Children's Brainwaves in Semantic Processing, Auditory Discrimination and Selective Attention

– in Deaf and Hard-of-Hearing and Typically Hearing Populations

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DOCTORAL DISSERTATION

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Title and subtitle: Children's brainwaves in semantic processing, auditory discrimination and selective attention – in Deaf and Hard-of-Hearing and Typically Hearing populations

Abstract:

In the present thesis, brainwaves analyzed as event-related potentials (ERPs), have been measured in children who are Deaf and Hard-of-Hearing (DHH) and in children with Typical Hearing (TH), in two different intervention projects. One investigated a computer-assisted reading intervention with a phonics approach for children with hearing loss, and one evaluated two different teaching methods in Swedish preschools. In study I and II participants were 5–7 years-old children with cochlear implants (CI. N=15), conventional hearing aids (HA. N=15) or typical hearing (TH. N=12). In study I the N400 component, reflecting semantic processing, was investigated and in study II auditory mismatch responses (MMR) were measured in a paradigm with contrasts in five auditory dimensions (duration, intensity, pitch, location and gap insertion). The purpose of study I and study II was to study group differences in processing, and to evaluate effects of a computer-assisted reading intervention with a phonics approach. In study I, a larger N400 effect was found in children with CI, compared to children with HA and TH. Since children with CI in this study had lower semantic skills compared to children with TH, and because ERPs differed at early latencies and as a function of semantic relatedness, this result was interpreted as a reflection of increased semantic top-down processing in children with CI. In study II we found a mismatch negativity (MMN) effect for the duration deviant, while other sound contrasts resulted in positive mismatch responses (pMMR), not typical for the present age group but often found in much younger children. Study III is a review of four existing N400-studies of semantic processing in children with CI. Participants with CI (N=88) in the included studies were 1–10 years-of-age. We found N400 effects in all participant groups except in very young children with additional impairments. A replication of the large N400 effect of study I, including the early latency effect is discussed and give suggestions for future research including studying children with HA, and understudied group. In study IV and V, we investigate 4–6-year-old children in preschools (N=431). The children participated in extensive behavioral testing, and a subgroup of 138 children tested auditory selective attention as differences in ERP responses to probe sounds embedded in attended and unattended stories. The goal of study IV was to evaluate cognitive effects of preschool teaching practices in a randomized control trial (RCT) intervention study and investigate effects of background variables such as socioeconomic status (SES). In study V we investigate relations between executive functions (EF), selective auditory attention and several measures of language skills in data from the same project. The preschool interventions of study IV did not result in better EF, language, communication or early math skills, compared to controls. SES did predict EF and early math. Selective auditory attention had an expected effect with positive polarity at early latencies and an unexpected effect with negative polarity in later latencies. In study V we found that vocabulary measures had the highest correlations with EF, suggesting that studies that only use vocabulary might overestimate the relationship between EF and language. The selective auditory attention measure did not correlate with any EF measures, but did have weak correlations with language tests. Results in study I and III suggest that semantic top-down processing can be enhanced to compensate for difficulties in language comprehension in children with CI. However, the compensatory top-down processing is limited by difficulty of the language material, noise, and in being effortful. Studies of auditory responses (study II, IV and V) include results that are not typical for the studied age groups. Atypical age effects could be related to task difficulty. The effect of SES on cognitive measures suggest that the compensatory mission of Swedish preschool policy is important, as cognitive differences are found already at this age. Results overall suggest continuous interaction between cognitive faculties that can sometimes take compensatory roles.

Key words: ERP, children, hearing loss, Cochlear Implant, semantic processing, N400, MMN, selective auditory attention

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Lately it occurs to me, what a long, strange trip it's been

The Grateful Dead

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Abstract

In the present thesis, brainwaves analyzed as event-related potentials (ERPs), have been measured in children who are Deaf and Hard-of-Hearing (DHH) and in children with Typical Hearing (TH), in two different intervention projects. One investigated a computer-assisted reading intervention with a phonics approach for children with hearing loss, and one evaluated two different teaching methods in Swedish preschools. In study I and II participants were 5–7 years-old children with cochlear implants (CI. N=15), conventional hearing aids (HA. N=15) or typical hearing (TH. N=12). In study I the N400 component, reflecting semantic processing, was investigated and in study II auditory mismatch responses (MMR) were measured in a paradigm with contrasts in five auditory dimensions (duration, intensity, pitch, location and gap insertion). The purpose of study I and study II was to study group differences in processing, and to evaluate effects of a computer-assisted reading intervention with a phonics approach. In study I, a larger N400 effect was found in children with CI, compared to children with HA and TH. Since children with CI in this study had lower semantic skills compared to children with TH, and because ERPs differed at early latencies and as a function of semantic relatedness, this result was interpreted as a reflection of increased semantic top-down processing in children with CI. In study II we found a mismatch negativity (MMN) effect for the duration deviant, while other sound contrasts resulted in positive mismatch responses (pMMR), not typical for the present age group but often found in much younger children. Study III is a review of four existing N400-studies of semantic processing in children with CI. Participants with CI (N=88) in the included studies were 1–10 years-of-age. We found N400 effects in all participant groups except in very young children with additional impairments. A replication of the large N400 effect of study I, including the early latency effect is discussed and give suggestions for future research including studying children with HA, and understudied group. In study IV and V, we investigate 4–6-year-old children in preschools (N=431). The children participated in extensive behavioral testing, and a subgroup of 138 children tested auditory selective attention as differences in ERP responses to probe sounds embedded in attended and unattended stories. The goal of study IV was to evaluate cognitive effects of preschool teaching practices in a randomized control trial (RCT) intervention study and investigate effects of background variables such as socioeconomic status (SES). In study V we investigate relations between executive functions (EF), selective auditory attention and several measures of language skills in data from the same project. The preschool interventions of study IV did not result in better EF, language, communication or early math skills, compared to controls. SES did predict EF and early math. Selective auditory attention had an expected effect with positive polarity at early latencies and an unexpected effect with negative polarity in later latencies. In study V we found that vocabulary measures had the highest correlations with EF, suggesting that studies that only use vocabulary might overestimate the relationship between EF and language. The selective auditory attention measure did not correlate with any EF measures, but did have weak correlations with language tests. Results in study I and III suggest that semantic top-down processing can be enhanced to compensate for difficulties in language comprehension in children with CI. However, the compensatory top-down processing is limited by difficulty of the language material, noise, and in being effortful. Studies of auditory responses (study II, IV and V) include results that are not typical for the studied age groups. Atypical age effects could be related to task difficulty. The effect of SES on cognitive measures suggest that the compensatory mission of Swedish preschool policy is important, as cognitive differences are found already at this age. Results overall suggest continuous interaction between cognitive faculties that can sometimes take compensatory roles.

Populärvetenskaplig sammanfattning

Hur världen uppfattas påverkas av uppmärksamhet och förväntningar som är baserade på erfarenheter. I den här avhandlingen visar jag hur samma bild, eller samma ljud ger upphov till olika hjärnvågsresponser beroende på uppmärksamhet och förväntningar. Oftast blir hjärnans responser större då något oväntat händer, och de förstärks även av uppmärksamhet i de flesta fall. Med hjälp av såna hjärnvågs-responser visar jag att barn med cochlear-implantat, som kan ha svårt att uppfatta tal, kompenserar för detta genom att aktivt gissa och försöka förutsäga vad som sägs. Vi mätte en typ av hjärnvåg som är kopplad till språkförståelse och hade väntat oss att barn med cochlear-implantat skulle få mindre responser än typiskt hörande barn utifrån deras sämre ordförråd. Ingen hade tidigare undersökt denna typ av hjärnrespons i en grupp barn med cochlear-implantat. Tvärtemot våra förväntningar var deras responser större och snabbare än kontrollgruppens. Resultatet tydde på att de hade starkare förväntningar och aktivt förutsåg vad som skulle hända. Detta resultat har senare upprepats i en större studie. I en av artiklarna i avhandlingen sammanfattar jag de andra studier på ämnet som följt på min, och föreslår hur man ska gå vidare.

I ett annat experiment undersökte vi 5–7 åringar med typisk hörsel, hörapparat eller cochlear-implantat. De fick höra en standardton om och om igen blandat med mer oväntade varianter på samma ljud, med variation i tonhöjd, ljudstyrka, längd mm. Den typ av hjärnvågs-respons vi väntade oss kallas mismatch negativity, och skulle responskurvan skulle alltså vara negativ men de flesta av responserna var istället positiva. Sannolikt var de många tonvarianterna som presenterades snabbt så pass svåra att diskriminera att responsen blev mer omogen, i det här fallet en positiv respons som är mer typiskt för yngre barns responser.

Uppmärksamhet förstärker oftast hjärnvågor. I den första experimentella studien med randomiserad kontroll någonsin inom svensk förskolepedagogik kunde vi mäta hur uppmärksamhet förstärkte hjärnvågs-responser bland förskolebarn. Uppmärksamhetseffekten korrelerade med språkmått och med socioekonomisk status. I experimentet skulle barnen lyssna på en saga och ignorera en annan saga som spelades samtidigt och troligen var språkförmågan viktig för att underlätta att följa med i den saga som skulle uppmärksammas. Detta visar hur olika kognitiva förmågor interagerar. Att socioekonomisk status ger effekt gäller inte bara hjärnvågor utan även andra viktiga mått som tidig matematik.

De många oväntade resultaten jag redovisar visar att hjärnvågor är känsliga. Små variationer i experimenten, hur svåra uppgifterna är och deltagarnas strategier, kan ge oväntade resultat. Responser som förväntades hos yngre barn dök upp hos äldre vid en svår uppgift och tvärtom fick förskolebarn responser som man vanligen ser hos äldre. Responser som antas spegla språkförmågan speglade i detta fall främst hur engagerat barn med cochlear-implantat försöker att göra förutsägelser. En uppmärksamhetsuppgift gav istället responser som verkar kopplade till språkförmågan. De olika kognitiva förmågorna som språk, uppmärksamhet och minne jobbar ihop och kan i viss mån kompensera för varandra. Hjärnvågor ger en inblick i hur intryck faktiskt processas och ofta är det mer komplicerat än väntat. Det är inte förvånande. Den mer komplicerade bilden ger uppslag åt ny forskning, och över tid kan man förstå hur saker verkligen går till!

List of Papers

Study I

Kallioinen, P., Olofsson, J., Nakeva von Mentzer, C., Lindgren, M., Ors, M., Sahlén, B. S., Lyxell, B., Engström, E., & Uhlén, I. (2016). Semantic Processing in Deaf and Hard-of-Hearing Children: Large N400 Mismatch Effects in Brain Responses, Despite Poor Semantic Ability. Frontiers in Psychology, 7. https://doi.org/10.3389/fpsyg.2016.01146

Study II

Uhlén, I., Engström, E., Kallioinen, P., Nakeva von Mentzer, C., Lyxell, B., Sahlén, B., Lindgren, M., & Ors, M. (2017). Using a multi-feature paradigm to measure mismatch responses to minimal sound contrasts in children with cochlear implants and hearing aids. Scandinavian Journal of Psychology, 58(5), 409–421. https://doi.org/10.1111/sjop.12391

Study III

Kallioinen, P., Olofsson, J. K., & von Mentzer, C. N. (2023). Semantic processing in children with Cochlear Implants: A review of current N400 studies and recommendations for future research. Biological psychology, 182, 108655. https://doi.org/10.1016/j.biopsycho.2023.108655

Study IV

Gerholm, T., Kallioinen, P., Tonér, S., Frankenberg, S., Kjällander, S., Palmer, A., & Lenz-Taguchi, H. (2019). A randomized controlled trial to examine the effect of two teaching methods on preschool children’s language and communication, executive functions, socioemotional comprehension, and early math skills. BMC Psychology, 7(1), 59. https://doi.org/10.1186/s40359-019-0325-9

Study V

Tonér, S., Kallioinen, P., & Lacerda, F. (2021). Selective Auditory Attention Associated With Language Skills but Not With Executive Functions in Swedish Preschoolers. Frontiers in Psychology, 12, 664501. https://doi.org/10.3389/fpsyg.2021.664501

Author’s contribution to the papers

Implementation, adaptation and piloting of all ERP experiments was done by the author without supervision. EEG was collected in collaboration with PhD candidates that were taught the ERP technique by the author: Elisabet Engström (study I and II) and Signe Tonér (study IV and V). In some cases, research assistants assisted in collecting data, such as Anna Ericsson (study I and II). In study I and II an additional team in Lund under the supervision of Marianne Ors recorded some of the children with DHH. The author did the preprocessing and analysis of all ERP data in study I and II, in study IV and V with the help of Signe Tonér, and input from Eric Pakulak.

