huge data collection, where my research assistant Linnéa and I drove across Skåne for months assessing children, carrying large suitcases containing our portable labs, and were continuously asked by students "Where are you going on vacation?" Then followed the PhD carousel of reading, writing, revising, taking courses, and our second daughter, Liv, was born. Following parental leave, the PhD carousel continued - there were dissatisfied reviewers, and supporting supervisors "Major revision is better than a reject!" So why the specific topic of children's speech processing in noise? At one time point it was a topic that was handed to me. However, I am deeply fascinated by the perceptual and cognitive processes enabling us to interpret the world, most often effortlessly and adequately. And on the contrary, what happens when our processing of the world is impaired or becomes disrupted? This thesis does not even cover a fraction of such a question, but this fundamental wondering has played an important role in deciding the direction of this dissertation.

I have many people to thank for supporting me throughout this journey. First, I am deeply grateful to my supervisor, Jonas, and co-supervisors Birgitta and Ketty. I am thankful to have had you as my team for more reasons than I can name. Jonas, thank you for your friendship and for guiding me through what was, at many times, a not so apparent path. Birgitta, without your ideas and support, I would not have even begun this project. Ketty, thank you for our many insightful discussions and your continuous encouragement. I would also like to thank Mary, my co-supervisor during the first year, and Roger, who has often acted as an unofficial co-supervisor, providing valuable input. To my parents, Anne and Lennart, I hope you will appreciate the archaeological touch of this dissertation. Thank you for providing me with an academic upbringing, though it may have felt frustrating at times, that fostered my curiosity and allowed me to find my own path. A special thanks to my dad, Lennart, for contributing to the settings of the LFM narratives. Thanks also to my parents-in-law Ingrid and Per for helping when it has been impossible to "vabba". To my colleagues at the Department of Logopedics, Phoniatrics and Audiology, for generosity and support, and for making it fun to come to work. To my husband Eli, who has supported (and distracted!) me in all ways possible throughout this journey. And to our daughters – I will write this in Swedish: Tanja och Liv, ett litet meddelande till er den dagen då ni öppnar denna bok. Tack för att ni har hållit mig (relativt) grundad i detta. Tack för alla era finurligheter och för att ni är precis som ni är (och ja, ni är lika bäst båda två).

The journey continues.

/Johanna, September 2024.

List of studies

Study I

Carlie, J., Sahlén, B., Nirme, J., Andersson, K., Rudner, M., Johansson, R., Gulz, A., & Brännström, K. J. (2021). Development of an auditory passage comprehension task for Swedish primary school children of cultural and linguistic diversity. *Journal of Speech, Language, and Hearing Research,* 64(10), 3883-3893. https://doi.org/10.1044/2021_JSLHR-20-00611

Study II

Brännström, K. J., Rudner, M., Carlie, J., Sahlén, B., Gulz, A., Andersson, K., & Johansson, R. (2021). Listening effort and fatigue in native and non-native primary school children. *Journal of Experimental Child Psychology,* 210, Article 105203. https://doi.org/10.1016/j.jecp.2021.105203

Study III

Carlie, J., Sahlén, B., Johansson, R., Andersson, K., Whitling, S., & Brännström, K. J. (2024). The effect of background noise, bilingualism, socioeconomic status, and cognitive functioning on primary school children's narrative listening comprehension. *Journal of Speech, Language, and Hearing Research,* 67(3), 960-973. https://doi.org/10.1044/2023_JSLHR-22-00637

Study IV

Carlie, J., Sahlén, B., Andersson, K., Johansson, R., Whitling, S., & Brännström, K. J. (2024). Culturally and linguistically diverse children's retention of spoken narratives encoded in quiet and in babble noise. *Journal of Experimental Child Psychology*, 249, Article 106088. https://doi.org/10.1016/j.jecp.2024.106088

Studies at a glance

Table 1. Summary of the included studies.
Abbrevations: LFM: Lyssna, Förstå och Minnas (English: Listen, Comprehend, and Remember). MTBN: Multitalker babble noise. WM: Working memory. CL-NWRT: Crosslinguistic Nonword Repetition Test. DSB: Digit span backwards. SES: Socio-economic status. BL: Bilingual.

Participants and general inclusion criteria	Primary school children aged 7-9 years attending grade 2 and 3 at primary schools of low SES where most students had Swedish (the school language) as their L2. Included children attended mainstream education, had normal hearing and completed the included tasks. Study-specific inclusion criteria is shown under each study.			
	Study I	**Study II**	**Study III**	**Study IV**
N (Study-specific inclusion criteria)	88	63 (Sufficient pupillometry data)	86 (CL-NWRT >-3 SD)	80 (CL-NWRT >-3 SD; retention interval 6-8 days)
Aim	Develop and evaluate a listening comprehension task for children of cultural and linguistic diversity.	Examine the impact of MTBN and school language exposure on listening comprehension, listening effort and fatigue.	Identify predictors for listening comprehension in quiet and in MTBN.	Examine how listening in MTBN affect memory retention of spoken narratives.
Data *	LFM immediate recall	Speech-picture verification task, pupillometry, self-reports	LFM immediate recall, CL-NWRT, DSB, SES, age.	Repeated recall (Immediate and delayed) of LFM with a 1-week retention interval, DSB.
Language measure	Monolingual, Simultaneous BL, Sequentual BL	Native and nonnative.	Continous: Swedish exposure index.	Continous: Swedish exposure index.
Listening conditions	Quiet, MTBN SNR + 6 dB.	MTBN SNR 0 dB and +10 dB.	Quiet, MTBN SNR + 6 dB.	Quiet, MTBN SNR + 6 dB.
Main findings & conclusions	LFM was developed and demed suiable for the target group and for investigating effects of MTBN.	Listening effort and fatigue increases in MTBN of SNR 0 dB as compared to +10 dB, especially for children with little school language exposure.	Listening comprehension increases with school language exposure and WM. Age differences in the use of WM across listening conditions.	MTBN had an immediate and temorary negative effect on listening comprehension, and did not impair memory retention.

* Listening condition and a measure for school language exposure was included in all studies.

Lay summary

The overall theme of this thesis is how processing, comprehension, and memory for speech is affected by noisy listening environments in primary school children from socio-economically disadvantaged areas, where most children have Swedish as a second language. In *Study I*, a task was developed to assess listening comprehension in these children reliably. To achieve ecological validity, the material follows a narrative structure. This narrative listening comprehension test was called Lyssna, Förstå och Minnas (English: Listen, Comprehend, and Remember; LFM). To compare performance across different listening conditions, LFM was composed of two parts, similar in content and difficulty. LFM was considered suitable for the target group: children in grades 2 and 3 of cultural and linguistic diversity, and the two parts were deemed comparable. *Studies II, III,* and *IV* investigated factors that may explain why babble noise impairs speech processing more in some children than others. In summary, the results from these studies indicated that children with more experience in the Swedish language could comprehend and remember Swedish narrative comprehension tasks better than those with less experience in the language. Regarding how background noise affects their performance on these tests, the results are ambiguous. It is possible that children with less experience in Swedish are more affected by background noise when speech intelligibility is compromised, tasks require rapid processing, and top-down processes cannot contribute to solving the task. *Study II* showed that children with less experience in the school language exhibited higher listening effort, but a positive association between successful comprehension and increased effort was only seen in children whose first language was Swedish. Higher working memory capacity was positively associated with comprehension and memory for spoken narratives. *Study III* revealed age differences in how working memory was used for comprehension and recall in noisy as compared to quiet conditions. In *Study IV*, memory for narratives encoded in quiet and in babble noise was examined over time. This study demonstrated an initial negative effect of background noise, but one week later, children could recall approximately the same amount of information from the narratives in both listening conditions. The conclusions from this thesis are that background noise negatively impacts real-time comprehension of oral narratives, but this effect may even out with long-term memory processes. It is possible that children with the school language as a second language have poorer comprehension of speech when tasks demand attention to details, require rapid processing, and when background noise affects speech intelligibility. It is also possible that children with the school language as a second language need to exert more effort when listening under noisy conditions, which in the long turn can cause increased fatigue.

Populärvetenskaplig sammanfattning

Det övergripande temat i denna avhandling är hur bearbetning, förståelse och minne för tal påverkas av bullriga ljudmiljöer hos lågstadiebarn från socio-ekonomiskt utsatta områden där majoriteten av barnen har svenska som andraspråk. I den första studien utvecklades ett material för att kunna bedöma språkförståelse på textnivå hos dessa barn på reliabelt sätt. För att skapa ekologisk validitet och samtidigt utgå från kunskaper som lågstadiebarn har, följde bedömningsmaterialet en narrativ struktur. Detta narrativa hörförståelsetest kallades Lyssna, Förstå och Minnas (LFM). För att kunna jämföra prestation mellan olika lyssningsvillkor, består testet av två delar med liknande innehåll och svårighetsgrad. I *Studie I*, beskrevs utvecklingen av testet, det utvärderas och bedömdes vara adekvat för målgruppen, alltså barn i årskurs 2 och 3 av kulturell och språklig diversitet. I *Studie II, III* och *IV* undersöktes vilka faktorer som kan förklara varför vissa barn har större svårigheter att bearbeta, förstå och minnas tal i buller än andra. Sammanfattningsvis visade resultaten från dessa studier att barn med mer erfarenhet av det svenska språket förstod och mindes svenska narrativa hörförståelseuppgifter bättre än barn med mindre erfarenhet av det svenska språket. Vad gäller hur babbel påverkar deras prestation på dessa tester, var resultaten tvetydiga. Det är möjligt att barn med mindre erfarenhet av svenska påverkas mer av babbel när hörbarheten av talet påverkas, när uppgifterna kräver snabb bearbetning, och när top-down processer inte kan bidra till att lösa uppgiften. *Studie II* visade att barn med mindre erfarenhet av svenska hade högre lyssningsansträngning, men att förståelsen bara påverkades positivt vid ökad ansträngning hos barn som hade svenska som förstaspråk. Högre arbetsminneskapacitet var positivt associerat med förståelse och minne för muntliga narrativer. *Studie III* visade på åldersskillnader i hur arbetsminne användes för förståelse och återkallande i babbel och i tystnad. I *Studie IV* undersöktes minne för narrativer inkodade i tystnad och i babbel över tid. Denna studie visade på en initial negativ effekt av babbel, men en vecka senare kunde barnen återkalla ungefär lika mycket information från narrativerna i båda lyssningsvillkoren. Slutsatserna från avhandlingen är att babbel har en negativ påverkan på förståelse för muntliga narrativer här och nu, men eventuellt jämnas detta ut med långtidsminnesprocesser. Det är möjligt att barn med svenska som andraspråk har en sämre förståelse för svenskt tal när uppgiften ställer stora krav på uppmärksamhet av detaljer, kräver snabb bearbetning och när babbel påverkar talets hörbarhet. Det är också möjligt att barn med svenska som andraspråk behöver anstränga sig mer för att lyssna i bullriga ljudmiljöer, vilket på sikt kan skapa en ökad trötthet.

Introduction

Children's spoken language comprehension is crucial for their social interactions, knowledge acquisition and curricular goal completion (O'Connor et al., 2018; Spencer et al., 2017). In this thesis, the term speech processing will be used as umbrella term for the processes of listening, comprehending, and remembering spoken information. The listening conditions in today's interactive classrooms are often less than ideal (Crandell & Smaldino, 2000; Wang & Brill, 2021). Noisy listening conditions negatively impact children's academic attainment in general (Dockrell & Shield, 2006), and their speech processing specifically (Schiller et al., 2022). Children vary in their ability to process speech, both in ideal and noisy listening conditions (Sahlén et al., 2020). Among those particularly vulnerable are bilingual children, listening and learning in their second language (L2). As of today, one in four Swedish primary school students have Swedish as their L2 (Swedish National Agency for Education, 2019). This is not unique to Sweden. The Program for International Student Assessment (PISA) of 2022 showed that a mean of 19% of students had the school language which was used in assessments as their L2 (Organisation for Economic Co-operation and Development (OECD), 2023). As knowledge in the school language used for instruction is crucial for school performance, these children are at a higher risk for not meeting the curricular goals of primary school than their peers whose first language (L1) is the school language (Agirdag & Vanlaar, 2016; Pace et al., 2019; Swedish National Agency for Education, 2019). Research suggests that the negative impact of noise on speech processing may be more pronounced when listening in a L2 compared to a L1 (Bovo et al., 2018; Lecumberri et al., 2010). This thesis aims to contribute to the body of knowledge in how noise affects speech processing in primary school children of diverse linguistic backgrounds. Speech processing can be assessed through a variety of tasks. In this thesis, the focus is on listening comprehension.

Listening comprehension

Listening comprehension is a term used here to define the comprehension of speech at a discourse level. Discourse constitutes passages with a scope beyond individual words or sentences, presented in a coherent structure, and serving a communicative purpose (Kim & Pilcher, 2016). Discourse encompasses different genres, such as narrative, expository, and procedural discourse (Ferstl, 2018). In this thesis, the focus lies on the narrative genre.

The narrative genre

Stories, or narratives, are commonly used for assessing children's listening comprehension. Narrative comprehension is indicative of academic achievement as narratives serve as a link between formal and conversational language (Bishop, 2014; Paul et al., 2024). While narratives can be constructed using complex language, the knowledge in the overall narrative structure (macrostructure) can be regarded as relatively language-independent and is known to most children of early primary school age (Hipfner-Boucher et al., 2015). The most common narrative macrostructure is called *Story Grammar* (Paul et al., 2024; Stein & Glenn, 1979) and children familiarize with this way of storytelling early on, from story books, everyday conversations and children's tv shows, as well as working with narratives at preschool and in primary school (Bishop, 2014; Bohnacker & Lindgren, 2020; Swedish National Agency for Education, 2022). If a narrative is told according to the *Story Grammar* principles, it contains two systems: one of settings and one of episodes. Characters and their surroundings are presented in the setting. The episode(s) that follow contain the plot(s), which usually includes an initiating event, followed by the protagonist's internal response to this event, their action in response to the event, a consequence of the action, and a resolution concluding the episode (Lepola et al., 2012; Stein & Glenn, 1979). As narratives are integral to children's everyday school activities, the use of narratives also provides ecological validity in assessments of listening comprehension.