Study I

The author did the piloting, adapted the experiment, collected, managed, processed, and analyzed the data, and wrote the paper with supervision by Jonas Olofsson. Other authors conceived and designed the experiment and the intervention it was embedded in. Cecilia Nakeva von Mentzer contributed by linking the manuscript to her language test results in the same project.

Study II

The data was collected in the same project and the same recording sessions as study I with similar contributions from the author regarding implementing, piloting and adapting the experiment, EEG data collection and processing. The author did the analysis with input from the first and second authors and wrote the result section.

Study III

The study was conceived by the author, who wrote the manuscript with input and supervision from Jonas Olofsson and Cecilia Nakeva von Mentzer. Jonas Olofsson contributed to early evaluation and framing of the project and supervision on writing. Cecilia Nakeva von Mentzer contributed with input on hearing, hearing loss and language testing, systematic review methods and supervision of writing.

Study IV

The study was part of a large project, Enhancing Preschool Children’s Attention, Language and Communication Skills, where the author contributed from an early stage, including grant writing. Hillevi Lenz Taguchi and other researchers from pedagogy, together with Tove Gerholm and the author from the linguistics department, wrote the grant application. The author contributed in areas of experimental design, cognitive neuroscience and ERPs and with specific experimental designs and neuroscientific concepts in the grant application. The author contributed throughout the project in the areas of experimental design, cognitive neuroscience and ERPs, areas where the other members of the project had little experience. Other areas in which the author contributed were in research ethics, statistics and scientific method. The author taught the PhD candidate of the project, Signe Tonér, the ERP technique, designed the mobile lab and collected and analyzed the EEG data. Specifically, in the study IV manuscript, the author and Signe Tonér were responsible for the ERP experiment and general text about analysis. The author, together with statistician Tatjana von Rosen, was responsible for the analyses of research questions 1–4 and 7.

Study V

The study was an analysis of relations between EF and language in the data collected for study IV. It was conceived and designed by Signe Tonér and the author. Signe Tonér performed the statistical analysis and the author organized and pre-processed the ERP data. Signe Tonér wrote the first draft, then the author and Fransisco Lacerda contributed to revisions.

Abbreviations

CI – Cochlear Implant

DHH – Deaf and Hard-of-Hearing

DIL – Digital and Individual Learning intervention

EEG – Electroencephalography

ERP – Event-Related Potential

fMRI – functional Magnetic Resonance Imaging

HA – Hearing Aid (conventional)

HI – Hearing Impaired

HL – Hearing Loss

ICA – Independent Component Analysis

ISI – Inter Stimulus Interval

MEG – Magnetoencephalography

MMN – Mismatch Negativity

NH – Normal Hearing, is used equivalent to Typical Hearing

PA – Phonological Awareness

PCA – Principal Component Analysis

pMMR – positive Mismatch Response

RCT – Randomized Control Trial

SEMLA – Socio-Emotional and Material Learning intervention

SES – Socio-Economic Status

SOA –Stimulus Onset Asynchrony

TH – Typical Hearing

Terminology

Some concepts regarding *brainwaves* are related and overlapping and need clarification. *Brainwaves* is a less formal term for *electroencephalography* (*EEG)* and *magnetoencephalography (MEG)* or other electrophysiological recordings of brain activity. They measure changes in electrical fields of the brain, or their magnetic counterpart. The term *brainwaves* is used throughout the thesis in less formal sections because of its self-explanatory elegance. When recordings or processing are discussed, the formal term *EEG* is used, referring to continuous electrical brainwave data. *Event-related potentials, ERPs*, are brainwaves in response to events. ERPs are the time-locked responses to a certain event or event type. The duration of this response is typically about a second after an event. ERPs are often presented as average responses of many events, since averaging is used to enhance signal to noise ratio. The terms *brain responses*, *cortical responses* or *electrical brain responses* are used in some thesis texts for an electrical or other brain reaction to an event. These terms are typically used in the beginning of a text before the formal terms such as EEG or ERPs have been introduced, or in less technical sections, in order to make general statements that are self-explanatory.

Background

Introduction

When walking home through the country-side of Hälsingland, late at night after a fiddler's gathering, you may suddenly hear a whole group of fiddlers playing a well-known tune behind a barn. You may think: –Why do they play here, out in the fields, at this time, far from the festival? You may even walk closer, only to realize that there are no fiddlers in the field. The sound actually comes from the noisy fan of a barn. The music was created in your mind due to excessive consumption of fiddle music the last few days. Perception is processed both bottom-up and top-down. Bottom-up processing is based on the actual signal picked up by eyes, ears, nose, touch and taste, while top-down processing is based on attention and expectations. After a week at a fiddle folk music camp, you are attuned to fiddle music to such an extent that you hear every noisy sound as violins; notably car engines, electric guitars, and fans in barns.

Enhanced top-down processing is a recurring theme of this thesis. My experience of fiddle-music from a barn fan is a curious example, but top-down processing is involved in most perception and cognition. In all of the studies of this thesis top-down processing is enhanced, often to compensate for adverse hearing conditions. In study I and III hearing is limited by hearing loss and listening through a cochlear implant (CI) or a conventional hearing aid (HA). In study IV and V top-down processing is challenged by the simultaneous sound of two stories, and the instruction to focus on only one of them. In study II expectations are manipulated in the presentation of a series of tone pips.

The studies in this thesis have a focus on language (rather than fiddle-music), the participants are children, and the central method of measurement used is brainwaves. Top-down processing is crucial for language comprehension, it is needed to process the fast rich and highly variable signal of language. Brainwaves allow us to investigate such processing, and find variation that is not visible in behavior.

Child-targeted interventions and event-related potentials

When a child is learning, changing or adapting, the locus of this change is in the brain. Therefore, it may seem that the ultimate way of evaluating intervention programs for children is to measure this change by studying brain responses. Among the methods available for studying brain responses, recording of brainwaves is one of the most child friendly, and least invasive and intrusive techniques.

This thesis is about brainwaves in child-targeted interventions designed to boost children's learning. It set out to investigate questions such as: Can interventions make a substantial impact on cognitive skills such as language and attention, and are changes due to interventions reflected in the electrical brain responses? What can neural data tell us about cognitive processing in the studied populations? As it happens, the second question get more attention in this thesis.

The thesis is based on two child-targeted intervention projects, the first studying Deaf and Hard-of-Hearing (DHH) children 5–7-years-old and matched controls before and after a computer-assisted reading intervention with a phonics approach. The intervention was accomplished using a Swedish version of a computer-assisted program that focused on training of phonological coding at letter, syllable (monosyllabic words) and word level (Lyytinen et al., 2009). The intervention program provides highly repetitive and individualized intervention in which the child matches auditory targets (phonemes or spoken words) with visual targets (graphemes or written words). The participating children practiced 10 min per day for 4 weeks in their homes. event-related potentials (ERPs) were recorded before and after the training period.

Sound discrimination was tested with the ERP component Mismatch negativity (MMN), and semantic processing with the component N400. The hypothesis was that phonological processing is the central difficulty for DHH children and that phonics training would increase phonological awareness (PA). PA was hypothesized to transfer to refined word discrimination skills that in turn would make semantic processing easier. This effect was tested using an experimental paradigm targeting the N400 component reflecting semantic processing (study I).

PA was also hypothesized to transfer to a general auditory discrimination ability in discriminating small auditory changes. An experiment using five basic sound contrasts with the ERP component MMN would test if auditory discrimination was affected by the intervention. Both study I and study II focus on group differences in cognitive processes as they are reflected in ERPs rather than intervention results. In study I the intervention did not have clear ERP effects, and study II presents pre-intervention results. The intervention results from other studies in the project are described in the section Intervention context of study I and II. Both studies presented here focus on differences between populations of children with typical hearing (TH), conventional hearing aid (HA) or cochlear implant (CI).

The second project "Hjärnvägar i förskolan" ("Brain ways in the preschool") was the first randomized control trial (RCT) study of pedagogics in Swedish preschools

(The Swedish Research Council, DNR nr: 721–2014-1786). The project was a collaboration with the department of Child and Youth studies of Stockholm University and investigated whether and how teaching practices affect language, executive functions (EF) including selective attention and early math in 4–6-year-old preschool children. A pedagogical practice called SEMLA (socio-emotional and material learning), a version of contemporary participatory pedagogics focused on group activities, communication and creativity, was compared to a practice called DIL (digital and individual learning for body and mind) that consisted of a cognitive training program including a computer-based training of early math. There was also a control group continuing their ordinary pre-school practice. Selective attention was studied with ERPs using a dichotic listening task, that is, a task where there are two sound sources at the same time that require selective attention to focus on only one of them. Study IV investigate intervention effects, but this thesis does not present the interventions themselves extensively. This is partly because the ERP results did not suggest clear differences between interventions.

The purpose of both intervention studies was to test if specific training or teaching programs can affect children's cognitive skills, and enhance communication and/or executive control, both for the children’s own benefits and to improve their school readiness and achievement. The project with DHH children wanted to evaluate a reading-training, phonics, that seemed to pinpoint language difficulties among DHH children. We also wanted to investigate "upstream" effects on semantic processing. Most research regarding hearing loss focuses tightly on auditory perception. Semantic processing was understudied in general at the time of the project, and a study of this kind had never been accomplished in a group of children with CI. In the preschool project the central goal was to evaluate aspects of contemporary preschool practices with experimental methods and a broad set of cognitive measures, methods that were new to the field of pedagogics in Sweden.

Both projects are motivated by an explicit task of the state (Swedish constitution, Chapter 1, Article 2. 1974, as amended to 2018) to ensure health, welfare, participation in society and equality for all, including children with disability such as DHH children, and children who are socioeconomically disadvantaged. To deliver on the fulfillment of human rights we need to learn about children's cognitive abilities, their variation and how to enhance them. The reasons for using brainwave methods to this end are many. First, because brain responses are part of the typical contemporary toolkit and theory of cognitive research. Second, and more specifically, because they are easy to adapt to children and provide responses also in passive tasks, thus, where children’s active response is not required. It is well known (see Mendel, 2008 for a discussion) that children’s ability to collaborate in active tasks and tests are different from adults. Finally, brain responses can give insights into neural mechanisms, i.e., how certain behaviors and skills are implemented in the brain. This potential of uncovering the actual mechanisms of cognition and behavior is a major attraction of neuro-methods for researchers, funders and laypeople. However, in practice, brain research approaches this goal slowly. ERPs are direct measures of electrical brain activity, but the measures are broad, vague and noisy. They are interpreted with extensive use of behavioral and experimental methods, preferably over the course of many studies. Besides the attraction of trying to reveal the brain mechanisms in children's language and cognition a final goal of this thesis is to present the ERP parts of the two intervention projects as well as replications of some of our results, to allow for a discussion of the ERP method in the context of interventions and children, including discussions about ethics and the strengths and weaknesses of ERPs.

ERPs' central measures are their components i.e., wave forms, or underlying patterns in wave forms, that have repeatedly been found in response to certain tasks, described by typical polarity, timing and topography and how they are manipulated. In this thesis, several different ERP components are studied: MMN and its variation, the positive Mismatch Response (pMMR) reflecting auditory discrimination and perceptual memory, N400 reflecting semantic processing, and selective attention as enhanced responses to probe sounds in the early broad P1 positivity of children this age. In the first project, with DHH children, brainwave recordings were made in a lab setting, in the second project a mobile lab was used to visit participating preschools. In both projects there was also extensive behavioral testing of language and cognitive skills.

Event-related potentials in brainwaves

Brainwaves are direct measures of brain activity in the form of changes in electrical and magnetic fields. They have been measured from before birth (Draganova et al., 2005) to their demise with death (Norton et al., 2017). The electrical field changes are both oscillatory, that is best characterized by changes in power in the frequency domain, and of non-oscillatory, monophasic, transient changes in amplitude, either positive or negative. Electrical fields are measured as electroencephalography (EEG), using electrodes placed on the scalp. The magnetic counterpart is measured in magnetoencephalography (MEG) using magnetic sensors. The sources of brainwaves are electrical fields of neurons (or magnetic counterparts) that, under the right circumstances, can be aggregated to large fields. When the polarity and the direction of the fields of neurons are aligned, the fields sum into larger fields. If polarity and direction is not aligned, the fields cancel each other out. The arrangement of neurons in the cortex, roughly in parallel, facilitates summation into larger fields, large enough to be measured on the outside of the head. Action-potentials are short and have an overshoot with opposing polarity, and thus must be precisely aligned in time not to cancel each other. Dendritic potentials are longer and monophasic and sum up more easily, resulting in most of both oscillatory and monophasic responses that can be measured at the scalp (Buzsáki et al., 2012). The oscillatory signals have larger amplitudes when a lot of neurons are synchronized, such as in the delta waves of deep sleep with slow high amplitude waves. Waking EEG, with varied ongoing processing, typically has much lower amplitudes and is more distributed over frequency bands.

Event-related potentials (ERP) are brainwave responses to events, such as the onset of a sound, image, scent or touch. The response to a single event is typically not discernable in the ongoing oscillatory EEG (amplitudes of ≈ 40μV), but through averaging over many events the ongoing signal and noise are suppressed and the specific response to the type of event can be seen. The resulting ERPs are at smaller amplitudes (at amplitudes of ≈ 1–10μV). ERPs can result from phase resetting of oscillatory signals and/or additive responses, and also with minor contributions from asymmetric potentials (Congedo and Lopes da Silva, 2018. Makeig et al., 2004). Waves and troughs of the ERPs are analyzed as components that are recognized by latency, polarity, topography and the type of stimulus manipulation that affect them. There is no theoretical limit to the timescale of EEG-recordings and ERPs. The first 10 milliseconds can be studied with 5 typical peaks of brain stem responses, early responses P1-N1-P2 the first 200ms after stimulus onset, and late responses after 200ms. ERP components have been named by different nomenclatures. Typical naming is based on polarity, P for positive and N for negative, and typical latency in milliseconds as in the P200, P300, N400 and P600, or order such as P1, N1, P2 and P3 (and less common N2 and N3 and sometimes N4 for N400). Other names are based on place such as vertex potential (P2) or functional descriptions such as bereitschaftspotential/readiness potential (BP/RP), and MMN. In the present work, general components such as P1, N1 and P2 will be mentioned, but the focus is on N400, MMN and the child version of P1 sometimes referred to as ‘broad positivity’ that is (confusingly) similar to P2 in adults.

Detailed neuroanatomic models of the generation of components are rare but do exist for prominent components such as the N400 (Almeida, 2021; Bornkessel-Schlesewsky and Schlesewsky, 2019; Kotchoubey, 2006). Such models bridge the gap between cognitive neuroscience, concerned with behavior, cognition and 'whole brain' neuroimaging, and neuroscience that is concerned with detailed function of neurons, medication and disease. However, ERP components are in general interpreted based on experimental control and correlated behavioral measures rather than through detailed understanding of the brain sources.

Auditory selective attention, MMN and N400

Auditory selective attention effects in adults and children

Already in the 1960s it was established that attention could modulate the size of N1 and P2 components, the main obligatory ERP responses to sound. However, because of predictability in the stimulus sequences of the early experiments it was not clear if this difference was due to a shifting state such as arousal or alertness, or a genuine effect of selective attention. In the beginning of the 1970s Steven Hillyard created an experiment that used both localization (left or right) and pitch to make differentiation of the attended or unattended stimulus trains easy (Hillyard et al., 1973). A difficult pitch-based oddball discrimination task relating to attended stimuli was also part of the experiment and the stimulus tone pips were delivered at a fast pace (ISI = 250–1250ms) making the oddball discrimination task impossible without focus on the attended channel only. In two experiments that differed in randomization strategies, it was shown that selective attention led to larger N1 components, leaving P2 unaffected, and also to a larger P3 to the attended oddball deviants (Hillyard et al., 1973).

Helen Neville, a student of Hillyard, and a pioneer of cognitive neuroscience of language, later adapted this paradigm to child participants by embedding the tone pip sequences in stories from children's books (Coch et al., 2005). Children were seated between two speakers and instructed to listen to one story while ignoring the other story. Attention to a story replaced the oddball discrimination task used by Hillyard and colleagues (1973). The stories were distinguished by place (left/right), and voice gender (female/male). The attended stories also had pictures presented on a screen in front of the child to make the task easier. Responses to probe sounds embedded in the stories were larger in the attended channel. For children, the affected component is typically not N1, as in adults, but a broad positivity between 100 and 200ms after stimulus onset that later develops into the adult P1 (Sharma et al., 1997). A version of this paradigm was used for measuring selective attention for study IV and V.

Neville's research group found that selective attention in children differed based on socio-economic status (SES), with children from low SES conditions showing smaller selective attention effects (Stevens et al., 2009). Diminished selective attention has been hypothesized to be related to various forms of stress related to poverty which has a general negative effect on the brain (Noble et al., 2012). Neville's group furthermore found that the selective attention effect could be enlarged by an intervention program (Neville et al., 2013) targeting family practices. Selective attention was of interest in the intervention research in study IV and V in the present thesis because of its relation to SES, the ability it has to change with training, and also because it is a positive predictor for school achievements (Neville et al., 2013).

Mismatch Negativity

The Mismatch Negativity (MMN) component is a negativity in the difference wave between standards and deviants in an oddball experiment using sound stimuli. In oddball paradigms there are standard stimuli and deviant stimuli defined by how common they are: for MMN, standards constitute 80-90% of the stimuli and deviants 10-20%. The MMN component is thought to be elicited by a mismatch from expectations produced by the deviant compared to the standard, and has been elicited by changes in acoustic features such as pitch, intensity, timbre, and sound location, as well as more complex features such as phonemes, word stress or abstract rules (Näätänen et.al. 2007. Näätänen et.al. 2017). There is a debate regarding the memory component of MMN, with alternative explanations based on neuronal populations coding for overlapping features of the standards and deviants instead of a separate memory process (May & Tiitinen, 2010).

Because oddball paradigms can have long duration, up to an hour to test a single deviant, multi-feature paradigms have been constructed where stimuli are varied over many different dimensions, while still reinforcing the standard stimulus trace. In study III we used the optimum paradigm where every other stimulus was a deviant in one dimension (pitch, intensity, duration, location or gap), while similar to the standards in other dimensions. With an optimum paradigm it is possible to test many deviants in less than 20 minutes (Näätänen et al., 2004).

In children, especially younger, the MMN is sometimes positive, a pMMR) (Shafer and Yu, 2010). pMMR is seen as an immature response, overlapping with and eventually replaced by a mature MMN at 8 years of age. pMMR is also more likely in response to difficult discrimination tasks such as non-native speech contrasts or small deviants (Shafer and Yu, 2010).

N400

The ERP component N400 is a negativity elicited by semantic deviants that peak around 400ms after stimulus onset. Topographic maximum is at centro-parietal sites for most language stimuli and at frontal sites for image stimuli. N400 may be one of the most studied specific brain responses related to language with more pubmed.com hits than Broca's area (N400 + language = 2118 matches, Broca's area + language = 1384 matches. Pubmed.com 31 Jan 2023). The literature on N400 is immense and complex and contains several unresolved issues, such as whether it reflects prediction or integration, if it reflects semantic memory processing directly or something more indirect, and also how it is related to psycholinguistic models. Kutas and Federmeier's review (2011) give a comprehensive overview of the N400 component.

The N400 component was famously discovered when looking for a P300 positivity that is a typical response to task relevant deviants (Kutas and Hillyard, 1980). Instead of the expected positivity when ending sentences in semantically incongruent ways, a negativity was found. Original examples of incongruent sentence endings were "I spread the warm bread with socks" where butter was expected. Semantic incongruence here means an incompatibility of meaning. Spread in this sense requires a soft food-like substance as an object. Later it became clear that any low probability ending will have a larger N400, and semantic incongruence is used in describing N400-paradigms in a less strict sense. The experiment also made clear that non-semantic means of making the last word deviate from expectations such as changes in font, did not result in an N400.

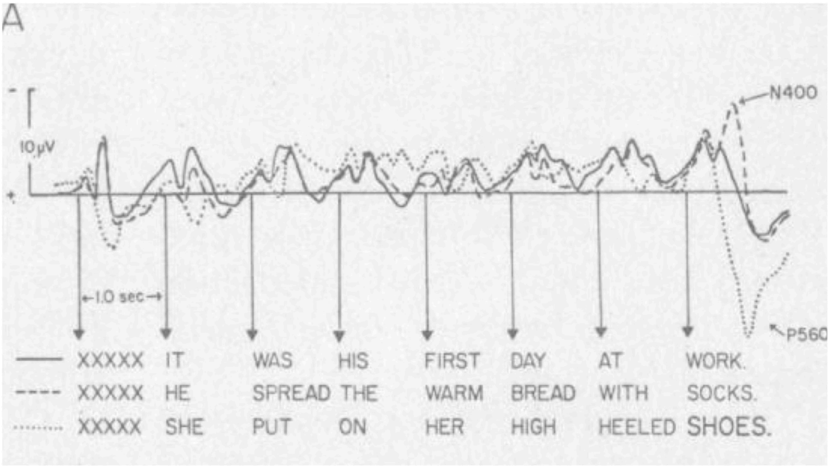

Figure 1. The first N400 figure, from Kutas and Hillyard (1980) showing responses that differ between an expected sentence ending, a semantic deviant (N400) and a font size deviant.

Low word frequency and low word probability are related to larger N400 amplitudes, the latter, called cloze probability, correlating with N400 amplitude at a whopping 0.9 at some electrodes (Kutas and Hillyard, 1984). Today surprisal is used to measure the probability of words based on context. Surprisal is an information-theoretic term for how unexpected an item is given its context calculated as negative log-probability. The relation is not as strong as cloze probability (Frank et al., 2015), partly because it is typically measured at all words and not just sentence endings, where expectations from context may peak with certain sentences, and also because surprisal is often used as a predictor of more naturalistic language that typically do not contain extreme semantic deviations. N400 can be modulated by wider context: typically, a phrase like "peanuts fall in love" would be seen as incongruent and elicit an N400. However, if this phrase is presented with a cartoon with peanuts embracing under a heart, the N400 will be small, reflecting the flexibility in interpretation triggered by the image context (Nieuwland and van Berkum, 2006). N400 can also be affected by social context and thus be enhanced because a person knows that another present person probably thinks something is unexpected or weird (Hinchcliffe et al., 2020. Forgács et al., 2022). N400 can be elicited by any meaningful stimuli. Under some circumstances N400 can even be elicited by grammatical deviations (Kutas and Federmeier, 2011) but almost all the known factors are related to semantic processing. The difficulty in pinpointing exactly what modulates N400 should not be surprising, semantic processing is more or less open ended. It is processing of meaning in a broad sense and is involved in both the most repeated associations and the most unique or hidden insights.