The continuous process of narrative listening comprehension

Listening comprehension is a complex endeavor where speech is processed at many levels. At a basic level, listening comprehension can be understood as incoming phonological stimuli being matched to their meaning in semantic long-term memory (Medwetsky, 2011; Rönnberg et al., 2022). However, to fully comprehend a narrative, the listener must create a *situation model* of the processed speech. This means that while listening, they must form a coherent mental representation of what the narrative is about. In the context of narratives, this situation model includes information about time and place, the protagonist(s) and their goals, problems, and the deuteragonists and objects they encounter, as well as the causation between the included elements. This mental representation is continuously modified as the narrative evolves, while the listener integrates and infer meaning across words and sentences – including how elements relate to one another and to the listener's prior knowledge and experiences (Kim, 2016; Kintsch, 1988). The neurocognitive process of building a situation model can be understood through the Theory of Event

Segmentation and Memory. This theory describes how perceptual stimuli implicitly and continuously are segmented into chunks, or events, in a temporal hierarchy. This begins with rapid low level processing in primary auditory regions where the stimuli is segmented into events representing phonemes (Baldassano et al., 2017; Jafarpour et al., 2022). These low-level auditory events are then further segmented into longer events representing words or sentences. As the narrative continues, the sentences are further segmented into one large event in cortical areas, a situation model. The brain thus implicitly segments auditory stimuli into larger and larger events the further a narrative continues (Baldassano et al., 2017).

Remembering speech

Comprehension in real-time is essential, but as learning is the goal of primary school real-time listening comprehension holds less value if it is not retained in long-term memory. Learning can be defined as the difference in knowledge between two timepoints (Roediger & Uner, 2022). As for long-term memory processes, this begins with encoding of information which is defined as the initial registration of information in long-term memory. When a narrative has concluded, or in other words, been segmented into one high-level event representing the situation model, it is transferred to the hippocampus where newly acquired memories are encoded into episodic long-term memory (Baldassano et al., 2017). Encoding is followed by consolidation processes where newly encoded memory traces are reorganized and stabilized in memory, which often means losing details and temporal aspects of the encoded information (Nadel & Hardt, 2011). Most importantly, memory consolidation occurs during sleep, but memories are altered and reconsolidated whenever they are reactivated. These consolidation and reconsolidation processes are the foundation of learning, as it allows for updating and modification of memories, but it also means that what we encode is not necessarily what we end up remembering. The “storage” of memories is called retention or persistence, and this is what happens after memory consolidation or between memory reconsolidations. Retention tangents to remembering but is not equal to it, as memories can be retained without being accessible. Memories may thus be retained but we are not always able to recall them. Still, retention is difficult to assess without measures of recall (Roediger & Uner, 2022).

Measuring narrative comprehension and memory

Memories of real and fictional past events are typically remembered in a narrative format, and this format also alleviate retention of long-term memories (Furman et al., 2007; Lee et al., 2020). Recall is the ability to actively access long-term memories, which includes the memory for speech we have listened to. As soon as the time- and capacity-limit of working memory is exceeded, we are measuring recall from long-term memory which we currently hold active in working memory (Cowan et al., 2021). While comprehension and recall are two distinct cognitive processes, they are highly intertwined in the context of assessing narrative comprehension. The language the narrative is composed of must be understood, but to comprehend a narrative, it also needs to be encoded and retained in episodic long-term memory. Comprehension of narratives are thus often measured by recall tasks (e.g. Pearson Assessment, 2013). Recall of long-term memories, including information from stories we have been told, is highly reliant on the cues we are provided with. These cues differ in how guided they are. That is, a location can be a cue for a memory, but cues can also be highly guided such as explicit questions asking for specific information cueing memory retrieval. From a memory perspective, free recall of narratives, such as retelling, is often considered better estimates for narrative memory (Lee et al., 2020). From a speech-language pathology perspective, measuring comprehension of speech by placing demands on a child's expressive language abilities such as during free recall tasks can confound comprehension measured. This is especially true when assessing children in their L2, as they often display a noticeable discrepancy between receptive and expressive L2 abilities (Gibson et al., 2014; Levlin, 2014).

What affects listening comprehension?

As previously indicated, listening comprehension places demands on several within-listener factors (i.e., cognitive processes), but it also depends on factors extrinsic to the listener (Table 2). Listening comprehension is highly reliant on adequate speech perception and requires relevant foundational language including vocabulary and grammatical knowledge in the assessed language. Listening comprehension is also reliant on working memory processing and goal directed attention, as well as higher order cognitive processes such as inference making and theory of mind. It further requires efficient temporal event segmentation for the integration of information into a coherent situation model (Ferstl, 2018; Kim, 2016; Kim & Pilcher, 2016). The listening conditions extrinsic to the listener are also important to consider. As seen in Table 2, these extrinsic factors include factors related to the target speech signal, such as the voice of the speaker and potential acoustical degradations of the target speech, such as the presence of background noise. Crucial factors for speech processing, including listening comprehension, have been summarized and classified by Mattys et al. (2012) as seen in Table 2. When these factors impair speech processing, they are labelled Adverse Listening Conditions.

Table 2.
Factors affecting listening comprehension as categorized by Mattys et al. (2012).

Factors extrinsic to the listener	Factors intrinsic to the listener
Voice and speech flow of the target speech	Prior knowledge
Frequency filtering (e.g. radio or phone)	Working memory capacity
Background noise	Cognitive load

In this thesis, the voice quality and speech flow of the target speech, as well as the quality of recorded speech signals have been controlled for. Four of these factors do, however, need further consideration: 1) Background noise, 2) Prior knowledge, 3) Working memory, and 4) Cognitive load. These factors will be described and discussed in the upcoming paragraphs.

Background noise

Background noise is an adverse listening condition which is extrinsic to the listener. It is widely recognized that background noise impairs speech processing and can degrade speech differently depending on the characteristics of the noise in comparison to the target speech signal (Sahlén et al., 2020; Schiller et al., 2022). One important aspect is the signal-to-noise ratio (SNR). The SNR is a measure of the difference in intensity between the target speech (signal) and the noise. At SNR 0 dB, the signal and the noise are of equal intensity. A negative SNR means that the noise is of higher intensity than the target speech. In studies of speech processing in noise, strong negative effects are usually seen when the SNR is 0 dB or below. At these low SNRs, the noise is likely to cause energetic masking, which means that there is a spectral overlap between the target speech and the noise. This makes it hard to perceive what is said (Brungart, 2001). Children need higher SNRs than adults for accurate speech perception (Leibold & Buss, 2019). Still, primary school classrooms are often noisy learning environments (Wang & Brill, 2021). Commonly reported SNRs ranges between -6 dB to +6 dB (Crandell & Smaldino, 2000). At the positive end of this range, and at even more favorable SNRs (Rudner et al., 2018), background noise can still impair speech processing (Brungart, 2001; Schiller et al., 2022). This is unlikely caused by energetic masking, but rather informational masking. Informational masking is caused by linguistic interference between the noise and the target speech. This is when the listener finds it challenging to separate the components of the target signal from a similar-sounding distractor even though the target speech remain audible (Brungart, 2001). One common kind of background noise in the primary school classroom which can cause informational masking is babble noise. The term babble noise is used to describe noise caused by competing speakers in the listening environment. This kind of background noise is among those which affect speech processing the most, and the ability to process speech in babble noise does not become adult-like until mid-adolescence (Leibold & Buss, 2019). A negative effect of babble noise on children's listening comprehension has been seen in a wide range of studies (e.g. Brännström et al., 2018; Nirme et al., 2019; Rudner et al., 2018; Visentin et al., 2023) In this thesis, the focus is on multitalker babble noise, which refers to noise caused by several competing speakers. In the primary school classroom, this most often means children chattering in the background.

Memory retention and learning in noise

Noise impairs children's learning in school (Dockrell & Shield, 2006; Hygge et al., 2002), but not all kinds of noise and not on all kinds of tasks (Stansfeld et al., 2005). The presence of background noise impairs speech processing, but most studies of speech processing in noise only measure perception or comprehension shortly after encoding (see e.g. Klatte et al., 2013; Schiller et al., 2022 for comprehensive reviews). These studies do therefore not capture later long-term memory processes, such as sleep consolidation, which is important for learning (Nadel & Hardt, 2011; Williams & Horst, 2014). Studies on children's word learning have pointed to negative effects of background noise during the learning/encoding phase (Avivi-Reich et al., 2020; Han et al., 2019). However, Riley and McGregor (2012) showed that learning of novel words was better when encoded in speech-shaped noise than in quiet when learning was measured by a multiple-choice task, but a negative effect of noise was seen for novel word production accuracy. Similarly, Stansfeld et al. (2005), found in a large cross-national study, negative effects of environmental noise on reading comprehension and annoyance, but positive effects of road traffic noise on episodic memory recall. General memory research has shown that the presence of background noise during encoding can improve learning (Pedraza et al., 2016). This is linked to that noise increases arousal, and this heighted alertness enhances memory consolidation (Krenz et al., 2021; McGaugh, 2006; Schwabe et al., 2012). As for written text, retention has been found higher when the text was read in the presence of background noise as compared to in quiet (Angwin et al., 2017; Brännström & Waechter, 2018). The study of most importance to the present investigation is Brännström et al. (2018) who assessed primary school children's immediate comprehension and retention of spoken narratives encoded in quiet and in multitalker babble noise. This study pointed to poorer immediate comprehension for narratives encoded in multitalker babble noise as compared to in quiet. There were also indications of poorer retention for narratives encoded in multitalker babble noise than quiet, suggesting that the noise did not only reduce immediate comprehension, but also memory retention (Brännström et al., 2018). While the effect of background noise on speech processing has been extensively researched, knowledge is spare about how speech processing in noise affects children's memory retention and learning.

Prior knowledge

One important within-listener factor for listening comprehension is the listener's prior knowledge in comparison to the speech. Children need both the relevant core language skills and knowledge of how the presented discourse genre (e.g. narratives) is typically structured for comprehension (Kim, 2016; Liles, 1993; Paul et al., 2024). This knowledge widens and deepens as children get older and their cognitive abilities develop (Bishop, 2014), which makes speech processing more efficient (Magimairaj et al., 2021; Richardson & Saxe, 2020). However, language is acquired through experiences and dependent on the input children receive. It develops within a context, and linguistic proficiency is thus dependent on children's linguistic, cultural, and socio-economic circumstances.

Bilingualism and school language exposure

Bilingualism is a factor which significantly impacts children's language development and linguistic knowledge. Bilingual language acquisition occurs under highly diverse conditions, and the consequences of growing up bilingual is thus difficult to generalize (Kohnert et al., 2021). Children whose school language corresponds to their L2 are at higher risk for not reaching the curricular goals in primary school as compared to their L1 peers (Agirdag & Vanlaar, 2016; Swedish National Agency for Education, 2019). Being bilingual does, however, not necessarily mean that the child has the school language as their L2. Many children acquire two or more languages from or around the time of birth, leaving them native to more than one language. These children are labelled simultaneous bilinguals and may have caregivers with different L1s or meet more than one language in society. Even though these children have been regularly exposed to both languages from a very young age, it is common that their proficiency is not balanced across languages, and language dominance may shift from one language to another at points in development (Kremin & Byers-Heinlein, 2021). Other children start out as monolinguals and begin acquiring a L2 later in childhood, as is often the case with children of migration background. These children are labelled sequentially bilinguals, and do, just like simultaneous bilinguals, constitute a highly diverse group. In the context of acquiring the school language as a L2, L2 acquisition is a gradual process where native-like performance in children is typically not reached until after several years of schooling (Soto-Corominas et al., 2020). Duration of L2 exposure is, however, not necessarily a sufficient predictor for L2 proficiency (Ebert & Reilly, 2022). L2 acquisition is also dependent on cognitive individual differences as well as the quality and quantity of input, and opportunities for speaking the language (Huang et al., 2018; Paradis, 2016, 2019; Soto-Corominas et al., 2020). There is still no consensus on a gold standard for measuring bilinguals' language exposure, which means that measures vary across studies (Kremin & Byers-

Heinlein, 2021; Marian & Hayakawa, 2021). In studies of speech processing in noise, group comparisons are often conducted between either monolinguals and bilinguals (Bovo et al., 2018; Filippi et al., 2020), or natives (listening in their L1) and nonnatives (listening in their L2) (Lecumberri et al., 2010). These rudimentary classifications do not, however, capture the diversity within the groups. A wide range of studies in adults' speech processing in noise have shown a disadvantage for bilinguals' listening in their second language (L2) (Lecumberri et al., 2010; Morini & Newman, 2020; Schmidtke, 2016). The few studies including children show inconclusive results (Leibold & Buss, 2019), but point to the same direction - that speech processing in noise is dependent on children's abilities in the assessed language, leading to a disadvantage for children listening in their L2 (Klatte et al., 2013; Schiller et al., 2022).

Socio-economic status

Children from families of low socio-economic status (SES), typically display poor language and general cognitive abilities including working memory capacity, as well as low curricular goal completion as compared to their higher SES peers (Chiat & Polišenská, 2016; Mooney et al., 2021; Spencer et al., 2017; Swedish National Agency for Education, 2019). SES is a measure of someone's social and economic position within a society. In children, this is often measured through parental education level and/or income. As children spend large parts of their days in school, another important aspect is the neighborhood SES, which can be indicated by the average parental educational- and income level of the school district (Neuman et al., 2018). Children who grow up under poor socio-economic circumstances are exposed to less advanced language and less cognitive challenging experiences (Meir & Armon-Lotem, 2017; Neuman et al., 2018). Children who grow up under disadvantaged socio-economically conditions, and in addition have the school language as their L2, are especially at risk for poor development of school language abilities (Andersson et al., 2019; Barragan et al., 2018). It has been noted that noise levels in areas of low SES tend to be louder compared to in higher SES areas (Casey et al., 2017). Further, low SES has been found negatively associated with both monolingual and bilingual children's listening comprehension in noise (Filippi et al., 2020).

Assessing children of cultural and linguistic diversity

When assessing children of cultural and linguistic diversity, it is important to consider how differences in culture-specific experiences can affect performance on linguistic tasks. It is expected that children with less experience and knowledge in the assessed language will have poorer listening comprehension than their more experienced peers. However, linguistic, and general knowledge acquired through experiences differ depending on children's cultural backgrounds, which can cause a disadvantage for children of cultural minorities (Ferstl, 2018; Larson et al., 2020). In recent years, several new tasks have been developed aiming to increase reliability in assessments of culturally and linguistically diverse children. The common ground in these projects is that they focus on the commonalities across cultures. One example is the Crosslinguistic Nonword Repetition Test (Chiat, 2015) which includes nonwords constructed by phonemes and phoneme combinations present in most languages across the world. A narrative material, is the Multilingual Assessment Instrument for Narratives (MAIN) (Gagarina et al., 2019; Gagarina et al., 2012). The MAIN narratives use the Story Grammar principles and include animals as characters which most children should know of. Another approach is the Global TALES project where children are asked to tell personal narratives based on emotions which can be considered "universal", such as a story about a time when they felt proud (Westby, 2021; Westerveld et al., 2022). Contrasting to this are approaches that focus on the common feature of *not knowing*. One example is Ljung et al. (2009), who developed expository texts of fictive civilizations which no participant could have any prior knowledge of. The present investigation was inspired by these approaches – what is common and not common knowledge in school aged children across most cultures?