In many cases, such as in the example with peanuts and context, it is obvious that some sort of prediction is involved in N400 processing. However, also words that are practically unpredictable but related in hindsight to the previous context can diminish the N400 response (Kutas and Federmeier, 2011). Prediction can be simple semantic priming, the passive spreading of activation among associatively related neurons. N400 can be used to study semantic priming, but this effect is short-lived and the prime must be presented very close to the target, typically within 200ms to have a strong effect (Franklin et al., 2007. Hill 2002). A more active prediction can produce a larger N400 as we argue in study I and III, and in previous literature (Brothers et al., 2015; Federmeier and Kutas, 1999; Lau, 2013; Wlotko et al., 2010). Interestingly N400 size seems to decrease across the life span, smaller N400 in older people compared to younger, and even larger among children (Federmeier et al., 2003. Holcomb et al., 1992). It would be fascinating if this had to do with experience, and that older people were better predictors, however that does not seem to be the case. Instead, young adult readers are more prone to predict and predict more specific details, whereas older readers wait more for what is coming next and only predict words probabilistically (Broderick et al., 2021). N400 relatedness effects can be found when the duration between prime and target is too long for semantic priming, and depends on prediction. In semantic priming paradigms N400 amplitude is smaller due to direct spreading activation or overlap of encoding neurons, but at longer timescales this only happens if the subject actively keeps the prime concept online. Thus, old readers do not have relatedness effects due to less predictive processing, and there are also less relatedness effects when words are presented selectively biased for the right hemisphere (Federmeier and Kutas, 1999. Franklin et al., 2007). Prediction and specificity of predictions could also explain effects of mood on N400 (Naranowicz, 2022) although the full picture is complex.

ERPs are often used in research independently of detailed analysis of their sources. There are models of N400 sources with more detailed neuroscience (Almeida, 2021; Bornkessel-Schlesewsky and Schlesewsky, 2019; Kotchoubey, 2006) but they are not yet having a big impact. N400 can be seen as an error signal in line with Friston's free energy principle for brain function (Friston, 2010). Federmeier (2021) has criticized this view arguing that N400 amplitude parallels an error signal in some cases, but not in others.

In sum, N400 is large when meaningful stimuli are not predicted and hard to integrate in previous context, and progressively smaller when prediction and integration is possible. This could be stated: contextual information reduces the N400 amplitude. This is true over isolated sentences, and it would have been neat if that explained the N400 reduction over life as well. However, the size of N400 can also be dependent on how much semantic processing is going on, this seems like this is the main reason older people have smaller N400. A similar explanation is put forward for the children with CI in study I that had larger N400 effects than children with typical hearing (TH) despite having lower semantic skills. Predictive processing reflected in N400 amplitude is thus not only dependent on ability to predict, but also how much predictive semantic processing is going on.

Semantics and semantic processing

Memory, meaning and semantics in a cognitive neuroscience perspective

A basic idea, you could even call it a dogma, in cognitive neuroscience is that memory is embodied as associative connections among neurons that are strengthened and weakened at various time scales. Central mechanisms for associative memory, such as Hebbian learning, were first hypothesized (Hebb, 1949) and then popularized as “neurons that fire together, wire together”. Later, Hebbian learning as a neuronal phenomenon was described in more detail, for instance as spike timing-dependent plasticity (Caporale and Dan, 2009). Contemporary AI, whose construction is based on idealized neurons, exemplifies the power of associative coding. Despite its status as dogma, this associative theory of memory remains a sketch. Some areas do not fit the associative pattern learning: How do associations become rules in logical operations that humans may be less good at compared to associations, but still are able to perform? Also, most of the detailed coding of memory is not understood: how important are overlapping neuronal ensembles coding for overlapping features of the world in memory processing? Overlapping neurons is a theoretical idea that cognitive neuroscience often uses (exemplified in Pulvermüller, 1999, and May & Tiitinen, 2010) but the relation between underlying mechanisms and high-level cognitive constructs are not well known. Perhaps neuronal ensembles need to be studied with higher resolution than EEG or fMRI such as optical imaging (Wenzel and Hamm, 2022), to be relevant? No doubt associations are important but memory is organized by many different principles: associations, hubs, specialized areas, hierarchical processing, error coding, predictive processing, embodied processing etc., that are fused based on successful function into a memory system. It is feasible that this system as a whole is not well described by simple associationist ideas despite their relevance at a more detailed level. The straightforward prediction that neurons in the foot motor area should be part of the network coding for words related to feet (Pulvermüller, 1999) may be too simplistic. There seem to be a lack of unifying theories for these various principles of memory organization, instead many of these concepts have been investigated one by one during a time of hype and popularity (i.e., ‘mirror-neurons’ discussed in Heyes and Catmur, 2022;).

In cognitive neuroscience and psychology semantics is typically seen as world knowledge, a very wide category with unclear borders. Thus memory, meaning and semantics are strongly overlapping in a cognitive neuroscience perspective. The philosophical analysis of meaning as sense and reference could in this perspective be described as associative patterns within brains, that can be communicated between brains and that can successfully address associative patterns in the world. In language development this tuning of associated networks of both language and world knowledge is reflected by the importance of joint or shared attention during communication (Tomasello, 1986). Meaning in a cognitive neuroscience perspective could be sketched as the ability of associative patterns of brains in communication to connect, reduce, and predict patterns of the world.

Semantic processing

Semantic processing concerns processing of meaning: that is lexical processing (concerning word meaning), sentence level meaning, but also non-linguistic meaning such as understanding a sequence of events or cause and effect and concepts based on experience. Part of semantic processing is predictive, based on conceptual understanding and experience.

In contrast to cognitive neuroscience and psychology, semantics in linguistics is sometimes treated as a limited area of lexical meaning. In cognitive sciences semantics is treated as a broader concept including words, concepts and world knowledge, related to the concept of semantic memory (Binder and Desai, 2011). In generative linguistics semantics was seen as dependent on syntax. Cognitive neuroscience points to a more independent semantic processing, with separate processing routes within the language network and development that is later for syntax based on ERPs (Morgan et.al. 2020) and later structural growth of networks for complex structural processing (Friederici, 2011; Klein et al., 2023). A separate processing of meaning and syntax is reflected in dual routes of processing (Hickock and Poeppel, 2004) with similarities to the dual routes of visual processing (Goodale & Milner, 1992) and for auditory and somatosensory processing (Sedda-Scarpina, 2012). Processing in these senses can be divided into a “what” and “where” streams of identification and motor processing. The semantic route may be less time critical in its processing, compared to articulation and syntax that is more directly involved in detailed motor-plans of production.

Semantic processing is central to the N400 component, however semantic processing is not analyzed in detail in the present thesis, as a functional process or more theoretically. The reasons are that while N400 effects reflect semantic processing, they do so in broad and unspecific ways, and there are even exceptions when grammar can elicit N400 effects (Kutas and Federmeier, 2011). In the seventies the discovery of priming led to hopes of elucidating how concepts are related in human cognition, essentially how knowledge is organized. Some results of this research are central today, such as prototype theory, but many questions, such as if concepts are organized hierarchically or through overlapping features etc. could not be straightforwardly answered by the priming paradigms of the time (Chang, 1986). It seemed that knowledge could be organized in many different ways, and probed in different ways. In a review of semantic structure in children (Nelson, 1977), it was found that a hypothesized syntagmatic-paradigmatic shift in children’s word associations did depend to a large extent on children re-interpretation of the task with age and school experience, rather than on a fundamental change in semantic structure. Young children used more syntagmatic associations, words likely to occur in the context of the target word, and school-aged children used more paradigmatic associations, words likely to be possible substitutions to the target word, such as other exemplars within a category. However, in summarizing the research the author suggests that results do not reflect changes in semantic organization, but more likely a change in what children perceive as salient, important features and relations of items, and a changed expectation about what the testers want them to answer. As in the review of the priming literature, the conclusion was that semantics are structured in many ways. There is some similarity in how the N400 is on the one hand clearly reflecting meaning processing, on the other hand still not pinned down to exact predictor variables or understood in theoretical detail. This despite being the most studied language component. Instead, the N400 results have had a disruptive role and made earlier detailed theorizing less believable (Kutas and Federmeier, 2011).

It is difficult to find fMRI parallels to N400 activity (Geukes et al., 2013; Lau and Namyst, 2019). There are no direct means of translating ERP results to fMRI activity, the latter reflect more total energy consumption at timescale of seconds, through the flow of oxygenated blood to an active area (i.e., the BOLD response). ERPs are, as mentioned, mainly based on dendritic activity and the N400 peak can be as short as 200ms. Lau and Namyst (2019) found effects of predictability in left posterior middle temporal gyrus and incongruity effects in the left precentral gyrus, and these effects may be fMRI parallels to N400, however the results are still unbalanced and they discuss why such a strong ERP response has such a weak fMRI counterpart.

Semantic memory and processing in fMRI are important areas since many theories about semantic structure, such as embodied cognition and various associationist accounts have predictions about place in the brain source rather than about time of the response. This is however beyond the scope of the present work. Central works on semantic processing from an fMRI perspective are pointing to hubs for semantic processing in angular gyrus/parietal junction (Binders and Desavi, 2011). N400 is thought to have highly distributed sources in the temporal lobes (Kutas & Federmeier, 2011), including areas close to or overlapping with the angular gyrus, to anterior parts of the temporal lobe.

In a recent attempt to describe what kind of semantic processing N400 reflects, Federmeier (2021) introduces the concept of semantic access. Semantic access refers to a fusing over time of new and old information in a distributed network of both linguistic and non-verbal conceptual knowledge (Federmeier, 2021). The concept is contrasted with lexical access, which refers to a specific point in time when a lexical item is identified and its word meaning is accessed in a hypothetical lexicon. Semantic access is distributed in time and neural networks, and is not word or even language specific.

Modeling semantic structure

The encoding of meaning is one of the great unsolved questions in cognitive science. In search of the structure of meaning taxonomies, feature lists and their overlaps, lexical distributional structure of co-occurrences, networks based on cognitive embodiment and experiential features have been invoked, and these structural suggestions have been probed with memory tasks, reaction time measurements, and ERP components including the N400 in priming experiments, and recently in modeling of fMRI data. In retrospect, it seems like theories were constrained by the computational resources of the time favoring simple taxonomic models in the 1960s, small connectionist models in the 1980s, text based distributional models in the 2000s, and presently deep learning models trained on enormous amounts of data, or models using crowd sourced data of experiential aspects of concepts (see Kumar, 2020 for an historical overview). Recent results are ambiguous. On the one hand the massive deep learning models are effective predictors of fMRI, on the other hand much simpler models based on experiential data are good predictors (Caucheteux et al., 2022. Carota et al., 2023; Fernandino et al., 2021). The latter result is in line with a view of semantic processing as drawing heavily on extra-linguistic experience, with a more limited role for lexical items and their internal relations. Distributional theories however, are not in principle limited to lexical items, and could be important in structuring of experiential features.

Children’s development of language and EF

In the present section brief outlines of children's language acquisition and development are presented, with focus on research with ERP methods. Executive functions (EF) are also presented briefly and one section discusses language and EF in DHH children.

Children’s typical spoken language development is robust and shows similar traits across the world. Regardless of culture and language, infants go from producing vowel-like sounds at 3 months, to babbling at 7 months, and on to producing their first words at around 1 year of age (Kuhl, 2004). Vocabulary grows just before two years of age in what is called a word spurt (Goldfield & Reznick, 1990; See also Ganger & Bent, 2004, for a different view). At two years of age children start to combine words and learn inflectional morphology and complex grammar (Clark, 2003. Gervain, 2020) and a continued growth of vocabulary is observed (Clark, 2016).