Working memory

Working memory is a within-listener factor which is crucial for listening comprehension: for integrating auditory stimuli with prior knowledge, for monitoring comprehension, and for segmenting continuous flows of events into meaningful episodes (Jafarpour et al., 2022; Justice et al., 2018; Radvansky, 2017). Working memory is the memory system of temporarily activated information and includes a spectrum of processing complexity, from automatic (implicit) sensory experiences to controlled, goal-directed (explicit) attention and memory formation (Cowan et al., 2021; Gray et al., 2017; Köster & Gruber, 2022). Working memory is thus the cognitive construct in which we process information, both incoming stimuli and already acquired knowledge in long-term memory. Children's working memory develops as they get older, and a change in processing strategies has been seen around the age of eight years (Gray et al., 2017; Roediger & Uner, 2022). Various working memory tasks measures different aspects of working memory (Gray et al., 2017), where a distinction between implicit and explicit working memory processing is of importance for understanding how speech is processed under different listening conditions (Köster & Gruber, 2022; Rönnberg et al., 2013; Rönnberg et al., 2022).

Implicit and explicit speech processing

A prominent theoretical framework for understanding individual differences in the ability to process speech in noise, is the Ease of Language Understanding (ELU) model (Rönnberg et al., 2021; Rönnberg et al., 2013; Rönnberg et al., 2010). The ELU model distinguishes between implicit and explicit speech processing. It describes speech processing under optimal listening conditions as an implicit process. That is, speech is processed automatically and subconsciously when the sound environment is quiet, the speech is clearly audible, and the content matches the listener's language proficiency and general knowledge. Explicit speech processing, on the other hand, is the deliberate processing of sensory stimuli in working memory. When we, for example, hear a word of which we are unsure of the meaning, or when the speech is too distorted to be implicitly matched to a lexical label in long-term memory, the phonological stimuli is processed explicitly in working memory. As an interaction between stimuli currently held active in working memory and knowledge in long-term memory, top-down processes are used to infer the meaning of the stimuli. This deliberate processing is slow and effortful and leaves less working memory capacity for higher order cognitive processing. According to the ELU model, it is thus the ability to temporarily store and explicitly process information in working memory which best predicts speech processing in noise. This means that when predicting individual differences of speech processing in noise, the ELU model emphasizes the use of explicit working memory tasks which require higher order information processing than solely rehearsal (Rönnberg et al., 2013; Rönnberg et al., 2010; Rönnberg et al., 2022). An important note concerning the ELU model, is that is derived from studies on adults, and that working memory capacity has not been as robustly linked to speech processing in noise abilities in children (Porto et al., 2023; Visentin et al., 2023). However, the distinction between implicit and explicit speech processing in working memory has served as a basis for the methodology of the included studies in this thesis. Two different working memory tasks were included, one to assess more explicit or deliberate working memory processing and one which mainly required implicit phonological processing or rehearsal.

Working memory and language learning

Increasing working memory capacity alleviates speech processing and allows for processing speech of higher complexity. In addition to post-diction of misperceived input, it allows for more efficient prediction of speech. These prediction processes are not deliberate in the same sense as post-diction processes and are thus more reliant on the implicit processing of speech in working memory (Rönnberg et al., 2022). Increasing working memory capacity is also an indicative factor for children's language learning and proficiency. One working memory task which has received much attention for its properties to predict children's language learning and language proficiency is the nonword repetition task (Adlof & Patten, 2017; Bowey, 2002; Gathercole, 2006a, 2006b). This task places demands on phonological rehearsal and implicit processing in working memory, but also requires children to use other abilities essential for language learning such as phonological awareness and oral motor planning skills. Nonword repetition thus resemble the situation when children encounter new words for the first time, and measures the ease with which children acquire the phonological representation of novel words (Chiat, 2015; Chiat & Polišenská, 2016). Nonword repetition accuracy is positively associated with various aspects of children's language learning, most importantly vocabulary acquisition, in both monolingual and bilingual children (Engel de Abreu & Gathercole, 2012). Further, impaired nonword repetition is considered a clinical marker for developmental language disorder displaying high sensitivity and specificity in the diagnosing of both monolingual and bilingual children (Schwob et al., 2021; Schwob & Skoruppa, 2022). In this thesis, nonword repetition accuracy has been used as an inclusion criterion to avoid including children with potentially undiagnosed language disorder. It has also been used a predictive factor for listening comprehension, where the primary purpose has been its properties to predict language proficiency and implicit speech processing rather than ability to predict differences in speech processing in noise.

Cognitive load

When listening conditions are challenging, the attempt to comprehend speech can cause a cognitive load. This is according to Mattys et al. (2012), a secondary effect of the previously mentioned factors affecting speech processing. According to the Cognitive Load Theory (Sweller, 2011), there are three kinds of cognitive load: Extraneous, Intrinsic and Germane load. Background noise can cause an extraneous load as it affects the format of the information. Inadequate prior knowledge can cause an intrinsic load as it relates to the complexity of speech in comparison to the listeners' abilities. Germane load is a term used to describe when the cognitive load is task relevant. This involves processes for integrating new information with existing knowledge, creating a deeper understanding of the information, but as such is also places a high load on working memory (Sweller, 2011). When a listener is motivated to comprehend speech, this cognitive load is likely to increase listening effort, and in the long term, cause fatigue (Pichora-Fuller et al., 2016).

What is listening effort and fatigue?

A motivated listener is more likely to make efforts to comprehend speech (Pichora-Fuller et al., 2016). Listening effort increases if the listener is motivated (i.e., has an interest of some kind) to comprehend speech, the speech is complex and/or presented in acoustically challenging conditions. Listening effort refers to "the deliberate allocation of resources to overcome obstacles in goal pursuit when carrying out a listening task" (Pichora-Fuller et al., 2016). Listening effort can thus be an indication of perceived effort, but also indicate heightened attentional focus which increases chances for successful comprehension (Alhanbali et al., 2019). In physical terms, effort in response to cognitive demands increases physical arousal allowing the listener to be alert and focused on the task at hand. This heightened task-evoked arousal can, however, not persist indefinitely. As cognitive demands continue or if the listener is unable to use the effort for successful comprehension, it can cause fatigue (Hockey, 2013). Fatigue is a state of physical or mental exhaustion which occurs as a response to sustained effort or stress. This exhaustion lowers physical arousal with the purpose of inducing rest and recovery. Short term increased effort can thus facilitate listening comprehension, but cause fatigue in the long term.

Measuring listening effort and fatigue

There are several ways to measure listening effort and fatigue. These measures capture different aspects of it and include self-reports of perceived effort and fatigue, behavioral measures such as dual task performance, and physiological measures of stress and arousal (Alhanbali et al., 2019; Bess et al., 2014; Murgia, 2024). A promising tool to capture arousal as an index for listening effort and fatigue is by detecting changes in pupil size using pupillometry (Alhanbali et al., 2019; McGarrigle, Dawes, Munro, et al., 2017; Van Engen & McLaughlin, 2018). The pupil responds to changes in light, but it also responds to changes in arousal. The pupil dilates in response to increased arousal as heightened sympathetic activity stimulates contraction of the iris dilator muscles. Conversely, the pupil constricts in response to decreased arousal as the heightened parasympathetic activity stimulates the iris sphincter muscles to contract (Steinhauer et al., 2004). There are two types of changes in pupil size which need to be considered: phasic and tonic changes. Tonic changes in pupil size are of importance for measuring fatigue effects. Tonic changes are slow and reflect more sustained alterations in arousal over time. A slow decrease in baseline pupil size thus indicates increased parasympathetic activity, which is considered to reflect fatigue. Phasic changes are of importance for measuring immediate listening effort. Phasic changes in pupil size are rapid moment-to-moment changes in response to immediate cognitive demands. This is believed to reflect listening effort in response to a task at a given moment. Pupillometry has been used widely to assess cognitive effort on a variety of tasks (Zekveld et al., 2018). Few studies have, however, used this method to assess listening effort and fatigue in children. One exception which has heavily influenced this thesis is McGarrigle, Dawes, Stewart, et al. (2017) who found that task-evoked phasic pupil dilations were greater in a poor listening condition (multitalker babble noise SNR -2 dB) as compared to a more favorable listening condition (multitalker babble noise SNR +15 dB). Research in adults suggest that L2 speech processing causes higher listening effort as compared to L1 speech processing (Bsharat-Maalouf et al., 2023), and that L2 listeners may experience higher effort when listening in noise as compared to L1 listeners (Borghini & Hazan, 2018).

Introduction overview

In summary, children's ability to process speech is foundational for their learning in school. Speech processing is negatively affected by noisy listening environments, and it is difficult for children to listen in their second language. Studies also indicate that it is more difficult to process a second language in noise as compared to a first language, likely due to that this requires a higher degree of explicit speech processing in working memory. This cognitive load is likely to increase listening effort and subsequent listening imposed fatigue. In this thesis, the interplay between listening in noise, listening in a second language and the role of working memory for children's speech processing, listening effort, and fatigue is investigated.

Aim

The overall aim of this thesis was to increase knowledge in how multitalker babble noise affects speech processing in primary school children of cultural and linguistic diversity.

To fulfill this overall aim, four research objectives were posed:

1) Develop and evaluate a listening comprehension task to increase reliability in assessments of young primary school children of cultural and linguistic diversity (*Study I*).
2) Investigate how multitalker babble noise affects speech processing, memory retention, listening effort and fatigue (*Studies I-IV*).
3) Investigate the role of school language exposure on speech processing, memory retention, listening effort and fatigue under different listening conditions (*Studies I-IV*).
4) Identify factors intrinsic to the listener, which best predict speech processing in quiet and in multitalker babble noise (*Study III*).

Methods

Sample

An invitation to participate in the research project was issued to all children attending mainstream education in school grades 2 and 3 at two Swedish public primary schools. These two schools had shared common features – both had, compared to the Swedish mean, a high number of enrolled students with immigration background (School A: 76%, School B: 74%, Swedish mean: 26%), and a low proportion of students with tertiary parental education level (School A: 30%, School B: 34%, Swedish mean: 60%) (Swedish National Agency for Education, 2019). A total of 98 children were recruited and tested.

Inclusion criteria

Individuals with hearing impairment face significantly greater challenges in processing speech in noise compared to those with normal hearing (Walker et al., 2019). The present investigation aimed to assess speech processing in noise in children with normal hearing. As such, all children who accepted the invitation to participate underwent a hearing screening. The hearing screening was conducted in a quiet room at the children's school. Due to this suboptimal screening condition, inclusion criteria were relatively wide: ≤25 dB BEHL at frequencies 500, 1000, 2000 and 4000 Hz. A total of 10 children were excluded from all studies due to failed hearing screening or for failing to complete the included tasks. The details of the hearing screening are described in all studies. In *Study II* (N=63), an additional 15 children were excluded due to missing pupillometric data, which was part of the outcome in *Study II*. In *Study III* (N=86), two additional children were excluded due to low performance on the Crosslinguistic nonword repetition task (<-3SD of the sample mean), as these low scores were indicative of possible undiagnosed language disorders (Schwob et al., 2021; Schwob & Skoruppa, 2022). We purposely made this exclusion criterion wide, as the published data of CL-NWRT is based on younger children, and we thus made exclusions based on our own data. In *Study IV* (N=80), where memory over time was investigated, the same two children with low performance on the CL-NWRT were excluded, as well as an additional 8 children who had extended retention intervals (>8 days) on the outcome task.

Measures of listening comprehension

The studies include two different materials of listening comprehension. *Study III* and *IV* use a narrative listening comprehension task developed and evaluated in *Study I*. As the development of this task, called *Lyssna, Förstå och Minnas* (LFM; English translation: Listen, Comprehend, and Remember), is part of the results of *Study I*, it will be described in detail in the Results. To briefly summarize, this task is composed of two Story Grammar structured narratives, similar in content, length and linguistic complexity. Comprehension of each narrative was measured by 10 corresponding multiple-choice questions, asking for information explicitly stated in the narratives.

Speech-picture verification task

In *Study II*, another measure of listening comprehension was used. The task was created to enable assessing young primary school children's speech comprehension while simultaneously measuring pupil size. To yield reliable results from the pupillometry, the task included 36 trials in total (18 per listening condition). Three trials per listening condition were excluded from analysis. Two of these were control trials and one (the first trial) was regarded as an exercise trial. In total, there were 15 trials per listening condition which were included in the analyses. The task was developed by and used in McGarrigle, Dawes, Stewart, et al. (2017) and was adapted to Swedish in the present study. The task was composed of short, three-sentence-narratives of everyday situations relatable to primary school children. As seen in Figure 1, one of the narratives was about a girl who went bird watching in a park. The first sentence provided the setting: "Linn lives near very nice park and loves walking there during the spring." The second sentence provided the critical word (a noun): "One day she brought a pair of binoculars to look for *doves* in the trees." The narrative ended with a sentence where a pronoun referred back to the critical word: "She was lucky this time as she spotted *one* sitting in their nest". In this narrative the word "dove" was the critical word. The critical word was only presented once. Except for four control trials, the critical word was always provided in the second sentence. After the narrative, the children were presented with a photograph of an object. In the example narrative, it could be either a photograph of a dove, or an unrelated object. The children were then required to determine if the object had been included in the narrative they had heard (by pressing a green key on a keyboard) or not (by pressing a red key on the same keyboard). If a child was quick to respond, the next trial was started immediately after their response. If they did not respond, the next trial started automatically after 10 seconds. Figure 1 displays how the how one trial was constructed and conducted.