When learning spoken language, infants face the problem of decoding a varied continuous speech stream into functional units and patterns. Contrary to common intuitions, the speech stream is not segregated into words, i.e., there aren’t pauses between words in spoken language as there are in written language. Infants identify and segregate words first by learning transitional probabilities among speech sounds

(Saffran et al., 1996. Aslin and Newport, 1998) and later at around 8-10 months of age using prosodic cues such as stress-patterns (Johnson and Jusczyk, 2001; Kuhl, 2004). Infants also use statistical learning to identify relevant speech sounds and segregate words from the speech stream (Kuhl, 2004). Among the 600 consonants and 200 vowels used in languages around the world, infants tune in on the relevant phonemes of their surrounding language (or languages). They start discriminating between these phonemes (which are categories of speech sounds), learn their categorical boundaries based on statistical distributions in the language they are exposed to, and ignore acoustic differences not relevant for the language in their input. Categorical perception of speech sounds constitutes a basis for the acquisition of meaning of spoken language since transitions between phonemes signal differences of meaning (Lian, 2016).

Statistical learning of vowels has been studied with head turn paradigms, utilizing infant's tendency to look at stimuli they are interested in and look away when bored. With head turns Swedish and American 6-month-olds respond to changes from prototypical vowels of their native language, while responding less to changes from prototype vowels in the foreign language (Kuhl et al., 1992). Researchers have tested this effect also by creating artificial category boundaries in phoneme patterns by presenting bimodal distributions around certain parameter values. Eight-month-old infants can pick up categorical information from these artificial distributional properties of phoneme parameters, measured as preferential looking (Maye et al. 2002). In short, infants look with interest when stimulated with changes they have learned is important, such as changes across learned boundaries, natural or artificial.

Infants use statistical learning to discriminate speech sounds and learn their typical combinations, the phonotax (Aslin and Newport 1998). Statistical learning interacts with the infant's own exploration of speech production from babbling to words (Vihman and Croft 2007). This is essential for learning words and building a lexicon in a process that also reinforces learning phonology (Swingley, 2017). Swingley concludes: "They seek out patterns and use them". Learning phoneme patterns (or signs among sign language learners), i.e., phonological acquisition, underpin vocabulary development and is a basis for later development of phonological awareness (PA). Children with hearing loss (HL) have various difficulties in discriminating speech sounds and thus difficulties in building phonological knowledge including phonological awareness, a key factor in study I and II.

A tuning to the first language is likely also in conceptual development, although this area is less studied than phonological acquisition. Just as phoneme boundaries differ between languages, concepts can differ. In English the concepts 'on' and 'in' are central, but in Korean they are not. In Korean, 'tight fitting' and 'loose fitting' are central concepts, but this is not the case in English. Using a habituation paradigm Hespos and Spelke (2004) found that Korean infants were sensitive to the tight fitting/loose fitting distinction just as adult Koreans, English infants and adults however, were not.

There are studies that investigate how children's semantic judgements develop from being associative and thematic, to more taxonomic use of categories (Lucariello et al., 1992; Fischer et al., 2014), that parallel the previous discussion of a syntagmatic-paradigmatic shift (Nelson, 1977). While studies show that such a development takes place, the discussion in Nelson (1977) is still relevant for evaluating the scope of these results: they may not reflect a development of semantic structure as implemented by neural associations, but could also reflect a better understanding of the central role of taxonomic categories in school and formal knowledge and an adaption to these norms.

The development described could be seen as a bottom-up piecing together of the building-blocks of language, however it takes place in the context of interaction and communication (Tomasello, 1986). Communicative language use is described theoretically as speech acts (Austin, 1962), and a flexible identification of common ground and presupposed knowledge (Bohn et al., 2018). Children hone their conversational skills not only by learning phonology, words and syntax but also by understanding common ground, and what their conversational partners know. Social factors in language learning include 9-month-olds learning foreign phoneme contrasts, but only from live interaction, not from mere exposure of recordings through screen and speakers (Kuhl et al., 2003). Learning words also include learning their referents, inferring what objects or events the speaker had in mind. Infants and toddlers do this by using information from gaze and sharing attention while interacting and communicating with their caregivers, thus mapping words and concepts to objects and events (Baldwin 1993. Tomasello, 1986).

At 4–7, the ages of the children in the present studies, typically developed children have incorporated the basic components of language. Their pronunciation of words is intelligible for strangers, they construct complex grammars by joining statements with “and”, “but”, and “because” etc. (Such as “I did it because I wanted to"), they learn to use tenses of verbs, they know the meaning of abstract words and words about inner states, they have developed in how they take turns in conversations and in understanding common ground. They can be more indirect in their communication (Clark, 2016) and they can tell stories much better than younger children (Berman et al., 1994).

ERPs in studies of children’s language development

ERPs have been used in investigating children’s spoken language development, from early MMN studies of discrimination of phoneme parameters and word stress patterns, to sensitivity to intonational phrase boundaries using the Closure positive shift (CPS) component, in lexical and semantic processing using N400, and sentence processing with ELAN and P600 (Männel, 2008). In studies of sign language ERPs are rare overall, and to my best knowledge there are no such studies of early language acquisition or children (see Hernandez, 2022). ERPs in infants and young children are characterized by longer latencies for most ERP components. Latencies decrease with age, with myelination as one important factor of this maturation (de Haan, 2007). Less focal topographies of components are also typical of infant and young children's ERP components, perhaps due to less specified functional networks and higher number of synapses in early childhood (de Haan, 2007). The auditory system as reflected in ERP responses, change throughout childhood, with a broad positive response at 100–200ms, similar to adults P2 but developing gradually with decreased latency into adult P1 (Sharma et al., 1997) and even in adolescence where P1 still decrease in latency and amplitude while N1 increases (Mahajan and McArthur, 2012). The broad positivity P1 is central in the studies II, IV and V. Neural specialization of language function is negatively affected by low SES, evidenced for example in volumetric brain imaging (Noble et al., 2012).

The use of ERPs in studies of children's statistical learning of first language speech sounds overall confirm the trajectory from general sensitivity to language contrasts to specific first language contrasts. At the same time, ERPs show a lingering sensitivity to nonspecific speech contrasts. In a study of first language and foreign language phoneme contrasts, MMN group effects seemed to confirm that 7-month-olds did discriminate between foreign language contrasts, while 11-month-olds did not. Upon a closer look, 11-month-olds did heighten their sensitivity to the first language contrast, but still responded to the foreign contrasts. They did so in ways not visible in the group average response, some individuals had positive ERP effects, some had negative ERP effects (Rivera-Gaxiola et al., 2005). This is an example of ERPs adding more detail in results that sometimes complicate the picture. The relation between learning and ERP effects is not always straightforward. Language learning represents the functional outcome, while ERPs give insight into the processing mechanisms eventually leading up to that result. The sensitivities of parts in the processing machinery can be different from the functional outcome. Learned first language phonemic contrasts seem to be extraordinarily resilient. Sensitivity to phoneme categories of their first language have been detected in adult adoptees decades after adoption that dramatically reduced exposure to their first language (Norrman et al., 2022).

N400-studies show lexical and semantic effects at an early age. Effects of repeated word presentations including N400 were demonstrated in 6-months-olds (Friedrich and Friederici 2011). 14-months-old children show semantic effects, and effects of familiar spoken word form are shown at 12 months (Friedrich and Friederici, 2005). A recent systematic review of twenty-nine N400 studies in children 0–24 months of age fail to draw strong conclusions about how the component develops with age. The authors were not able to determine a consistent trajectory regarding latency, topography and sensitivity of the component (Junge et al., 2021). Despite several findings of longer latencies with younger age, and correlations or group differences in the direction of larger N400 effects connected to language proficiency such as vocabulary size, there are also many studies that do not conform this pattern (Junge et al., 2021). Junge and colleagues (2021) argue that methodologies differ between studies in ways that hamper aggregation of results. In the present thesis, results in various ERP components often do not confirm expected age trajectories. While Junge and colleagues (2021) focus on technical differences between studies in EEG recording and processing, their heterogeneity of results could also reflect sensitivity in exact implementation of experiments, and between participant populations. For further elaboration on these aspects, see discussion.

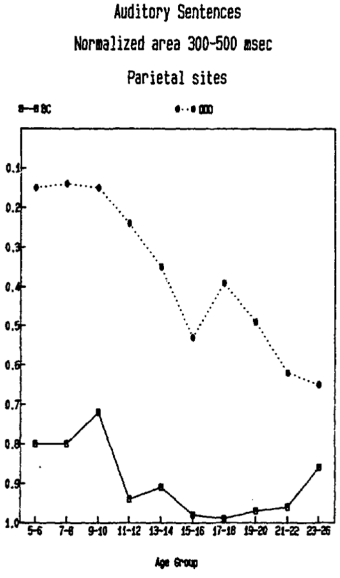

Figure 2. Circles ad squares represent the mean normalized amplitude 300-500ms (negative polarity up) after onset of sentence endings at parietal electrodes for groups with ages between 5 and 26 years. Circles and dotted lines represent responses to anomalous word sentence endings, and squares and solid lines represent the responses to the best word completing a sentence. There is an overall decline of the response to anomalous sentence endings with age, with minor deviations, while response to the best sentence endings change less. N = 11–22 in all age groups except age 23–26 with n=6. In the normalization procedure used, amplitudes were translated to values between 0 (most negative) and 1 (most positive), and positive is plotted downwards. From Holcomb et al., 1992.

Studies of the N400 in older children have resulted in more clear trajectories, at least when many age groups have been studied in the same study. A central study examined N400 effects in children from 5 years of age, adolescents and adults and found decreasing latencies and amplitudes between 5–26 (Holcomb et al., 1992). Another study found decreasing latencies between 6–10 years of age but similar amplitudes (Hahne et al., 2004) and N400 effects in 3–4-year-old children (Silva-Pereyra et al., 2005). Looking at detailed trajectories results from Hahne and colleagues (2004) are largely consistent with Holcomb and colleagues (1992) in that N400 amplitude does not change much between 6 and 10 years of age. Importantly, N400 effects have been found in all age groups, and also in populations with specific language impairment (Pijnacker et al., 2016) and low IQ (Wray and Weber-Fox, 2013).

One important conclusion in studies of young children is that semantic processing as indexed by the N400 develops before ERPs show signs of structural processing (Morgan et al., 2020). Structural processing in left-lateralized early negativity (ELAN) and P600 have been seen in 32 months old toddlers (Oberecker et al., 2004, 2005). ERP evidence indicates that semantic processing is not dependent on syntax as was thought in earlier linguistic theory (Morgan et al., 2020). This result is broadly in line with dual path models of language processing as a whole (Hickock and Poeppel, 2004), with a ventral path for semantic processing and dorsal path(s) for structural and articulatory processing. The pathway for complex structural processing is maturing late, at around 6–7 years age and the ability to process complex structure develops into young adult age (Skeide et al., 2016; Friederici, 2011).

Executive functions and selective attention

Some cognitive processes are not automatic, immediate and intuitive, but require effort and concentration and involve countering our impulses to take effortful top-down control. These are executive functions (EF). EFs have been described as constituted by three core skills: working memory, cognitive flexibility/shifting, and inhibition (Miyake and Friedman, 2012. Diamond, 2013). Inhibition involves behavioral inhibition, cognitive inhibition and selective attention. These core skills are thought to be the basis for more complex, later developing skills such as problem-solving, reasoning and planning. Children's language processing in the previous paragraph is largely described as a processing of incoming percepts and production of words in utterances. However, language use in communication also involves EF, for focus on the relevant input, inhibition of distractions, and maintaining goals of communication.

Strong EFs are associated with many positive outcomes from physical health to school and job success and public safety (Diamond & Lee, 2011; Diamond, 2013). EF skills can be trained making them the focus of interventions (Diamond & Lee, 2011. Neville et al., 2013. Pauli-Pott et al., 2019.). EFs are sensitive to emotional and social and physical stressors such as being sleep-deprived or not physically fit (Diamond, 2013). Among the EF-skills, inhibitory control specifically is very difficult for children. Inhibiting responses is more difficult for children than keeping a high number of associations in memory, while the opposite is true for adults (Diamond, 2013). EF-skills are described as more unitary in children, and as a set of more distinct but related abilities in adults (Downes et al., 2017).

In study IV and V of this thesis ERPs are used to measure selective attention. Although selective attention is seen as part of the third core skill in EF, inhibition, there is some debate about its role. Selective attention is sometimes conceptualized as a prerequisite for EF rather than a part of it. This is discussed in study V. As mentioned, low SES is related to low auditory selective attention (Stevens et al., 2009).

EF has been studied with many different ERP paradigms focusing on components such as N200, P300, error- and feedback-related negativity and Contralateral delay activity (Downes et al., 2017). ERP responses in EF paradigms develop into adolescence, typically with shorter latencies with increasing age for individual components (Downes et al., 2017).

Auditory selective attention in paradigms similar to study IV and V of this thesis show a clear developmental trajectory. In these paradigms probe sounds are inserted in stories that are played simultaneously, and the task is to listen to one story and ignore the other. Probe sounds are linguistic, the syllable “Ba”, or a non-linguistic noise “Bzz”. Average responses to the probe sounds are analyzed, separately for probes in the attended stories, and in the unattended stories. The difference constitutes a selective attention effect. For 3–5-years-old children the effect of selective attention is seen as higher positive amplitude in the broad positivity P1 (Karns et al., 2015, see also study IV and V). In older children (from ≈ 10 years) and adults, selective attention for linguistic probe stimuli is instead seen as a negative N1 effect (Karns et al., 2015). In response to nonlinguistic probes the attention effect is smaller and remains positive and unspecific in adolescence and adulthood despite a development to morphologically more specific ERPs with separate P1, P2 and N1 waves (Karns et al., 2015). The responses to linguistic probes however, are dominated by P1 and N1 from 10 years of age to adulthood. The negative attention effect reflects a maturation, and therefore the negative attention effect in study IV and V is of special interest, since ages 4–7 years typically has seen only a positive attention effect (see study IV, V and discussion).

In the studies of this thesis several EF or EF-related behavioral tests have been used. In studies I and II there was a focus on working memory and relatively complex EF tasks (see Nakeva von Mentzer et al., 2014b): Nonverbal reasoning ability was tested with Raven's colored matrices. Complex working memory, the ability to store and simultaneously process information was tested with a sentence completion and recall test. Visual working memory was tested with a Visual Matrix test (Wass, 2008). In study IV and study V all the core aspects of EF were tested with three behavioral tests. Cognitive flexibility was tested with Dimensional Change Card Sort. Inhibition was tested with the Fish Flanker task. WM was tested with Forward and Backward digit span. Importantly, the ERP paradigm Swedish auditory selective attention test, Swedish AudAt, tests selective attention.

Language and EF in Deaf and Hard-of-Hearing children

Hearing loss (HL) is common, affecting 1–3 out of 1000 newborn infants, and more in some developing countries (World Health Organization, 2010; Neuman et al., 2020). Hearing below the normal range is considered HL; for children the threshold is 15dB below average for pure tones at frequencies between 500–4000Hz. By the age of 18 the prevalence of HL is 18% (Lieu et al., 2020).

DHH children are children with hearing loss described as moderate (41-70 dB HL), severe (71-90 dB HL) or profound (more than 90 dB HL). More than 90% of DHH children are born with hearing parents without sign language skills, and therefore do not get typical language input (Curtin, 2021). Early identification of HL is therefore essential, and in most rich countries of the global north 85–100% of all newborns are screened for HL, while numbers are considerably lower in most countries in the global south; 1–49% in most countries of Latin America and 0–9% in most countries of Africa and south-east Asia (Neumann et al., 2022). Based on the degree of HL, children can get amplified hearing with HA or get access to sound through CI. A brief overview of CI technology is presented in study III. An important factor in hearing through CI is the limitation in spectro-temporal resolution. In a CI sound is translated to power in a relatively small number of frequency bands transmitted through 12 to 22 electrodes implanted in the cochlea. In contrast a fully functioning ear has 15.000–18.000 hair cells with different functions. Among the consequences are difficulties in learning phonology and especially consonant clusters (Nakeva von Mentzer, 2014a).

Among both children with CI and children with HA factors supporting their language development are early fitting of hearing aids, the use of residual hearing, maternal education (i.e., SES), and nonverbal intelligence (Lieu et al., 2020). In children with HA also audibility through the HA and more consistent use of the device are positive factors for language development (Lieu et al., 2020). In children with CI early intervention services, updated processor technology are positive factors (Lieu et al., 2020), and also focus on auditory and oral instruction is reported as a positive factor (but see Kral and Sharma, 2023 for a recent change in the view on harmful effects of visual communication).

Learning language is however more complex than hearing. HL affects spoken language processing more than processing of other sounds, and general problems with semantic and phonological content is found in relation to degree of HL (Jerger, 2007). The phonetic segments of language do not have invariant acoustic signatures, it is necessary to infer phonetic segments based on language specific flexible knowledge of language structure, where a phoneme is realized in different ways in different contexts (Nittrouer, 2002). Related to the theme of top-down and bottom-up processing, there is no pure bottom-up processing among language users. Knowledge of linguistic structure is necessary for identifying even the basic units of language. Children must first learn what acoustic contrasts are important for identifying phonemes of their language, then learn to adapt these contrasts flexibly depending on context, and only later this knowledge amounts to a general phonological awareness (PA). At 8 to 10 years PA still varies considerably among TH children, with poor readers and low-SES children having less PA (Nittrouer, 2002). The challenge for children with HL is primarily to build this knowledge about language, despite challenged hearing. Over time many aspects of language processing that become largely automatic for children with TH, are still more controlled and require effort in children with HL. When more mental resources are used for basic processing, there is less capacity left for deeper processing (Jerger, 2007). The intervention context for study I and II focused on phonology, as it is seen as a critical bottleneck for language development in DHH children.

Study V concerns relations between language and EF and discuss how language skills and EF skills interact in complex ways. This interdependency is also relevant for a wider discussion of the results in study I and III. Wass (2008) found that children with CI had problems with tasks that required phonological working memory, whereas their visuo-spatial working memory was similar to children with TH. There are however results that show EF impairments in deaf populations (see them summarized in Hall et al., 2018) and these results have been interpreted as showing that either lack of auditory input or lack of linguistic input could impair development of EF. Hall and colleagues (2018) compared children with TH, deaf children with signing parents, so-called “native signers”, and children with CI who used oral communication, in parent reported EF and performance-based EF tests. They found that orally communicating children with CI had more EF problems according to parental reports compared to children with TH and native signers. The performance-based tests did show a non-significant trend in the same direction. They conclude that these results give support to the hypothesis that language deprivation rather than auditory deprivation is the likely cause of poor EF results in deaf children. An overwhelming majority of deaf children have hearing parents, so getting access to high quality sign language is difficult.

There are results that indicate that the relation between EF and language skills is stronger in DHH children compared to children with TH (Kronenberger et al., 2013, Pisoni and Kronenberger, 2021). Jamsek and colleagues (2022) found that EF skills at baseline predicted language performance one year later for DHH children, but not for children with TH. This is very likely an effect of the more controlled, less automatic top-down processing needed for comprehending speech in children with DHH. EF is both more vulnerable and at the same time more strongly linked to language skills in DHH children compared to children with TH.

Intervention context of study I and II

The experiments of studies I and II were done in the context of intervention, yet they do not focus on the intervention effects. In study I this is due to a lack of relevant results, and in study II because it describes baseline measurements, before the intervention took place. Other studies in the project however did investigate the intervention, with results that are presented here. The computer-assisted reading intervention with a phonics approach led to improved accuracy in grapheme-phoneme correspondence in all children (Nakeva von Mentzer et al., 2013). The intervention also affected the phonological composite, with a negative correlation between results at first measurement, and the difference between measurement 2 and 3, before and after the intervention. This correlation indicates that participants that started with low scores, developed more in the intervention period (Nakeva von Mentzer et al., 2013). In contrast to the ERP study that measured children twice, before and after intervention, there was another behavioral baseline test, allowing for a quasi-experimental intervention analysis, comparing two measurements pre-intervention and one post-intervention. With the extra baseline, behavioral tests could be assessed better than the ERP studies in relation to intervention, but it was still difficult to disentangle the impact of maturation and test-retest effects from that of intervention. An analysis of reading skills (Nakeva von Mentzer et al., 2014b) showed that, among our participants, factors predicting reading improvement during the study were different for DHH children and children with TH: while reading improvement was related to visual working memory and letter knowledge in DHH children, they were associated with complex working memory and phonological skills in children with TH. This result suggests that DHH children have difficulties in using their phonological knowledge for reading, and rather use visual cues to decipher text. Another study in the same project (Nakeva von Mentzer et al., 2015) compared non-word repetition in children with bilateral CI and children with TH and found patterns of errors that suggest that fine-grained phonology is particularly difficult in children with bilateral CI.

Study II presents baseline results of the MMN paradigm in the intervention project with DHH children. The ERP results of the intervention have been presented in a series of articles by Engström (Engström et al., 2019; Engström et al., 2020; Engström et al., 2021). In the first of these papers, children with TH and children with HA were compared before and after intervention. There were no differences in mismatch effects between pre- and post-intervention and no interactions between mismatch effects and intervention (Engström et al., 2019). Furthermore, polarities of mismatch effects (i.e., MMN or pMMR) were compared pre- and post-intervention, and polarity pre-intervention did not predict polarity post-intervention at the individual level. On the group level however, there was a pattern where all responses in children with HA have higher amplitudes post-intervention, and all responses for children with TH have slightly smaller responses. These changes include standard responses, and are significantly different pre-intervention, but disappear post-intervention as the two groups' responses become more similar (i.e., HA responses have higher and more positive amplitudes post-intervention except for duration, while mismatch effects in children with TH become slightly smaller). The duration deviant was the only deviant with consistently negative mismatch response in both groups, pre- and post-intervention. In a separate study, children with CI were compared to children with TH (Engström et al., 2020). Responses post-intervention were smaller for both for children with CI and children with TH (except for duration in children with CI), the differences were all small and non-significant. Mismatch effects were only found when separating individuals with pMMR and MMN, and there was a tendency for polarity change between pre- and post-intervention.

In a follow-up study three years after the time of study I and II, Engström and colleagues (2021) found that children with HA (n=7) and children with TH (n=10) had substantially higher peak amplitude responses to sounds compared to pre-interventions measurement baseline, but not children with CI (n=6). Children with HA had statistically different responses between follow-up and baseline. There were differences in the mismatch effects between baseline and follow-up in the duration mismatch for children with HA, and in the location mismatch for children with CI. Both these effects were close to zero in the baseline data (a subset of the participants in study II), and more negative in the follow-up.

The strongest pattern over the four studies (Study II; Engström et al., 2019; Engström et al., 2020; Engström et al., 2021) is larger P1 responses for children with HA, suggesting that the initial low amplitudes in responses in this group changed over time for the better, while CI responses did not change much. The ERPs of children with HA and TH have very articulated morphology in the follow-up study, with a large P1 followed by a negativity, while children with CI have a smaller P1 and the following negativity is hardly noticeable. In study I and II the low amplitude responses to sounds in children with HA were interpreted as reflecting insufficient amplification in their hearing aids. The pattern over time is interesting, but is undermined somewhat by the small number of participants in the follow-up study. In conclusion, the larger P1 over time for children with HA, suggest a positive trajectory of maturation of their auditory responses, in contrast to the small responses in this group that are presented in study I and II. A small positive difference in hearing status is also found in this group.