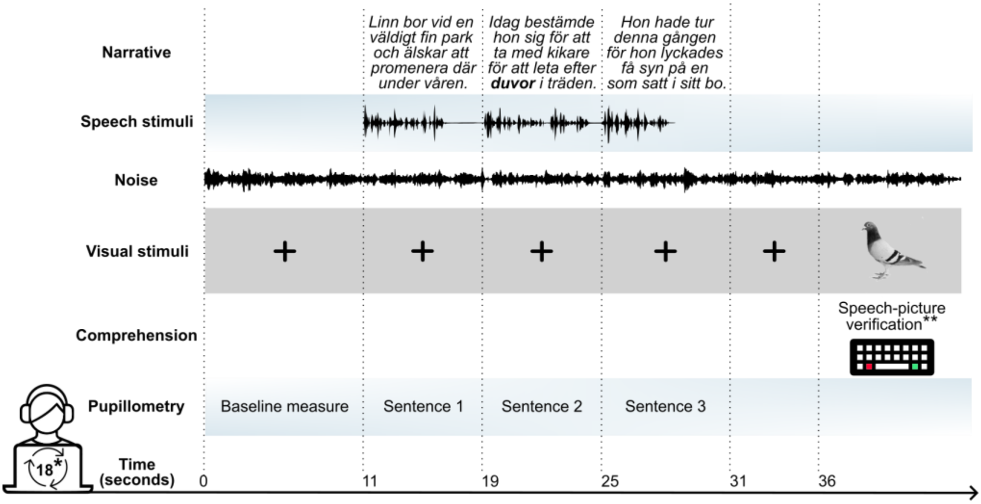

Figure 1.
Flowchart displaying one trial of the speech-picture verification task.
* 18 trials per listening condition.
** Red key = No, the object was not mentioned in the narrative. Green key = Yes, the object was mentioned in the narrative.

Measuring listening effort and fatigue

As seen in Figure 1 above, comprehension was not the only outcome of interest for this task. The children's pupil size was recorded using an eye tracker during the whole test session. As the pupil responds to changes in light, the windows were covered with curtains or blinds and ceiling lighting was switched on to keep light conditions even. The children were required to look at the computer screen where a black cross on a grey background was shown throughout the test. For speech-picture verification, the cross changed to a greyscale photo of an object. Phasic changes in pupil size, reflecting moment-to-moment listening effort were estimated by calculating the change in mean pupil size at each sentence from the baseline measure recorded just before each narrative (trial). Tonic changes in pupil size, reflecting general arousal and task engagement, were measured as the cumulative effect of mean pupil size at each baseline measure. A tonic constriction over time indicated decreased task-engagement, or increased fatigue as the task continued. Fatigue was also measured using self-reports. The children were asked to rate their experienced fatigue following each listening condition block. This self-report scale was developed by Bess et al. (2014) to assess children's current level of fatigue and was also used by McGarrigle, Dawes, Stewart, et al. (2017). The self-report scale is composed of five statements with accompanying pictorial support. The statements were: "I feel tired," "It is easy for me to do these things", "My head hurts", "It is hard for me to pay attention", and "I have trouble thinking". These statements were translated to Swedish in *Study II.* We also modified the response method. Instead of using digits (Bess et al., 2014; McGarrigle, Dawes, Stewart, et al., 2017), the children rated their self-perceived effort using a VAS scale of four circles increasing in size, ranging from the smallest circle (Not at all – 0 points) to the largest (Yes, a lot – 3 points). The scoring of the positive statement "It is easy for me to do these things" was inverted. A higher score on this self-report scale thus indicated a higher level of fatigue.

Multitalker babble noise

All studies investigate the effect of multitalker babble noise on children's comprehension and recall of spoken narratives. The same multitalker babble noise recordings, created by von Lochow et al. (2018), were used throughout the studies. It consists of four-talker babble of primary school children (girls aged 9-11 years). The noise was created by individual recordings of the children reading aloud from an age-adequate book. These individual audio files were then merged into a four-talker babble noise audio file in which individual words were indistinguishable. Three different signal-to-noise ratios were used across the studies, corresponding to what has been reported as common in primary school classrooms (i.e., SNRs -6 to +6 dB). In *Studies I, III* and *IV*, SNR +6 dB was used (Crandell & Smaldino, 2000). In these studies, the target speech was presented at 65 dB SPL. In *Study II*, two noisy listening conditions were compared: SNR 0 dB versus SNR +10 dB. These two SNRs were used as the lower (0 dB) could cause energetic masking and thus have a higher impact on bottom-up processing, while the positive would mainly cause cognitive interference through informational masking, but still be lower than what is recommended for learning activities in normal hearing children (Wang & Brill, 2021). In *Study II,* the main speech's sound level was manipulated (65 dB vs. 75 dB SPL) and the noise levels were kept constant, as potential listening difficulties would not depend on differences in absolute noise levels (Winn et al., 2018).

Quantifying school language exposure

As there is a lack of consensus regarding how to categorize and quantify bilingual language exposure, different methods for this were used in three of the four studies. In *Study I*, the children were divided into three groups: monolingual, simultaneous bilingual or sequentially bilingual. As this study included an extensive evaluation of the methodology of LFM, there was no room to develop and describe a nuanced differentiation of school language exposure. In *Study II*, several children had to be excluded due to missing pupillometry data, and thus a more rudimentary division was made. The children were labelled as either native (monolingual and simultaneous bilingual) or non-native (sequentially bilingual) Swedish speakers. As for *Study III* and *IV*, an index of school language (Swedish) exposure was used were several factors known to influence bilingual language acquisition considered. This was based on information provided by the children's caregivers and was grounded in the bilingualism and L2 acquisition research in school aged children by (Huang et al., 2018; Kohnert et al., 2021; Paradis, 2016; Soto-Corominas et al., 2020). As seen in Table 3, each of these statements can yield a score of either 0 or 1, leaving the range of the school language exposure index 0-5 points, where 0 points represent children who had been speaking Swedish for <3 years and who were not exposed to Swedish in the home, whereas in the other end, 5 points represent monolingual Swedish speaking children.

Table 3.
The creation of the Swedish exposure index: the questions the caregivers were asked about their child, and how their responses were scored.

Question	Response	Statement	Scoring
Do you as a family speak Swedish at home?	Yes	Swedish is spoken at home	1
	No	Swedish is not spoken at home	0
Do you as a family speak another language than Swedish at home?	Yes	Bilingual	0
	No	Monolingual Swedish speaker	1
Has your child always spoken Swedish?	Yes	Swedish as L1	1
	No	Swedish as L2	0
*If no, how old was your child when they started speaking Swedish?**	Age of acquisition in years*	Duration of Swedish exposure	
		< 3 years	0
		> 3 years	1
		> 6 years	1
Range			0-5

* Duration of Swedish exposure was calculated by subtracting age of acquisition from the current age. In L1 Swedish speakers the duration of Swedish exposure was thus equivalent to their age at the time of assessments. The children who had spoken Swedish for >6 years were awarded 2 points from this statement: 1 point for >3 years and 1 point for >6 years.

Working memory measures

Two working memory tasks were used: a nonword repetition task and a digit span backwards task. The idea of using these two tasks was twofold. Nonword repetition measured implicit phonological processing and is also a task which is indicative of language learning ability. The digit span backwards task was included as digits are overlearned early in both L1- and L2-acquisition, and the task also to tap into more complex cognitive processing by requiring simultaneous processing and recall of numbers.

The Crosslinguistic Nonword Repetition task

As the participants were of diverse linguistic backgrounds, the Crosslinguistic Nonword Repetition Test (with language-specific Swedish prosody) was used. This task was developed by Chiat (2015) in order to minimize effects of language background on performance, and is composed by CV-syllables of increasing length using phonemes and phoneme combinations present in most languages across the globe. The test includes 16 nonwords consisting of two syllables to five syllables, and there are four nonwords per syllable length. These crosslinguistic nonwords are dissimilar from complex Swedish words as they do not include, for example, consonant clusters (Chiat, 2015). Still, the task has been found equally difficult for monolingual and bilingual children regardless of which language is their L1 (Boerma et al., 2015). It has also been found to have high sensitivity and specificity for diagnosing developmental language disorder in both monolingual and bilingual children (Schwob & Skoruppa, 2022). The children were presented with audio recorded nonwords through a loudspeaker at a comfortable speech level and were instructed to repeat the nonwords exactly as they heard them (see *Study III* for details). Their responses were audio recorded and scored offline using a whole item approach. A nonword repeated correctly was awarded one point and an incorrectly repeated nonword was awarded 0 points.

The Digit Span Backwards task

The Digit Span Backwards (DSB) task was used as a phonological working memory task, relatively independent of language abilities, as digits are overlearned early in both monolingual and bilingual language acquisition (Engel de Abreu et al., 2013). The DSB task was used to tap into more explicit working memory processing as the task requires reorganization of information. The task used was the subtest Digit Span Backwards from the language assessment material Clinical Evaluation of Language Fundamentals – Fourth Edition, Swedish (Pearson Assessment, 2013). In addition to a practice block, the task is composed of 14 digit sequences of increasing length, divided into seven blocks. Each block contains two digit sequences of the same length, starting with two digits and potentially ending with nine digits. The children were presented with the digit series verbally by the test administrator and were instructed to repeat the exact same digits but in reversed order. The task was administered following the CELF-4 instructions. The children's responses were thus scored during assessment, and the test was terminated when the child had failed to accurately repeat two digit sequences of the same length.

Procedures

The children were assessed at two timepoints, labelled *Assessment 1* and *Assessment 2*. The intention was that these two assessments would be separated by 7 days. Due to school scheduling and unforeseen school absences, there were differences in the intervals between the two assessments: 6 days (n=20), 7 days (n=58), 8 days (n=2), 10 days (n=1) and 17 days (n=6). However, in *Study IV*, where differences in LFM recall over time was examined, children with > 8 days retention intervals were excluded. As seen in Figure 2, hearing screening, working memory tasks and LFM listening and immediate recall were conducted during Assessment 1. During Assessment 2, the children were assessed with LFM delayed recall and the pupillometry speech-picture verification task. The assessments also included additional linguistic and cognitive tasks not reported on here.

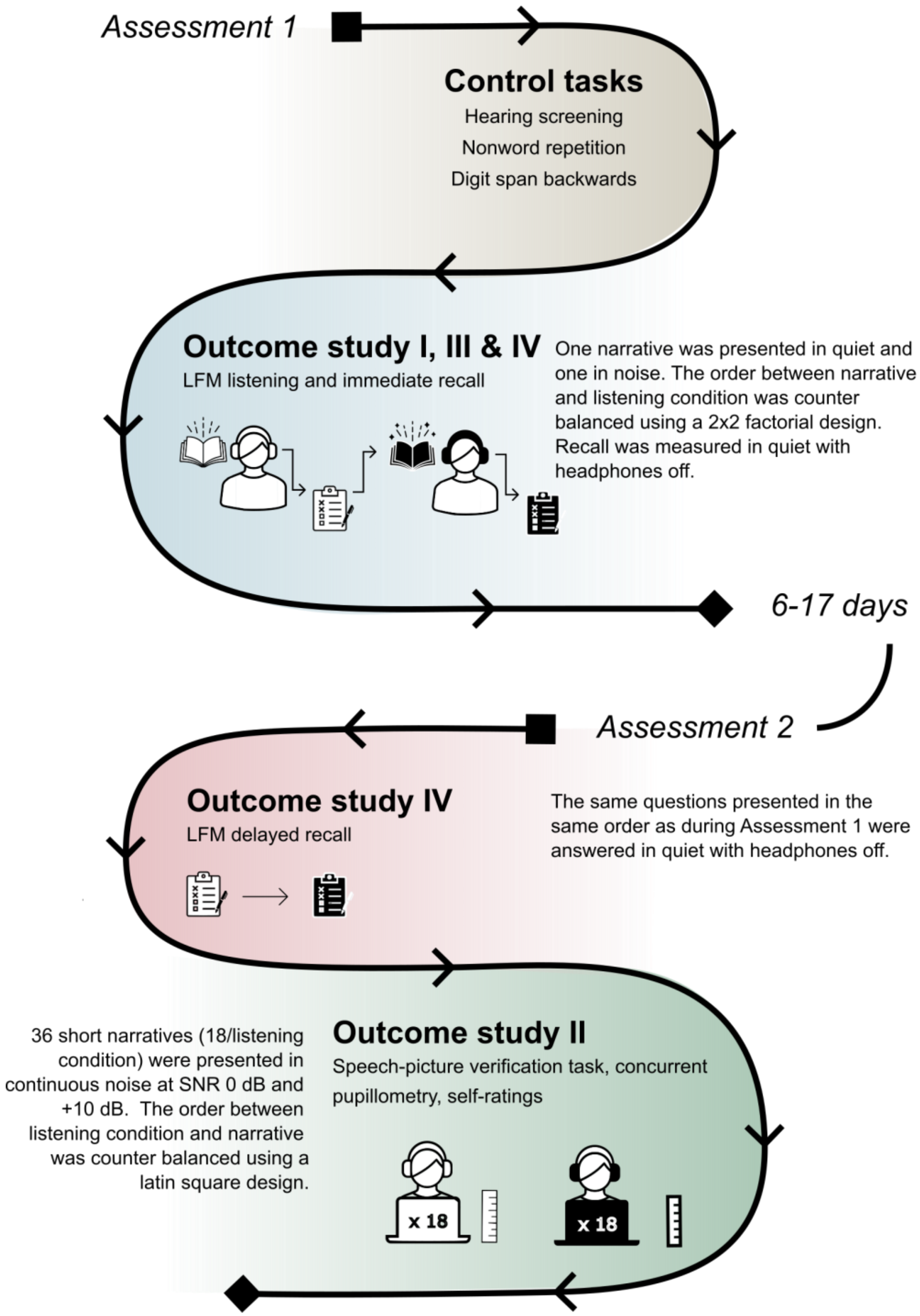

Figure 2.
Flowchart displaying the timeline of assessments as well as the counter balancing of listening conditions in LFM and Pupillometry.

Ethical considerations

The present investigation included participants who are vulnerable for several reasons. Firstly, the participants were children, and they were recruited and assessed in a context of authority – their school. Secondly, most of the children who accepted the invitation to participate in the research project had Swedish as their L2, and so did their caregivers. When recruiting through an institution of authority (school) it is essential to clarify that participation is voluntary. Prior to all assessments, I spoke to each class that was invited to participate, described the project, and emphasized that participation was voluntary. The children were made aware that they were able to withdraw their participation at any time, and the missing pupillometry data in *Study II* is partly because of this. This task was exhausting for some children who terminated the task before it ended. To study children with varying degrees of exposure to the school language, we needed to recruit children who were relatively recently exposed to the Swedish language, and as such we needed formal consent from both the children and their caregivers. The fact that caregivers could be inexperienced in the Swedish language was considered when writing the informed consent forms. The language was kept av simple as possible and included both a version written to the caregivers and one version directed to the children. To gather reliable demographic data, questions concerning the children's backgrounds were posed in accessible language and did for the most part only require a YES/NO response. In cases where we were unsure of the caregivers' responses, the caregivers were contacted again and ambiguates were solved.