Methods

Recording and processing of EEG

In this section methods that are central to all the studies are presented, i.e. EEG recording and processing for extracting ERPs, and it is followed by a section presenting ethical considerations and practices for having children as research participants that was developed and used in study IV and V. The EEG and ERP methods used in the projects are described here, and conform in a large part to typical instructions such as presented in handbooks (Luck, 2014), but also with some more unusual processing methods (i.e., Dien, 2010).

EEG in study I and II was recorded with high-density electrode nets from EGI (Electrical Geodesics Inc.). The nets had 125 electrodes that are embedded in sponges filled with salt water to enhance electrical conductivity to the scalp. In study IV and V another system with 16 active electrodes from Biosemi (BioSemi, Inc.) was used. With this system conductive gel is used to make contact between electrodes and scalp. The practical part of EEG recording involves placing the electrodes well on the head of the participant, achieving good contact between each electrode and the scalp. However, children participants put severe constraints on time to handle bad electrodes. The two systems used here represent different approaches to this problem. The EGI nets with 125 electrodes are relatively easy to apply all at once, but further adjustments are usually needed. Each of the 16 electrodes in the Biosemi system are placed individually which takes time, instead each electrode has a better signal.

A large part of practical work with brainwaves and ERPs is processing and cleaning the data. The signal is noisy and even a good recording requires several processing steps to make it interpretable. First, the data need to be high-pass filtered to take away the DC-potential that does not contain relevant information for typical ERP studies. The high-pass filter is usually 0.01Hz, 0.1Hz or 1Hz, with higher cut-off optimal for later ICA-analysis, and lower cut-off possible if the participants are able to sit very still. Children tend to move quite a bit so a higher low-pass cut-off can be useful to attenuate mild movement artifacts.

In a recording any bad electrodes, that is electrodes that did not make good contact with the scalp (or in rare cases were broken), need to be identified, removed, and later interpolated. Other parts of general processing are optional low-pass filtering (often with a cut-off at 25–40Hz to avoid contamination from electrical mains at 50Hz or 60Hz), re-referencing from recording reference to mastoid electrodes or average reference, epoching i.e. cutting the continuous EEG into the parts of the event-related responses of interest (often 500–100ms before stimulus onset and about a second after), and baseline correction (subtracting the mean from a baseline period, usually a few hundred milliseconds before stimulus onset, from the epoched data). In study I and study II a FIR filter using a passband between 1 and 40 Hz was used. In study I epochs were extracted from -200 to 1200ms around the visual target stimuli. In study II epochs were extracted from -100 to 500ms. The data for study IV and V was filtered using a passband between 0.1 to 40Hz and epochs were extracted from -100 to 500ms.

The identification of specific artifacts is sometimes done using continuous data, sometimes using epoched data. The eyes have large electrical fields, and movement or the closing of the eyelids during blinks change these fields creating large artifacts. These artifacts are morphologically homogeneous, and can be rejected based on inspection or be isolated automatically using ICA (Makeig et al., 2004). Movement artifacts or not homogenous and cannot be isolated with ICA, they can be rejected by inspection, by some criterion, usually amplitude, or using specific movement artifact attenuation based on PCA (Dien, 2010).

EEG data from study I and study II was processed with the EP-toolkit (Dien, 2010), a system that combines several specific methods to automatically detect and remove bad channels, eye artifacts (using ICA), and movement artifacts (using PCA). In this process the author also used ICA to identify and remove CI artifacts for study II where the target stimuli were auditory. CI components can be isolated using ICA (Miller and Zhang, 2014). ICA components with CI artifact were identified by their contribution to the peak time of the artifact, 0–50ms, and by other features. 94% of epochs in study I and 73% of epochs in study II were retained after artifact rejection.

In study IV and V the data was processed with a more traditional combination of amplitude criteria followed by visual inspection of all epochs in the data. EEG from children typically have lots of movement and other artifacts and it is not unusual to reject around half the data. 50% of all epochs were retained in study IV and V. In the studies I and II much less data was rejected, instead the artifacts were isolated and removed from the data. Both methods are used extensively, with simplicity and transparency favoring rejection by simple criteria, and more advanced methods saving data but at the expense of transparency. Visual inspection could also be seen as an advanced method with less transparency in what is rejected. The best method in my experience is combining automatic methods for rejection with extensive control using visual inspection to understand what the automatic methods do.

Ethics in ERP research with children as participants

Research ethics is a vast area that is concerned with weighing legitimate interests of researchers, participants, funders and the public. Broad principles, such as reliability, honesty, respect and accountability are described in the European code of conduct (ALLEA - All European Academies, 2023) and are also the basis for Swedish research guidelines (Vetenskapsrådet, 2017).

Central to research with children as subjects is the part of research ethics that is concerned with experiments with human subjects, where principles have been formulated for a medical research context in the declaration of Helsinki (World Medical Association, 2013). Among many principles in the declaration, informed consent is central. Any human in an experiment must be informed about the research project, risks, aims and methods, so they can rationally and voluntarily choose to participate or not. That is if they are capable of consent. Children cannot give consent to research participation, since they have limited understanding of risks and consequences, and may be more easily affected by other people compared to adults. Instead, their legal guardians can give consent, and information is usually directed to them, followed by a consent form that they can sign. The child, if old enough, may be informed and asked for additional consent in a less formal way, and may be carefully attended to with regard to its willingness to participate, but the care-takers have the legal responsibility for consent.

EEG is often used in child research, because it is noninvasive and can be done passively, i.e., most experiments have very simple tasks, and the children can often sit and watch or listen to the experiment as the responses of interest are recorded from the brain. However, the child needs to be motivated and feel at ease with the general situation for optimal participation. In all research involving children, they should be informed about the purpose and procedure in a relevant way. In study I and II that were conducted in lab settings typical methods of informed consent were used, verbal and written information was directed to the caregivers who signed a formal consent form. Children were informed verbally at the site of recordings, and gave additional consent verbally or implicitly by agreeing to instructions.

In a preschool pedagogic context child agency is central (Bodén, 2021), and therefore in study IV, we sought ways of systematically strengthening child agency with regard to research participation. This was done in conjunction with ordinary practices of informed consent such as those just described, in addition to the consent of the legal guardians. The means of strengthening child agency were (1) specially adapted information material directly aimed at children, (2) practices that would make it clear what was research and what wasn't, (3) practices that directly address children's choice of participation, and (4) attenuation of researcher's interests that could come in conflict with children's decisions to participate. These practices are presented here because they were central to the project (study IV and V), and could be of general interest to researchers in child populations.

The information material aimed at children (1) was a small booklet that described what selective attention is, and how it could be measured using brainwaves, and also information regarding other aspects of the research project. This book was read at preschools in advance of the recordings. After the first wave of recordings we also created a video about EEG recordings, since we wanted the equipment and method to be recognized and understood in a more concrete way than what was possible using the booklet. The video was shown in advance of recordings at preschools. The researchers had short presentations of themselves, the research and the mobile lab at preschools based on the perceived need for further information.

Some practices were aimed at clarifying various aspects of the research (2): All researchers in the project wore blue t-shirts with the text “Forskning pågår” (“Research is ongoing" in Swedish), to make them recognizable in their role as researchers and differentiated from other personnel. Visualizations of the phases of the research project were pasted on the floors of the preschools to help children identify what was going on at the moment and what would happen in the future: preparation, testing, intervention, etc.

Practices to enhance children’s say in research participation (3) included the stop sign using your hand, which was taught as a way for children to communicate that they did not want to be part of research. This hand sign was particularly relevant for children in relation to research documentation, such as filming of day-to-day preschool activity.

We organized the flow of participants to EEG recordings in a particular way to strengthen the children’s agency (3), and at the same time having effective recordings (4): Due to the large number of children that could potentially participate, there was minimal pressure on individuals to participate. For each preschool unit we would organize a queue based on a randomized priority list with all the children whose parents had agreed to participate. In collaboration with the preschool teachers, we would have children sent to us based on the list. The randomization was used to minimize bias in participation, i.e. to avoid a selection based on children’s eagerness to participate and to have an approximately equal number of boys and girls participating. In the background, preschool staff, who knew the children well, would manage the list, and send children to the temporary lab room when they were ready and willing. The decision to participate was thus initiated in the social context of staff that the children knew well, rather than with the researchers. When a child appeared in the recording room, we asked basic questions about the procedure to check that they were informed, and if there was any ambiguity about the willingness to participate, we would ask the child straightforwardly if they agreed to participate.

In this situation the ‘medical’ look of the equipment was a factor that could frighten some children, while curiosity and a sense of being important and getting lots of attention by adults, seemed like the main motivating factors for participation. In our efforts to record an equal number of boys and girls, we biased the list for more boys, as a higher number of girls chose to participate. We speculate that this reflects that girls were more in tune with the teachers and therefore more willing to participate in something their teachers seemed to value, and perhaps also being more socially curious. It seemed that boys on average were a bit more suspicious about the project their teachers presented, and less willing to disrupt their own play. The queue based on a randomized priority list ensured that we could go on to the next recording with minimal delays when children did not want to participate. In this way we could avoid potential conflicts between researcher's wishes to collect data and children's agency in participation. In typical lab settings, when children and care-givers are booked in advance at a certain time, there is a large investment from the care-giver and the researchers that might result in adults putting pressure on children to participate. The care-giver may feel that their invested time was not worth it if the child doesn't comply, or that it somehow invalidates them as care-givers. A researcher on the other hand may be pressed to collect the data in time. These kinds of potential pressures were avoided with the combination of many potential participants, and a queue. Another minor issue appeared instead, that some children who wanted to participate were not allowed to do so, due to a random assignment.

During the recordings the main ethical concerns were to ensure that the equipment is comfortable, that the tasks are not too boring and that the child feels at ease with the recording personnel. EEG caps are reasonably comfortable, but a chin strap that is too tight can become a problem. After a recording, removing face electrodes that were fitted using an adhesive ring can be uncomfortable if not made carefully. Residual gel in the hair was mentioned as a reason not to participate again by some children in study IV. Overall, we had low attrition (six children declined to participate in the second recording), and that is perhaps the best measure that most children found these nuisances to be mild. In study I and III we used equipment from EGI that does not need gel or adhesive rings, but it is not clear if this difference was important for child comfort.

Passive tasks without meaningful content to attend to become boring very fast. In study II, the sounds of the MMN experiment were presented while the listeners were watching an entertaining silenced, cartoon, and in study IV and V the stories the children attended to were engaging and interesting. Sometimes active tasks are used, and if they are well designed, they can be engaging. In study I, children heard prime words followed by images and were instructed to press buttons to indicate if the image depicted the same concept as the word. The first participants were sometimes confused and pressed the buttons repeatedly. We added visual feedback to the button presses to solve this problem, resulting in a small change of procedure but better experience for the participants. Extensive piloting before study IV made us aware that some stories had problems that made them less engaging. Some stories were too difficult, or too long, and the accompanying images did not feature any multi-ethnic people in contrast to the preschool population with diverse ethnic backgrounds. In response, we recorded new stories, introduced shorter stories and with images that better represented the participating population. These kinds of adjustments based on actual interaction with the target population is essential for developing child-friendly experiments.

To avoid boredom, it is also important to apply equipment fast and not have too long recordings. The double experiments of study I and II could be challenging with a total of about 30 minutes after application of equipment. The recording time in study IV and V was around 16 minutes.

Giving children meaningful insight and agency in the research they participate in is not only ethical, but is also a way of getting better data and lowering attrition, assuming that children's own motivation is stronger than external pressure.

Interdisciplinary discussions and participatory ethics

The project of study IV and V was accomplished in collaboration with researchers in pedagogy. While researchers from pedagogics had initiated the study, and were eager to expand their methods into RCT research, the Swedish and international community of pedagogic researchers harbor a pronounced skepticism towards testing methodology (Frankenberg et al., 2018. Bodén, 2021). There was a fear that testing methodology would amount to an instrumental attitude towards children as research objects without agency. Participatory research is seen as the ideal form based on the value of inclusion (Bodén, 2021). In the planning phase of the project these matters were challenging. The author and the team from linguistics insisted that participation in research could be meaningful and dignified even with minimal influence over the research methods, such as when using standardized tests or experiments, provided that it was based on age-adapted information and consent.