For the individual children, the risks included being exposed to high noise levels, missing school lessons, and feelings of discourage if they perceived that their test did not go well. These risks were reduced as we checked noise levels prior to fitting headphones on the children. We also planned the timepoint of assessment in discussion with their teachers, so that for example, a child who was falling behind in mathematics would not be missing their mathematics lesson. We further explained to the children that the tasks included in assessments were difficult and that we did not expect that they would get all the answers right. We also praised all children doing a good job focusing on the tasks. There were also benefits for the individual children. These benefits included awareness of how straining listening in noisy environments is. This was something many children made spontaneous reflections on. Another benefit for the individual child was the insight into how research works. Many children found the pupillometric assessment interesting as they could see how their pupils were measured during the initial calibration and gained age-appropriate knowledge of how the pupil responds to stimuli. An important benefit for the individual children was being represented in research. They represented a group who is relatively underrepresented in research of speech processing in noise. As this thesis investigates the challenges children of immigration background face during listening activities in the school language

(Swedish), there is a risk on a societal level, that the results may be used for anti-immigrant political purposes. The benefits on a societal level include an increased understanding of how children of cultural and linguistically diverse backgrounds are affected by noisy listening conditions, which may serve as a guide primary education. The overall research project, Eyes right – listening effort and Swedish as a second language in the classroom, was approved in advance by the Swedish Ethical Review Authority (Registration No. 2019–02665). The research project was financed by the Swedish Research Council (Grant number 2018-04160 awarded to K. Jonas Brännström). There are no financial disclosures to declare in any of the included studies nor in the introductory part of the thesis.

Results

The results will start with a description of the development and evaluation of the narrative listening comprehension task, including the task in its whole as well as details of the task not published before. After this, the predictors of listening comprehension, recall and listening effort in each study will be summarized thematically.

Listening comprehension task

In *Study I*, the narrative listening comprehension task Lyssna, Förstå och Minnas (LFM; Eng. Listen, Comprehend and Remember) was described and evaluated. This task was developed in several steps to ensure that the two narratives were as similar as possible in overall content and linguistic complexity. A pilot version of this task was created, and tested in Carlie (2018) and Carlie and Dahlquist (2019). The premises when creating the task was that it should be similar in scope as the narratives in the subtest “Listening comprehension” in the language assessment material Clinical Evaluation of Language Fundamentals, – Fourth edition, Swedish version (CELF-4) (Pearson Assessment, 2013). These narratives had been used in prior studies of primary school children’s listening comprehension in noise (Brännström et al., 2018; Nirme et al., 2019; Rudner et al., 2018; von Lochow et al., 2018), and were deemed suitable for the purpose when assessing children of Swedish origin, but less reliable when assessing children of non-European backgrounds who might not have had the same culture-specific experiences as the Swedish and European born children had.

Prior knowledge: Cultural and linguistic considerations

One approach to get around culture-specific settings and plots was tested by Ljung et al. (2009), who created fictive cultures which no one could have any prior knowledge of. Inspired by Ljung et al. (2009), the narratives were thus set in fictive pre-historic civilizations. An archaeologist provided contextual information of two specific stone age and bronze-age excavations in southern Sweden. These descriptions served as an inspiration for the settings of the narratives. Although not explicitly stated, Narrative A was set in a bronze-age village, and Narrative B was about a stone-age nomadic people. Not only the settings should be “universal”, meaning that all children, regardless of cultural heritage should have equal prior knowledge of them, but also the plots. The plots of classic fables were explored, and two common overarching plots were found: to fool and to be fooled. These two plots were considered to be relatable to most children of primary school age. In Part A, the plot is about the consequences of lying when making a mistake. In Part B, the plot is about trying to please bullies to make them your friends. To make the narratives relatable to the children listening, the protagonists were children – a girl in Narrative A and a boy in Narrative B. The ages of the protagonists are not stated, but they are described in a way that it is implied that they are of primary school age.

Narrative plots

In Table 4, the two narratives are presented in full. As seen in Table 4, the narrative of Part A is about a girl called Naba. She lives with her large family in a village and is responsible for collecting water in a nearby river to the family every morning. One morning she is tired, and it is raining, so she cuts a corner and collects water from a dirty puddle. As the day continues, and the family is drinking the dirty water, her brother is starting to get ill. The family calls a doctor, who does not know what to do since they do not know the cause of his illness. Naba struggles to tell the truth, but eventually does so. The doctor is then able to cure Naba’s brother, and Naba concludes that she should never collect dirty water again. As seen in Table 4, the narrative of Part B is about a boy called Anak who lives with a nomadic people who are on a long migration towards a new settlement. Anak is a lonely boy who only has a father and a horse which his dead mother gave to him. On this long migration, a boy pretends to befriend Anak and tricks him that his sister has injured her foot so that they do not have to walk like most of the others do, but ride Anak’s horse instead. Anak is happy that someone wants to be his friend and lend the siblings his horse. When they finally arrive Anak realizes that they have tricked him. The boy did not want to be Anak’s friend, and the sister did not have an injured foot. Anak then concludes that he should not trust everyone.

Table 4.
The narratives of Lyssna, Förstå och Minnas (LFM)

Part A	Part B
Det fanns ett land för länge sedan som hette Kolani. Landet bestod av flera hundra öar. På en av öarna fanns en by som hette Vator. Där bodde åtta familjer i varsitt stort hus. I ett av husen bodde flickan Naba tillsammans med sina föräldrar, sin mormor och fem syskon.	För många tusen år sedan fanns ett ställe som hette Tonam. Det låg långt bort vid havet. Då fanns en grupp människor som kallade sig för Panose-folket. De brukade bo där under somrarna. När det blev vår började de vandra dit. De vandrade varje dag i nästan två månader för att komma fram.
Naba gick för att hämta vatten i en flod tidigt varje morgon. Floden låg några hundra meter utanför byn. På vägen dit fick Naba hoppa över ett staket som gick runt byns åkrar. De var tvungna att ha staket där. Annars åt djuren upp maten som de odlade. Efter åkrarna gick Naba genom en skog. Där växte höga träd med små gröna och gula blad. Hon hade med sig två gråa trähinkar för att hämta vattnet i. Det var tungt att bära, men Naba var van. Hon hade haft ansvar för att hämta vatten till familjen varje morgon i två år nu.	De flesta gick hela vägen, men det fanns några som hade hästar att rida på. En av dem var en pojke som hette Anak. Han hade inga syskon och var ganska ensam. När hans mamma dog hade han fått hennes häst. Den var svart och ganska liten och den finaste häst Anak någonsin sett. Många var avundsjuka på honom, särskilt de som aldrig hade ridit innan. En kille som hette Mile hade sagt att han skulle försöka ta hästen från Anak. Men alla visste att Anak älskade sin häst. Därför trodde de inte att han skulle lyckas.
En morgon vaknade Naba och kände sig tröttare än vanligt. När hon tittade ut genom dörren såg hon att det regnade. På väg till floden upptäckte hon en liten grop. Den var nu helt vattenfylld av regnet. Hon tog sina hinkar och fyllde dem med vatten från gropen. Det såg lite smutsigt ut, men hon tänkte att ingen skulle märka det.	En morgon satt Anak på en sten och åt frukost. Då kom killen fram och satte sig bredvid honom. Han bjöd på lite nötter. De småpratade en stund och hade sedan sällskap under vandringen. Anak kände sig glad över att äntligen ha fått en vän.
Under dagen drack hela familjen av vattnet som Naba hade hämtat. Nabas syster lagade soppa till middag. Ingen märkte någon skillnad. Men så blev Nabas lillebror Abim plötsligt väldigt sjuk. Ingen förstod varför han hade blivit så sjuk. Men Naba vågade inte berätta om vattnet. Hon var rädd att de andra skulle bli arga på henne.	Några dagar senare berättade killen att hans syster hade skadat sig i foten. Han frågade om han kunde få låna hästen för att rida med sin syster. Anak ville inte lämna ifrån sig hästen. Men när han såg att systern haltade tyckte han synd om henne, så han lämnade över hästen till syskonen.
Allt eftersom dagen gick blev Nabas lillebror bara sjukare och sjukare. Familjen hämtade byns doktor. Doktorn sa att om hon bara visste varför han hade blivit sjuk så skulle hon kunna göra honom frisk igen. Under kvällen blev han ännu sjukare. Familjen trodde att han inte skulle överleva.	De red på den varje dag under resten av vandringen. Varje natt fick Anak mata hästen med extra gräs för att den skulle orka bära båda syskonen. Anak frågade om han kunde få tillbaka hästen flera gånger, men de sa nej varje gång. Anak fick fortsätta att gå helt själv. Dagarna var väldigt varma och han blev alldeles svettig av att gå.
Då bestämde sig Naba för att berätta om vattnet för doktorn. Då kunde doktorn ge rätt medicin. Nästa morgon var Nabas lillebror trött men frisk. Doktorn gick hem. Naba tänkte: Jag ska aldrig hämta smutsigt vatten igen.	Efter fem veckor kom de fram till havet. Killen och hans syster hoppade ner från hästen och sprang iväg till de andra barnen i gruppen. Systern haltade inte längre. Anak stod kvar ensam med sin häst, men utan vänner. Nu hade han själv ont i benen. Anak tänkte: Jag kanske inte kan lita på alla.

Difficulty level

The narrative texts were analyzed and compared using a Swedish readability index, Läsbarhetsindex (LIX) (Björnsson, 1968; Semios) in order to estimate the linguistic complexity of the narrative texts as well as to discover potential differences in linguistic complexity between them. As seen in Table 5, Part A is a bit shorter, includes a slightly greater number of long words (>6 characters) and slightly shorter sentences than Part B, but overall, they are similar in linguistic complexity.

Table 5.
The readability index (LIX) analysis for the two narrative texts: Part A and Part B.

LIX analysis	Part A	Part B
Sentences (N)	39	36
Words (N)	354	365
Words >6 characters (N)	48	39
Average sentence length	9.08	10.14
Proportion long words	13.56	10.68
Readability index (LIX)	23	21
Interpretation	<30: Children's book	<30: Children's book

Measuring comprehension and recall

The narratives were created side-by-side with the multiple-choice questions. There were more questions in pilot version (24 questions/narrative) than in the final version (10 questions/narrative) described in *Study I*. As seen in Table 6, the pilot version questions helped guide the narrative content, so that the same number of sub-plots, deuteragonists (N=2/narrative) and details were included. Informal assessments including both children and adults were conducted where the narratives, the questions and response options were evaluated and modified. To avoid floor- and ceiling- effects, the aim was to have a correct response distribution between 30-70%. These pilot testings showed that the two narratives yielded similar test scores as measured by a set of multiple-choice questions. The mean and distribution of scores also indicated that the task was of adequate difficulty for the target group. When preparing for the present investigation, the number of multiple-choice questions were deemed too extensive as the children were to perform a battery of cognitive tasks. While the pilot testings showed that the two narratives were similar in difficulty as measured by the multiple-choice questions, the questions that were matched, were not of equal difficulty. We thus analyzed the previously collected data (Carlie, 2018; Carlie & Dahlquist, 2019) to reduce the number of questions. The number of questions were reduced to N=10/narrative based on an integrated evaluation of Intraclass Correlations analyses, Chronbach's Alpha and to keep a spread in the chronological order of the questions. The final multiple-choice questions for Part A are seen in Table 7, and for Part B in Table 8.

Table 6.
The multiple-choice questions of the pilot version including 24 questions per narrative, which were matched in content between the two narratives. The questions of Part A are presented in chronological order of the narrative, and the questions of Part B are presented to display how they were matched to Part A. The final included questions are highlighted in italics.

Part A		Part B	
1	Vad hette landet i berättelsen?	1	Vad kallades folket i berättelsen?
2	Vad hette byn som de bodde i?	2	Vad hette platsen vid havet?
3	Vad hette flickan i berättelsen?	3	Vad hette den första pojken i berättelsen?
4	Vad hette flickans lillebror?	4	Vad hette den andra pojken i berättelsen?
5	Var låg Vator?	6	Var låg Tonam?
6	*Hur många familjer bodde i byn?*	9	Hur många syskon hade Anak?
7	Vilka bodde Naba tillsammans med?	12	Vilka var mest avundsjuka på Anak?
8	Var brukade Naba hämta vatten?	15	Var satt Anak och åt frukost?
9	*När brukade Naba gå och hämta vatten?*	8	När började Panose-folket vandra till Tonam?
10	*Vad fanns innanför staketet som Naba hoppade över?*	*16*	*Vad bjöd killen på till frukost?*
11	*Hur såg bladen på träden i skogen ut?*	22	Hur var vädret i slutet vandringen?
12	Vilken färg hade Nabas hinkar?	*11*	*Vilken färg hade hästen?*
13	*Hur länge hade Naba hämtat vatten åt familjen?*	*5*	*Hur länge sedan levde Panose-folket?*
14	Hur upptäckte Naba att det regnade?	*7*	*Hur tog de flesta sig till Tonam?*
15	*Var hämtade Naba vatten denna dagen?*	19	Var hade systern skadat sig?
16	*Vilka drack av vattnet som Naba hade hämtat?*	21	Vilka gick Anak med under resten av vandringen?
17	Vem var det som blev sjuk?	10	Vem hade Anak fått sin häst av?
18	*Varför vågade Naba inte berätta att hon hade hämtat smutsigt vatten?*	18	Varför lämnade Anak ifrån sig hästen?
19	Vad gjorde familjen när Abim blev sjukare?	*13*	*Vad exakt sa killen till de andra att han skulle göra?*
20	Varför blev familjen oroliga när det blev kväll?	*14*	*Varför trodde inte de andra att killen inte skulle lyckas?*
21	*Varför kunde doktorn ge rätt medicin till Abim?*	*20*	*Varför var Anak tvungen att ge hästen extra mat?*
22	Hur kände sig Abim dagen efter?	17	Hur kände sig Anak när han först lärde känna killen?
23	*Vad hände efter att Abim hade blivit frisk?*	*23*	*Vad gjorde systern när de kommit fram till havet?*
24	Vad tänkte Naba efter att Abim blivit frisk?	*24*	*Vad tänkte Anak när de hade kommit fram till havet?*

Table 7.
The final multiple-choice questions and response options for Part A.

Part A		
Questions		**Reponse options**
1)	Hur många familjer bodde i byn?	a) Sex. b) Tio. c) Åtta. d) Tolv.
2)	När brukade Naba gå och hämta vatten?	a) Tidigt på morgonen. b) När alla hade vaknat. c) Efter frukost. d) Tidigt på kvällen.
3)	Vad fanns innanför staketet som Naba hoppade över?	a) Djur. b) Hus. c) Åkrar. d) Ängar.
4)	Hur såg bladen på träden i skogen ut?	a) Små. b) Avlånga. c) Runda. d) Träden hade inga blad.
5)	Hur länge hade Naba hämtat vatten åt familjen?	a) Två månader. b) Tre år. c) Tre månader. d) Två år.
6)	Var hämtade Naba vatten denna dagen?	a) I en brunn. b) I en damm. c) I en grop. d) I en flod.
7)	Vilka drack av vattnet som Naba hade hämtat?	a) Hela familjen. b) Hela byn. c) Bara Abim. d) Alla utom Naba.
8)	Varför vågade Naba inte berätta att hon hade hämtat smutsigt vatten?	a) Hon visste inte att vattnet var smutsigt. b) Hon var rädd att de skulle bli arga på henne. c) Hon orkade inte gå och hämta nytt vatten. d) Hon var rädd för doktorn.
9)	Varför kunde doktorn ge rätt medicin till Abim?	a) För att Abim blev sjukare och sjukare. b) Doktorn visste redan varför Abim var sjuk. c) Doktorn hade läst det i en bok. d) Naba berättade att hon hade hämtat smutsigt vatten.
10)	Vad hände efter att Abim hade blivit frisk?	a) Abim kräktes igen. b) Doktorn stannade en dag till. c) Abim bad om vatten och mat. d) Doktorn gick hem.

Table 8.
The final multiple-choice questions and response options for Part B.

Part B		
Questions		**Reponse options**
1)	Hur länge sedan levde Panose-folket?	a) Många hundratusen år sedan. b) Många tusen år sedan. c) Många hundra år sedan. d) Många tiotusen år sedan.
2)	Hur tog de flesta sig till Tonam?	a) De red. b) De gick. c) De sprang. d) De åkte häst och vagn.
3)	Vilken färg hade hästen?	a) Brun. b) Grå. c) Svart. d) Mörkbrun.
4)	Vad exakt sa killen till de andra att han skulle göra?	a) Han skulle hjälpa sin syster. b) Han skulle rida tillsammans med Anak. c) Han skulle rida tillsammans med sin syster. d) Han skulle ta hästen ifrån Anak.
5)	Varför trodde de andra inte att killen skulle lyckas?	a) För att han var dålig på att luras. b) För att han var en bra vän. c) För att han inte kunde rida själv. d) För att Anak älskade sin häst.
6)	Vad bjöd killen på till frukost?	a) Frön. b) Frukt. c) Nötter. d) Bröd.
7)	Varför var Anak tvungen att ge hästen extra mat?	a) För att den skulle orka bära syskonen. b) För att det var en så liten häst. c) För att vandringen var så lång. d) För att den alltid var så hungrig.
8)	Hur var vädret i slutet vandringen?	a) Väldigt varmt. b) Väldigt kallt. c) Ljummet och skönt. d) Det regnade.
9)	Vad gjorde systern när de kommit fram till havet?	a) Hon hade ont i benet och haltade fortfarande. b) Hon klappade hästen. c) Hon hoppade ner och sprang iväg. d) Hon tackade Anak för att hon hade fått rida på hans häst.
10)	Vad tänkte Anak när de hade kommit fram till havet?	a) Att det var bra att ha en häst. b) Att han hade fått nya vänner. c) Att han kanske inte kunde lita på alla. d) Att han hade ont i benen.

Comparisons between the two LFM parts

The findings of *Study I* showed that the two parts were similar in level of difficulty. There were no significant order effects. There were no significant differences in mean scores between Part A and B, and no significant differences depending on the order (Part A followed by Part B or vice versa) in which they were presented. The mean scores in a quiet listening condition were rounded to 6 out of 10 points in both narratives. In percentage, this was similar as seen during pilot testings (Carlie, 2018; Carlie & Dahlquist, 2019). As seen in Figure 3, the distribution of scores were slightly wider for Narrative B than for Narrative A, and this was also seen during the pilot testings (Carlie, 2018; Carlie & Dahlquist, 2019).

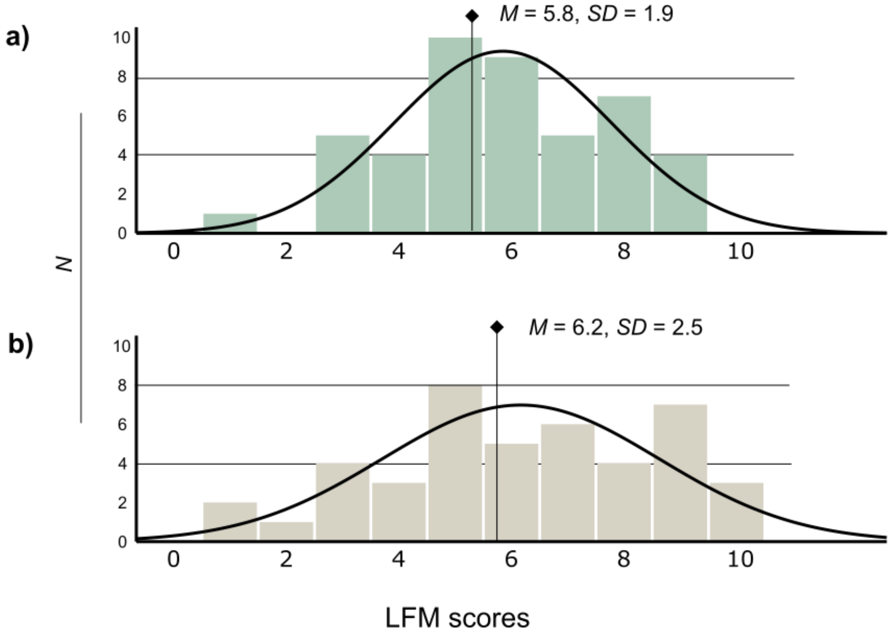

Figure 3.
Histograms displaying the distributions, mean scores and standard deviations of LFM recall in the quiet listening condition for a) Narrative A (n=43) and b) Narrative B (n=45). Mean scores were similar between the two narratives, but Narrative A had a slightly narrower distribution of scores compared to Narrative B.

Multitalker babble noise

All studies investigate the effect of multitalker babble noise on children's comprehension and recall of spoken narratives. In *Study I, III* and *IV*, LFM performance in quiet was compared to LFM performance in multitalker babble noise at a SNR of +6 dB. In *Study II*, two noisy listening conditions were compared: SNR 0 dB and SNR +10 dB. As seen in Table 9, all studies pointed to negative effects of multitalker babble noise on speech comprehension.

Table 9.
Summary of the findings concerning the effect of multitalker babble noise. Memory retention refers to the difference in performance between immediate and delayed recall. Listening effort refers to a pupil dilation between a baseline measure and the mean pupil size of Sentence 2 in the speech-picture verification task. Fatigue refers to a tonic pupil constriction (in baseline measures) as a function of trials (time).

Study	Immediate recall	Memory retention	Listening effort and fatigue
II	Higher recall accuracy for the narratives encoded in SNR +10 dB as compared to 0 dB.	-	Higher listening effort in SNR 0 dB as compared to in +10 dB. Increased fatigue over time in SNR 0 dB as compared to +10 dB. Self reports of fatigue did not differ between listening conditions.
III	An average of 1 point higher recall for the narrative encoded in quiet compared to in multitalker babble noise.	-	-
IV	Higher recall accuracy for the narrative encoded in quiet than in multitalker babble noise.	Similar recall accuracy on delayed recall for both listening conditions. Retention was better for the narrative encoded in multitalker babble noise than in quiet.	-

School language exposure

As seen in Table 10, there was an overall positive effect of increased school language exposure on performance on the listening comprehension tasks throughout the studies. This positive effect of increased school language exposure was present regardless of how the children's extent of experience in the Swedish language was measured.

Table 10.
Summary of the findings concerning the effect of school language exposure on listening comprehension and recall. Memory retention refers to the difference in performance between immediate and delayed recall. Listening effort refers to a phasic pupil dilation between a baseline measure and Sentence 2 during the speech-picture verification task. Fatigue refers to a tonic pupil constriction in baseline measures as a function of trials (i.e. over time).

Study	Immediate recall	Memory retention	Listening effort and fatigue
II	Higher overall recall accuracy in the children with L1- than L2- school language. The difference in recall accuracy between the two listening conditions was only seen in the children with L2 school language.	-	Higher listening effort in SNR 0 dB as compared to in +10 dB in children with L2-, but not L1- school language. Higher effort was associated with a correct recall response in children with L1-, but not L2- school language. No evidence for differences in fatigue between the language groups, neither concerning self-ratings nor pupillometry.
III	Higher recall scores with increasing school language exposure, but no interaction effect with listening condition.	-	-
IV	Increasing recall accuracy with increasing school language exposure, but no interaction effect with listening condition.	No difference in memory retention in either listening condition depending on language background.	-

Working memory

Working memory capacity was assessed using two different tasks, the Digit Span Backwards (DSB) task and the Crosslinguistic Nonword Repetition Task (CL-NWRT). As seen in Figure 4, the children's distribution of scores were rather narrow on both tasks. There were two outliers on the CL-NWRT who were excluded from *Study III* and *Study IV*, as these low scores were regarded as indicative of potential undiagnosed language disorders (Boerma & Blom, 2021). The children's DSB mean scores (3.88 points) were rounded to 4 points which is equivalent to being able to repeat 3-digit series backwards, which according to the CELF-4 normative data is average for the age span 7-9 years (Pearson Assessment, 2013). The children's mean CL-NWRT score was 13.5 (13.7 points excluding the two outliers), which is slightly higher than available data on typically developing 7-8 year-old monolingual and bilingual children (Boerma & Blom, 2021). This indicates that the included children had typical working memory capacity for their age. There were no significant differences in working memory capacity, on neither test, between the children with low versus high experience in the school language, regardless of how school language exposure was measured.

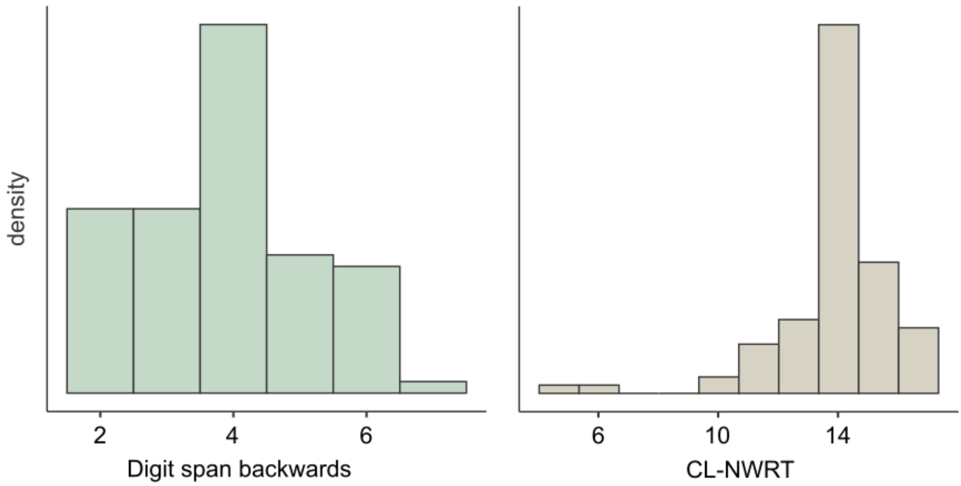

Figure 4.
Histogram showing the distribution of scores on DSB (left) and CL-NWRT (right) for the children included in *Study I* (n=88). The two outliers which were excluded from *Study III* and *IV* are seen at the lower end in the histogram of CL-NWRT.

Working memory as a predictor for listening comprehension and memory recall

In *Study III*, accuracy on the CL-NWRT was positively associated with LFM comprehension/recall in both listening conditions. Performance on the CL-NWRT was a strong predictor for LFM performance, with a similar predictive value as school language exposure. There was no significant interaction effect between CL-NWRT performance and listening condition, suggesting that phonological rehearsal ability, or implicit working memory processing, was of equal importance in both listening conditions. Performance on the Digit Span Backwards (DSB) task was a significant predictor for recall accuracy in *Study IV* but crossed the line to non-significant in *Study III*. *Study IV* showed stronger positive associations between recall accuracy on LFM (immediate and delayed recall combined) for children with increasing school language exposure. *Study III* pointed to age differences in associations between listening comprehension (LFM) and working memory as measured by the DSB task. In the younger children, there was a positive association between DSB scores and LFM performance in quiet, but not in multitalker babble noise. In the older children, this association was reversed. In these children, there was a positive association between DSB scores and LFM performance in multitalker babble noise, but not in quiet.

Associations between the working memory tasks

Study III was a comprehensive study including several sub-aims and multiple predictors for narrative listening comprehension. One aspect which was not covered in this study was a deeper analysis of what the interaction effect between digit span backwards, age and listening condition could be caused by. The discussion of *Study III*, covers a qualitative shift in working memory processing around the age of 8 years as described by Gray et al. (2017) as a possible explanation for these age differences. A deeper dive into the *Study III* data showed that the association between the two working memory tasks differed depending on age. In the younger children (grade 2, mean age=8:5 years:months, SD=5 months) there was no significant association between DSB (mean=3.8, SD=1.3) and CL-NWRT (M=13.7, SD=1.6), r=-.008, p=.961. In the older children (grade 3, mean age=9:4 years:months, SD=4 months), there was a significant association between DSB (M=4.0, SD=1.3) and CL-NWRT (M=13.6, SD=1.4), r=.453, p=.003. Overall, this suggests developmental differences in working memory processing between the age of 8-9 years.

Cognitive load

The included studies were all designed to experimentally cause a cognitive load. The comprehension/recall scores overall decreased with decreasing exposure to the school language. Lower comprehension as measured by recall scores indicates poorer school language proficiency but can also indicate an increased cognitive load. The noise also decreased comprehension/recall which is indicative of a cognitive load. Most clearly, lower a lower SNR in *Study II*, was associated with higher listening effort and a steeper decline in tonic pupil size, indicative of fatigue as compared to a higher SNR.

General discussion

The aim of this thesis was to investigate how multitalker babble noise affects speech processing, listening effort and fatigue in children of cultural and linguistic diversity. To fulfill this aim, we first needed a listening comprehension test suitable for young primary school children of cultural and linguistic diversity. This task, Lyssna, Förstå och Minnas (LFM) was developed and evaluated in *Study I*. Using LFM, we demonstrated decreased comprehension, as measured by recall using multiple-choice questions, in multitalker babble noise as compared to in quiet, and in children with less exposure to the school language (Swedish) as compared to children with more exposure to the school language. In all, it was deemed that LFM was a suitable task for assessing comprehension and memory for speech in the target group. The effect of multitalker babble noise on comprehension and memory of spoken narratives was investigated. All studies pointed to negative effects of multitalker babble noise on immediate listening comprehension. This was seen when comparing performance in quiet to performance in noise in *Study III*, but also when comparing two noisy listening conditions in *Study II*. Multitalker babble noise with decreasing SNRs impaired comprehension of spoken narratives. Using pupillometry, the results of *Study II* pointed to that a decreasing SNR increased listening effort and subsequent task disengagement, interpreted as fatigue. *Study IV* pointed to that the negative effect of multitalker babble noise may be temporary, as we found no negative effects of noise on memory retention. Less straight forward was the results on the effect of multitalker babble noise in children with varying degrees of experience in the school language (Swedish), used in assessments. The studies utilizing LFM, did not find a difference in the effect of multitalker babble noise depending on school language exposure, regardless of how this was measured. *Study II,* which used a different task, including more and much shorter narratives, found that children with less experience in the school language had poorer task performance and increased listening effort in multitalker babble noise with a low SNR as compared to a high SNR. There was little evidence for a mediating effect of working memory capacity for speech processing in noise, as described in the ELU model (Rönnberg et al., 2021; Rönnberg et al., 2013; Rönnberg et al., 2010). *Study III* pointed to a positive association between nonword repetition and comprehension overall, and age differences in the association between Digit Span Backwards and comprehension/recall across the two listening conditions.

Listening comprehension

Two measures for listening comprehension were used in the included studies: in *Study II*, 36 three sentence narratives developed by McGarrigle, Dawes, Stewart, et al. (2017) and in *Study I*, *III* and *IV*, LFM, composed by two longer Story Grammar structured narratives.

Listen, Comprehend, and Remember

The narrative listening comprehension task (LFM), developed in *Study I*, was considered to be of appropriate difficulty level for the target group, and the two narratives were deemed to be of similar difficulty. This is in line with the findings of Dzgoeva and Westerberg (2023) and Bengtsson and Ewald (2023) as well as studies using the pilot LFM version including 24 multiple-choice questions per narrative (Carlie, 2018; Carlie & Dahlquist, 2019). The narrative comprehension task differentiated between immediate listening comprehension under different listening conditions, and performance increased continuously depending on children's extent of exposure to the Swedish language. In all, this points to the validity of the task. LFM fills a gap in the array of test materials available in Swedish which can be used in within-subject studies on young primary school children's comprehension and memory for speech under various listening conditions.

Comparisons between listening comprehension tasks

The two tasks used to assess listening comprehension in the included studies, share some common features. They both include passages in the narrative genre as well as protagonists within the primary school range. Although they differ in scope and how comprehension is measured, the ratio between length of the narratives and number of questions are similar. The *Study II* narratives have one speech-picture verification comprehension "question" per three sentences. As for the LFM, the ratio is 3.9 (Part A) versus 3.6 (Part B) sentences per comprehension question. However, aside from this, the tasks are quite dissimilar. The LFM narratives took about 2 minutes and 30 seconds to listen to. This means that the children most likely had the time to form a somewhat complete situation model of the narratives. The short narratives of *Study II* did not include all Story Grammar components, they took only about 20 seconds to listen to, and the shift between a concluded narrative and a new one was fast. After the children had responded to the speech-picture verification task, each passage started with 10 seconds of isolated multitalker babble noise where the child could be attuned to the upcoming speech passage. This fast shifting between tasks was not present in the LFM. Answering the LFM recall questions took about 5-10 minutes per narrative, depending on how quick the child was to respond. This means that the children did not have to switch fast between completely different speech materials during LFM as in the *Study II* narrative task. There was also a difference in how comprehension was measured in *Studies I, III* and *IV*, as compared to *Study II*. The LFM questions could be complex, and linguistically dense. They did not only require the children to remember if an object was mentioned or not, but what qualities that object had and in which context it was presented. However, the LFM multiple-choice questions also provided cues for memory retrieval as they were linguistically dense. These semantic cues were not present in *Study II*. A possible advantage of *Study II* was that the speech-picture verification task was visual and did not place any demands on spoken language comprehension as the LFM multiple-choice questions did. Further, comprehension was measured at word level (was an object mentioned or not) in *Study II*. This is a rudimentary measure of narrative comprehension, but it is also a high-stake comprehension measure. To get the answer wrong, it only required a child to lose focus for a brief moment when the critical word was given or lack semantic knowledge of solely the target word, while comprehending the rest of the speech passage. The narratives of *Study II* were also less dynamic than the LFM narratives. Regardless of the duration of the previous sentence, the next sentence always began at the same time point. This could have influenced the children's perception of the task, but also made the narratives of *Study II* more predictable than the LFM narratives. During assessments, the children were perceived as more engaged while listening to the LFM narratives than the *Study II* narratives. During the narrative assessment of *Study II*, several children had to be reminded to focus on the task as their gaze started to wander, and some children discontinued the task as they found it too effortful to complete. It is possible that children were less motivated during the assessment of *Study II*, than during the LFM assessments.

Potential future improvements of LFM

LFM was created specifically to enable within-subject studies of the effect of adverse listening conditions on listening comprehension. The overall structure of the task was highly influenced by the narratives in CELF-4 (Pearson Assessment, 2013) which had been used in prior studies of children's speech processing in noise (e.g. Nirme et al., 2019; Rudner et al., 2018). In these studies, the comprehension questions had been modified from open ended questions which were difficult to score for quantitative analyses, to multiple-choice questions. LFM only asks for information explicitly stated in the narratives, although there are questions which are more easily answered if the child has made adequate inferences from the narrative. The use of questions solely tapping explicitly stated information was based on the findings of Nirme et al. (2019), which suggested that the ability to answer inferential questions were not as impaired by babble noise as questions tapping explicitly stated content. In hindsight, the lack of inferential questions limits the task's area of application, as the ability to make adequate inferences of the presented discourse is an essential component of listening comprehension (Kim, 2016). The studies of Dzgoeva and Westerberg (2023) and Bengtsson and Ewald (2023) included more monolingual children, and in line with the finding of the present study, the mean scores were slightly higher for this population, suggesting that the task could be too easy for assessing monolingual children with typical language development in grade 3 (Swedish system). Alterations to the task, such as more extensive narrative content, and modifications of the multiple-choice questions and their response options, could extend the test's area of application. The similarity between the response options could have confused some children and is also a factor which should be considered.

Multitalker babble noise

Throughout the studies, multitalker babble noise had a negative effect on the children's ability to comprehend and recall spoken information. *Study II* pointed to negative effects of decreasing SNRs. As positive SNRs are less likely to cause energetic masking, *Study III* pointed to negative effects of informational masking and cognitive interference beyond disturbed bottom-up processing (Brungart, 2001). Overall, the findings of negative effects of multitalker babble noise are in line with prior studies of children's speech processing in a broad sense (Klatte et al., 2013; Lamotte et al., 2021; Porto et al., 2023; Schiller et al., 2022; Shield & Dockrell, 2003), but also narrative listening comprehension specifically (Brännström et al., 2018; Lyberg-Åhlander et al., 2015; Nirme et al., 2019; Rudner et al., 2018; von Lochow et al., 2018).

Retention and learning in noise

In *Study IV*, memory retention for speech encoded in multitalker babble noise was investigated. *Study IV* showed that the initial negative effect of multitalker babble noise on comprehension and recall of speech was temporary and that encoding (i.e. listening) in noise did not lead to impaired memory for speech over time. On the contrary, *Study IV* pointed to forgetting rates for the narrative encoded in quiet, but not for the one encoded in multitalker babble noise with similar recall scores on both narratives one week (+/- 1 day) after encoding. *Study IV* could to a certain extent be considered a replication of Brännström et al. (2018) where narrative listening comprehension and memory retention (difference between immediate and delayed recall) was investigated in primary school children. Contrary to *Study IV*, Brännström et al. (2018) found impaired memory retention for both noisy and quiet listening conditions, and the descriptive findings indicated that memory retention could be poorer in noise than in quiet. *Study IV* pointed to large individual differences in retention, especially for the noisy listening condition. Although there are few studies on the specific topic of how encoding (i.e. listening) in noise affects later retention of speech, noise may actually increase episodic memory recall (Stansfeld et al., 2005), possibly due to increased arousal enhancing memory consolidation (McGaugh, 2006; Schwabe et al., 2012). It is also possible that the use of multiple-choice questions accounted for a more stable retention of the narrative encoded in multitalker babble noise than the one in quiet (Riley & McGregor, 2012). While studies on adults' reading also have shown positive effects of noise (Angwin et al., 2017; Brännström & Waechter, 2018), it is important to note that the children in *Study IV* were only exposed to the multitalker babble noise for about 2 minutes 30 seconds, which is a short duration of noise exposure as compared to a full school day. This duration was likely too brief to cause fatigue effects, which as seen in *Study II* did not become evident until after a few minutes of listening. However, what *Study IV* points to is that the immediate negative effect of noise on speech processing does not necessarily translate to impaired learning.

Prior knowledge

Unsurprisingly, the findings of the included studies showed that children's extent of knowledge in the assessed language was crucial for their listening comprehension. Regardless of how school language exposure was measured, children with higher degrees of exposure to Swedish had better comprehension and recall of speech. The Swedish exposure index pointed to that language acquisition is a gradual process, and for children learning a second language, it takes many years of schooling to reach L1 proficiency (Kohnert et al., 2021; Paradis, 2019; Soto-Corominas et al., 2020).

Measuring experience in the school language

When preparing for the data collection, we did not have full control over recruitment. As the children were recruited through their schools, all children who wanted to participate were welcome to do so. Initially, our goal was to compare monolingual children to bilingual children. During recruitment and assessments, it became apparent that the children were of much more diverse linguistic backgrounds than we anticipated. The group of monolingual children who accepted the invitation to participate was small in comparison to the number of bilingual children. Within the research group, we had recurring discussions of how to best represent these differences. This became a challenging task as there is no consensus for how to measure and quantify bilingual language exposure, and studies point to vast challenges in collecting reliable language exposure estimates from children's caregivers (Marian & Hayakawa, 2021). From our prior experiences regarding collecting information from caregivers who are nonnative to the Swedish language, it was deemed crucial to keep information and questions concise and easily comprehensible. For example, to determine Age of L2 Acquisition, we did not ask the caregivers "How long has your child been exposed to Swedish?". Instead, we phrased it "Has your child always spoken Swedish? (YES/NO)", and a follow-up question, "If no, how old was you child when they started speaking Swedish?". Based on the children's age at the time of assessment, we calculated their duration of exposure. Although our main interest was when the children were first exposed to Swedish, we chose to use the term "speak" as we determined it would yield higher reliability in the caregivers' responses. As for extent of Swedish exposure, we asked the caregivers about home exposure to Swedish. Outside classroom exposure to a second language is important for L2 development (Huang et al., 2018). We phrased this as "Do you as a family speak Swedish at home?" as we believed this was a statement that most caregivers would be able to provide a YES/NO answer to. We did not demand any information concerning who spoke Swedish in the household, but just a concise YES/NO. When meeting the individual children, we always started out going through their informed consent form, to confirm that the information provided by their caregivers matched the children's own perceptions. If any information was ambiguous, we either asked the caregivers to fill out the form again adding some clarifications or contacted them through phone at a later point. Using these rather simple questions, based on bilingual language acquisition research (Huang et al., 2018; Kohnert et al., 2021; Paradis, 2019; Soto-Corominas et al., 2020), the school language exposure index was created and applied in *Study III* and *IV*. The approach of creating an index was inspired by the work of Kremin and Byers-Heinlein (2021).

School language exposure and speech processing in noise

The studies using LFM found no difference in the ability to process speech in noise depending on degree of school language exposure, but such a difference was found in *Study II*. The use of different methods to measure school language exposure throughout *Studies I-IV* can complicate the comparisons between the studies. The finding of a disadvantage for speech processing in a more adverse listening condition in children with L2 school language in *Study II* could be due to the measure of school language exposure. To resolve this question, the LFM data was informally re-analyzed using this group division. When re-analyzing the data using the L1/L2 groups, there was no evidence that the effect of listening condition differed depending on extent of school language exposure. When informally reanalyzing the *Study II* data using the Swedish exposure index, the overall results remained the same, although crossed the line to non-significant, likely due to the smaller sample size in *Study II*. There are other methodological differences between the studies which can account for the different outcomes. On aspect concerns duration and the complexity of the narratives and the comprehension measure. *Study II* included short narratives, and comprehension was measured immediately with a speech-picture verification task requiring a true-or-false-response. In all, this was less linguistically demanding than the LFM task used in the other studies. In these many short tasks, it was not required, and likely not enough time, for the child to form a situation model of the narrative. While the task technically included brief narratives, it is possible that these brief narratives represent sentence comprehension rather than comprehension of discourse. Narrative event segmentation increases and stabilizes throughout childhood and adolescence (Cohen et al., 2022). It is possible that the task in *Study II* required fast processing and quickly shifting between sub-tasks, and therefore increased the cognitive load on the children speaking Swedish as a L2. Hippocampal activity at the end of a long scale event reflects long-term memory encoding of the narrative (Baldassano et al., 2017). While transitions between and stability within short events are less evident in younger children, hippocampal activity at the end of long-scale events is high in young school aged children (Cohen et al., 2022). It is possible that children with less experience in the language of assessment, are more vulnerable in low time scale processing (of e.g. phonemes, words, and individual sentences), and fast switching between discrete events, but not when the task enables the long-time scale processing and chunking of a narrative into a situation model and encoding of this chunked synthesis. *Study III* included a crude, but still more fine-grained estimation of knowledge in the school language as compared to *Study II*. The descriptive results of *Study III* indicated that children with medium school language exposure experienced stronger negative effects of babble noise on their comprehension as compared to children with both less and more experience in the school language. As this was only shown descriptively, there are no clear conclusions to be drawn. It is also important to note that babble noise is more likely to cause informational masking when the babble corresponds to the listener's L1 (Lecumberri et al., 2010). This may have caused an advantage for the children with little experience in the Swedish language, as the noise, although edited, also was constitutes of Swedish.

Socio-economic status

When degree of school language exposure and working memory capacity had been accounted for, SES was still a significant predictor for narrative listening comprehension, albeit with a relatively small effect size. Unlike Filippi et al. (2020), we did not find any association between an effect of background noise and the children's SES. Further, unlike many prior studies (see Mooney et al., 2021 for a comprehensive review), our overall findings did not show that performance on the included working memory tasks differed depending on SES. This, in combination with the small effect size of SES in *Study III*, could indicate two things: either our measure of SES was insufficient, or SES was not an important factor for the children's cognitive development and performance in this context. The included children all attended schools in similar neighborhood SES areas (Neuman et al., 2018). As shown by Andersson et al. (2019), low family SES, migration background and low neighborhood SES often come hand in hand in Sweden, and when these factors are combined, primary school children's school language abilities are notably low. The studies included in this dissertation were based on data collections made at schools similar to the low neighborhood sample in Andersson et al. (2019). Another possible explanation for a relatively low predictive value of SES for children's listening comprehension is that educational levels have different interpretations depending on country and culture. Many caregivers had immigration background and originated from a variety of countries.

Assessing children of cultural and linguistic diversity

To conduct reliable and valid assessments of culturally and linguistically diverse children, several factors were considered when planning this overall research project and deciding which tasks to include. Inspired by the works of, for example, Gagarina et al. (2012), Ljung et al. (2009) and Chiat (2015), the LFM task was designed by considering what is and is not common knowledge in young primary school children, regardless of cultural background. Even when considering this, children with less experience in the school language, had poorer comprehension. The included working memory tasks were selected to minimize the impact of language background on performance. A digit span test was used, as digits are typically overlearned early in language acquisition (Brännström et al., 2023; Engel de Abreu et al., 2013). We also used the Crosslinguistic Nonword Repetition test which was developed specifically to be equally difficult regardless of linguistic background (Boerma et al., 2015; Chiat, 2015). These tasks were likely reliable options, as we found no differences in performance on the working memory tasks depending on degree of school language exposure. Many of the short narratives of *Study II* were quite western European in cultural context. More specifically, they were set in a UK cultural context including, for example, lunch boxes and school uniforms. We modified narratives including such concepts, which Swedish children would most likely be less able to relate to. We also changed the personal names of the protagonists in cases where they were unusual in a Swedish context. We tried to make the translations of the narratives sound as natural as possible in Swedish. However, as the three sentences had to remain in their original order, and as the reference object was only permitted to me mentioned using the noun once, some translations were somewhat awkwardly phrased. It is possible that the results had been different if the *Study II* narratives had been more culturally neutral.

Working memory

Working memory was assessed through two different tasks in this thesis: the Digit Span Backwards (DSB) and the Crosslinguistic Nonword Repetition Test (CL-NWRT). The rationale for including these two different tasks were based on the distinction between implicit and explicit speech processing as described in the Ease of Language Understanding (ELU) model (Rönnberg et al., 2013; Rönnberg et al., 2010; Rönnberg et al., 2022).

Implicit working memory processing

The CL-NWRT was included as a measure of implicit working memory processing, as this is a task which primarily require phonological rehearsal (Gray et al., 2017). Nonword repetition is also a test which is highly indicative of children's ability to learn language (Gathercole, 2006a, 2006b). Indeed, performance on the CL-NWRT had a high predictive value for listening comprehension in *Study III* but was not related to any advantages for processing speech in noise. This is in line with the Ease of Language Understanding model, emphasizing the role of explicit working memory processing for speech comprehension in noise (Rönnberg et al., 2021; Rönnberg et al., 2013; Rönnberg et al., 2010). The results of *Study III* also validates the CL-NWRT as useful for predicting linguistically diverse primary school children's ability to comprehend language (Boerma & Blom, 2021). A likely explanation to the high predictive value of the CL-NWRT for LFM performance in *Study III*, is that nonword repetition holds a stronger predictive value when children are younger or earlier in their language development in a given language (Gathercole, 2006b). Important to note is that when the same task has been used in a majority monolingual setting, the same associations has not been seen (Dzgoeva & Westerberg, 2023). The included children were typically developing, however, many of them were in the process of acquiring Swedish as a second language. The interpretation of this finding is that while the extent of L2 exposure is important for children's listening comprehension in the same language, so are their cognitive prerequisites for language learning and speech processing which nonword repetition is believed to measure. This importance of cognition in addition to language exposure is in line with prior studies of school children's acquisition of the school language as a second language (Kohnert et al., 2021; Paradis, 2019; Soto-Corominas et al., 2020).

Explicit working memory processing

Using the Digit Span Backwards (DSB) task, we identified age differences in the association between working memory and listening comprehension (LFM performance) across the two listening conditions in *Study III*. These findings suggested that the younger children could use explicit working memory processing for comprehension in quiet, but not in noise. In the older children, this association was reversed. A positive association between DSB scores and LFM performance was seen in noise, but not in quiet. The use of the DSB task was motivated by the fact that it is a common task used in working memory assessments of children, relatively independent of language abilities and would tap into explicit working memory processing (Hilbert et al., 2015; Pearson Assessment, 2013). The finding of age differences in working memory associations was unexpected and observed in the exploratory statistical model in *Study III*. Due to this, an older LFM data set including another complex span working memory task was re-analyzed (Carlie & Dahlquist, 2019), in which the same pattern was found. The children included in *Study III* were not perfectly balanced for experience in the Swedish language across the age span. As noted in *Study IV,* children with increasing school language exposure had stronger associations between DSB performance and LFM scores overall (including both immediate and delayed recall data). Including the children of *Study III,* there was only a positive association between CL-NWRT and DSB in the older children. As there has been noted a developmental shift in working memory capacity at around the age of 8 years (Gray et al., 2017), and that the differences noted in these data sets (Study III; Carlie & Dahlquist, 2019) are seen at around that age, this shift in working memory processing is a possible explanation for the findings. Children younger than approximately the age of 8 years may have difficulties in using their ability to process complex information in working memory in noisy listening conditions. Most importantly, the finding implies that when investigating the role of working memory in children's speech processing, it cannot be taken for granted that children of different ages process information in the same manner.

Methodological considerations in working memory assessments

While the CELF-4 manual (Pearson Assessment, 2013) regards the DSB task as a complex span working memory task, it is generally not considered as such (Mashburn et al., 2020). The DSB task requires reorganization of information. However, to assess more complex processing in working memory, manipulation of information where children cannot rely on rehearsal strategies are generally needed. Other options, such as the digit span running task or auditory n-back could have been better options (Gray et al., 2017). We decided to administer and score the DSB task as described in the CELF-4 manual. In hindsight, a more nuanced administration and scoring would likely have yielded better estimations of working memory capacity (Wells et al., 2018). Further, as shown by Gray et al. (2017), specific working memory tasks tap into different aspects of working memory, and primary school children's performance on these tasks are not necessarily associated with each other. Thus, a battery of working memory tasks is needed to get reliable estimates of working memory capacity.

Cognitive load

The included children conducted several tasks intended to increase their cognitive load. The multitalker babble noise was used to cause an extraneous load (Sweller, 2011). Based on the findings, the multitalker babble noise most likely caused an increased cognitive load during speech processing. The linguistic content also most likely increased a cognitive load in the children with little exposure to the school language which we used in assessments. In *Study II*, we went beyond behavioral assessments and aimed to capture listening effort and fatigue physiologically.

Listening effort and fatigue

A decrease in test scores during more challenging listening conditions can be an indication of listening effort and fatigue (Alhanbali et al., 2019). As such, all included studies point to the increase of listening effort and/or fatigue during listening comprehension in noise. In *Study II,* behavioral measures of listening effort were supplemented with self-reports of task-related fatigue and a physiological measure of listening effort and fatigue. While pupillometry has long been used to capture cognitive load, few studies have used the method to investigate listening effort in children (Gómez-Merino et al., 2020). Pupillometry tracking the children's pupil size during the task was used to measure both phasic and tonic pupil dilations and constrictions, reflecting listening effort and fatigue (Winn et al., 2018). *Study II* was designed based on the methodology of McGarrigle, Dawes, Stewart, et al. (2017), and extends their findings. Just like McGarrigle, Dawes, Stewart, et al. (2017), we found increased task-evoked pupil dilations when children were listening in lower as compared to higher SNRs. However, *Study II* points to that this difference is present at smaller SNR differences: 0 dB versus +10 dB in our study as compared to -2 dB versus +15 dB in the study of McGarrigle, Dawes, Stewart, et al. (2017). Our findings also demonstrated that these differences could be detected using fewer trials (i.e., shorter assessments) and in a portal lab at the children's school as compared to a highly controlled sound treated booth. The findings of *Study II* pointed to increased listening effort during the second sentence of the narratives where the critical word was mentioned. This increase in effort emerged slightly prior to the second sentence. This indicates that the children were preparing for listening attentively when the critical word was mentioned, highlighting the role of motivation for making attempts to comprehend speech (Pichora-Fuller et al., 2016). As we had no ceiling effects on task performance in *Study II*, we were able to investigate differences in task-evoked listening effort between correct and incorrect responses. Our findings showed that the children who had Swedish as a L1 had higher task-evoked pupil dilations during this second sentence when they provided a correct response. Conversely, this was not the case for children listening in their L2, who most likely already were exerting as much effort as they could to. Overall, the findings display the importance of language proficiency for being able to use effort for successful comprehension, which has been described in studies of adults (Borghini & Hazan, 2018). A tonic pupil constriction over time was found in both listening conditions, indicating task-disengagement, or fatigue (Hopstaken et al., 2015). However, this decrease in baseline pupil size was greater in the less favorable (SNR 0 dB) listening condition than the more favorable one (+10 dB), suggesting that the children became more tired from listening in SNR 0 dB than in +10 dB. During pupillometric assessments, the children were generally not perceived to consider the task very engaging or fun. Task disengagement could thus be an indication of increasing task aversion. However, this would not explain the differences in decreased baseline pupil size over time between the two listening conditions. The study also pointed to a lack of congruity in children's self-report and physiological measure of fatigue, a discrepancy which is commonly seen in studies of listening effort and fatigue (Alhanbali et al., 2019; Wang et al., 2018).

Limitations

The present investigation was conducted in areas of low socio-economic status where most students had immigration background. While it is unlikely that cognitive processing is inherently different depending on socio-economic and linguistic surroundings, it is important to keep in mind that the results presented here may not be generalizable to other settings and populations. The children had highly diverse linguistic backgrounds. They spoke many different languages and differed greatly in their extent of exposure to the Swedish language. The sample also included Swedish monolingual speaking children, albeit few in comparison to the bilingual majority. The index used to quantify Swedish exposure was treated as a continuous variable in the statistical models in *Study III* and *Study IV*, as group comparisons between the different "levels" of exposure would have been unreliable due to the sample size. When descriptively viewing the LFM scores in quiet and in noise, the data points to an increased negative effect of noise for the children with medium Swedish exposure. No firm conclusions can be drawn from this, but it is something that can be considered in future studies. Further, it is important to keep in mind that the results of *Studies I-IV* are based on two 45–60-minute assessments of the children, and thus only provides a glimpse of their cognitive abilities. Concerning methodology, one important limitation is the measures which were not included in the studies. These measures include assessments of non-verbal intelligence, attention, bilinguals' L1 proficiency, and motivation, as well as core Swedish language skills, and working memory assessments, either non-verbal or in the children's L1. Some of these measures were planned to be included but had to be removed as the assessments otherwise had become too extensive to be practically possible to conduct. Other assessments, such as measures of attention, bilinguals'

L1 proficiency, and motivation were included, but either yielded ceiling effects, or proved difficult to reliably score. If included, these measures would have provided a better understanding of what factors are of most importance to children's speech processing under different listening conditions.

Implications and future directions

A wealth of studies during the last decades have demonstrated the negative effects of background noise on children's (and adults') speech processing, from speech perception to comprehension and recall of spoken discourse. However, primary school is an institution where lots of interaction – which causes noise – takes place. This means that there is a need to identify when, where and with which students, educators should prioritize silence. Based on the findings of the studies included in this thesis I would recommend the following:

- Listening conditions should be monitored during listening-based activities, especially during detail-oriented listening activities, such as during complex oral instructions.
- To decrease the risk of listening-related fatigue, children should not be required to listen in noisy listening conditions for longer periods of time (on a minute scale). This may be even more important to consider for children listening and learning through their second language.
- In less detail-oriented listening activities, listening in relatively mild multitalker babble noise for a short period (a few minutes) is unlikely to impair learning.

Directions for future research

During this dissertation project, we have developed, adapted, and evaluated several methodologies. Some of these methods may be relevant for clinicians within the fields of speech-language pathology, audiology, and psychology, and some mainly for researchers. In summary:

- Pupillometry can be used to capture physiological listening effort and fatigue in children. It is possible that this approach could be used to assess noise sensitive pediatric clinical populations affected by listening effort and listening imposed fatigue.
- Accuracy on the Crosslinguistic Nonword Repetition Test is sensitive to predict performance on a task indicative of second language proficiency in linguistically diverse young primary school children.

- When trying to predict children's proficiency in the school language as a second language, it is important to consider factors beyond duration of exposure.
- When designing studies on children's speech processing in noise, there is a need to consider possible developmental differences in working memory processing even within a relatively narrow age span.
- The developed narrative listening comprehension task, Lyssna, Förstå och Minnas is sensitive to detect differences between listening conditions and in exposure to the assessed language. It is thus deemed that this task is suitable for studying young primary school children's speech processing under adverse listening conditions.

Conclusions

The developed narrative listening comprehension task, *Lyssna, Förstå och Minnas* (English: Listen, Comprehend, and Remember; LFM) was considered a valid and reliable material for assessing young primary school children's comprehension as measured by recall of speech.

Short-term exposure to multitalker babble noise interferes with children's ability to immediately comprehend and recall spoken information. However, it is possible that this negative effect on comprehension and recall is only temporary, and evens out with memory consolidation and the act of recall.

Poorer listening conditions cause increased listening effort and listening imposed fatigue. It is possible that children with little exposure to and knowledge in the school language are more susceptible to the negative effects of multitalker babble noise on tasks which rely highly on adequate speech perception and fast processing and switching between tasks, but not on longer narrative tasks such as the LFM task.

Crucial factors for speech processing in all listening conditions include implicit working memory processing capacity as measured by nonword repetition and increasing experience in the school language (Swedish). Younger children may have a more difficult time processing speech in noise due to age differences in the ability to use working memory processing to facilitate comprehension. A better understanding of primary school children's working memory development and how they use working memory for speech processing under optimal and adverse listening conditions is needed.

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The aim of this dissertation was to increase knowledge in how background noise affects listening comprehension, memory retention, listening effort and fatigue in young primary school children of cultural and linguistic diversity.

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