Discussions that were based in different perspectives on child research participation were productive and inspired many of the practices described earlier, and was the impetus for starting another study related to the project, that focused on how children experience participating in research (Bodén, 2021). In that investigation, the author Bodén realized that her own research, which adhered to the participatory ideals, could be questioned, partly because it was less clear for the children that research was ongoing and how, while the testing situations including those with EEG were salient and separate from other preschool activities and therefore easier to frame as research for children at preschools, in turn making participation clearly voluntary.

She analyzed the prevailing ethical assumptions as an ethical scale where prepositions "on, to, with, for, by" describing relations between research and participants, was used, and where more participation (research 'by' children) was always better than less (research 'on' children) from an ethical stance. She concludes that describing research 'on 'children as less ethical than participatory methods, are at risk of missing that these methodologies are often underpinned by an ethics of fairness, with knowledge claims focusing on effects and generalizability for children in general (Bodén, 2021. See also Frankenberg et al., 2018.). The project also prompted other ethical analyses that discuss how ethics in research is often seen as protection against abuse, and that this focus can lead to ignoring positive values in participation from a child point of view (Aronsson, 2022).

Summary of the studies

Summary of study I and II

The context of the studies I and II was a computer-assisted reading intervention with a phonics approach (Lovio et al., 2012) to target phonological skills in DHH children. All participants received the intervention in the same period, so there is no experimental test of the intervention (see section Intervention context of study I and II). However, in the behavioral testing there were two baseline tests (Nakeva von Mentzer et al., 2013, 2014b) to facilitate analysis of intervention effects. The ERP experiments were done on two occasions only, before and after intervention. The main hypothesis for the intervention was that the phonics training would strengthen phonological awareness, and that this would have up-stream effects on semantics, and down-stream effects on perception of auditory detail. Increased phonological awareness was hypothesized to help DHH children to form more distinct phonological representations of words, that would in turn lead to larger N400 effects. The same phonological awareness was hypothesized to enhance discriminations of sounds in the MMN paradigm. The MMN paradigm was constructed with tone pips that tested discrimination of basic auditory properties such as pitch, loudness, duration, direction and auditory detail (inserted short gaps).

Thirty DHH children between 5–7 years old participated, 15 with HA and 15 with at least one CI. 12 matched controls also participated. Controls are called normal hearing (NH) in study I and study II, but will be referred to as TH in this text, for consistency. These three groups are called hearing groups in the following. Children with HA and CI had hearing thresholds of 20–40 dB when using their aids, with higher values for high frequencies in children with HA. Without aid, 17 of the DHH children had severe/profound hearing impairment with hearing threshold >70 dB, and 11 had moderate hearing impairment with thresholds between 40–60 dB, and two had mild hearing impairment at <40 db. For more detail about hearing background, see table 1 in study II where etiology, age of diagnosis and amplification aid is listed for each individual.

The phonics training intervention did have effects on phonological skills, especially for those who started out with lower skills (Nakeva von Mentzer et al., 2013) and on reading skills (Nakeva von Mentzer et al., 2014b). These results are presented in the section Intervention context of study I and II, neither the N400 experiment nor the MMN experiment had any clear effects of intervention. In study

I there is an interaction between N400 effect, training (intervention) and hearing group, but it is a weak effect (partial eta = 0.113) that does not involve larger N400 and hence there is no clear interpretation that this is a positive effect of intervention. Due to the lack of intervention effect in study I and because study II describes pre-intervention effects study I and study II focus on ERP differences between children with CI, HA and TH and their cognitive interpretation.

Study I

The N400 paradigm in study I used spoken primes, common concrete nouns, followed by target images. There were three experimental conditions. When the speech prime words were followed by images of the objects they named, the condition was called congruent or matching. In some trials the target image does not match the prime word, these conditions were called incongruent or mismatches and had two sub-types. The pictured object could be related to the prime, by being another object from the same category, this is called within-category mismatch or related mismatch. The object could also be semantically unrelated, from another category and not commonly associated with the prime word; this was called a between-category mismatch or an unrelated mismatch. The difference between congruent/matching and incongruent/mismatching in the N400 response amplitude is called the N400 effect. In study I there were two N400 effects termed within-category and between-category. Category membership is one type of semantic relatedness, but the stimuli in study I were in fact not only distinguished by category membership, between-category images were also not associated with the targets by other means, and a few of the categories in the within-category condition could actually be better described as semantic fields or associations (i. e. one of the categories is 'baby things', that is defined by association rather than hyponymy). In study III the terms related and unrelated mismatches are used instead of within- and between-category to fit the broader literature that use these terms.

In N400 literature the word incongruent is often used instead of mismatch, but mainly in the context of sentence endings and sometimes reserved for words with semantics that are incompatible with the previous sentence context. In the present studies the term incongruent is used as an equivalent to mismatch without implying a deeper semantic incompatibility.

The responses to target images, i.e., the mean amplitudes per subject in the N400 time window, were analyzed with a repeated measures ANOVA, with the three within subject semantic levels, two within subject levels for pre and post intervention, and three between subject levels for hearing group. There was a semantic main effect, an interaction between semantic and group conditions, and an interaction between semantic, group and intervention levels discussed earlier. The semantic effect does not have a post hoc analysis in study I, but we can see from the means that congruent is least negative, and that between-category mismatch is most negative, and within-category mismatch is in the middle, somewhat closer to the between-category mismatch. In the semantic and group interaction, we see that for NH children the two mismatches do not differ much, in fact contrary to expectations, the N400 amplitude for within-category is slightly larger than for between-category condition. For children with HA, all three condition responses have more similar amplitudes, and for children with CI, the between-category response is larger than for children with NH, and the within-category response is smaller than the between-category response. In the follow up analysis with 50ms bins for separate groups we see much stronger between-category effects in pairwise t-tests for the children with CI compared to children with NH and HA. Also, we see within-category effects after the N400 time window in children with NH and HA, while the maxima of effects are right within the N400 time window for children with CI. These results together present something very different from our predictions about the groups. In study I we argue that the large between-category effect and the smaller within-category effect in children with CI, in contrast to smaller between-category effect with a within-category effect of the same size in children with NH is most consistent with stronger semantic top-down processing among children with CI compared to children with NH. There are essentially three aspects of the ERP results that indicates semantic top-down processing: differences between between-category and within-category N400 effects depend on active predictions (Federmeier and Kutas, 1999; Franklin et al., 2007; Wlotko et al., 2010; Kiang et al., 2013). There are early latency between-category differences in children with CI, and early effects are a sign of more detailed predictions (Bornkessel-Schlesewsky et al., 2016; Brothers et al., 2015; Lau et al., 2013). Finally, the larger between-category effect in children with CI compared to children with NH indicates that the effect is not based on semantic skills, but consistent with a stronger emphasis on prediction. There were also some support for such a processing strategy in the literature on children with CI (Lyxell et al., 2009; Nakeva von Mentzer, 2014a). We discuss two alternative explanations, but they are both more ad hoc, with little support in literature or data.

The weak N400 effects in children with HA could indicate that their amplification did not work as well as the CI implants in the experiment. This result could be an effect of children with HA having less medical focus and resources compared to children with CI, resulting in hearing devices that are checked less often. It is likely that the situation for children with HA is under-researched (Moeller, 2007).

In the supplementary data we make a control analysis, because we had changed the paradigm a little due to problems with feedback buttons. We remade the analysis with only the children recorded after the feedback button change, and got similar results but with higher partial eta. The change seemed not to affect the direction of the effects but made them stronger.

The exact time window was determined by a series of t-tests of the two mismatch effects, between 350ms to 500ms both mismatch effects were significant. This time-window is the second most common in a recent review of N400 methodologies (Šoškić et al. 2019), with the most common being 300–500ms. In the topographical plots of figure 1b there is a frontal negativity and a parietal positivity indicating

N300 in the 300–350-time window) and only children with CI had a weak effect here. If anything was missed this was the later maxima for the related mismatch effect 500–550ms, which is then outside of typical N400 time windows in the literature. There are no easy solutions in selecting time windows for ERP components. Rigidly using time windows from the literature involves risks of missing a real effect, optimizing the time window based on visual inspection can inflate an effect. The time window in study I is in practice a compromise between commonly used time windows, testing that amounts to an innocent form of double dipping, and an analysis of the topography of the effects. In retrospect it seems like a separate time window for the related effect could have been a good option, but that would have made the two effects less comparable, and it would have been more ad hoc instead of based on typical N400 time windows in the literature (Šoškić et al. 2019). Another way of extracting effects and time-windows based on data are using mass univariate statistics or permutation tests (Groppe et al., 2011; Koenig et al., 2011).

The up-stream effects on semantics were predicted since phonology is important for word learning and would be tested with a N400 paradigm with image targets. The hypothesis was based on a view of the N400 effect as a neural measurement of semantic skill, and the effects were hypothesized to be larger in TH children, smaller in children with HA, and even smaller in children with CI. After the intervention period the effects were hypothesized to be larger for DHH children reflecting better semantic ability. The main results were in direct contrast to the hypothesis, children with CI had larger N400 effects, and also a smaller response to related mismatches, and early differences in the time period before the N400 time window. These results indicated that N400 effects in this experiment did not measure semantic skills, but rather a top-down semantic processing strategy. This strategy is suggested in paper I and further discussed in study III.

Study II

In study II we used Nätäänen's multi-feature MMN paradigm Optimum (Näätänen et al., 2004) to test discrimination and memory for tone sequences. With an ordinary MMN paradigm the time for testing one sound contrast is almost an hour. The Optimum paradigm tests five contrasts in shorter time, by using stimuli that deviate in one of five different dimensions, while at the same re-enforcing the standard features in the other dimensions (Näätänen et al., 2004). Pitch, loudness, location of sound source and duration are basic sound dimensions that are tested, the fifth-dimension concerns auditory detail in the form of a short gap. The test is completely passive and the participating children could watch a silenced cartoon during the experiment. The N400 experiment of study I was first delivered and then, after a pause, the MMN "Optimum" paradigm of study II, during the same recording.

The specific research question for study II is exploring if the optimum paradigm would capture relevant variation in auditory processing, showing a profile of sensitivity to the five dimensions of the paradigm, that would correlate with severity of HL and delay in language development. Also, a larger MMN as after intervention was expected but not found (See Intervention context of study I and II). Study II was a presentation of the pre-intervention results in the MMN-experiment. The results were largely unexpected. While a significant duration MMN was found in children with TH and CI, other deviants had positive mismatch responses on average in the typical MMN time window, followed by late discriminative negativity, LDN, at around 300ms in children with TH and HA, but followed by a late positivity in children with CI. In individual inspection children's MMR (the difference wave between standard responses and the mean of all deviant responses except duration) 14 had pMMR, 19 had MMN, 9 had unclear response. Negativity correlated with age, but this effect was strongest among the children with TH. pMMR is often found in young children but is less typical in children of this age (5–7 years), and is associated with immature auditory systems, and with fine contrasts and also complicated sound stimuli.

Due to the lack of a clear MMN peak the results were presented in time windows based on the visible components in the waveform. TW2 (80–220ms) captures the P2-like wave common among children’s responses to sounds, that eventually evolves into the adult P1 (and therefore called P1 in the manuscript). This time window overlaps to a large extent with typical MMN time windows (150–250ms) where most of the results are found. The results were presented descriptively because of their unexpected nature.

The small P1 response among children with HA compared to children with CI or NH might reflect insufficient amplification through their hearing device. pMMR seen for contrasts except duration could reflect immaturity of the auditory system both because of age and hearing loss. In children with NH the correlation with age is quite strong for the intensity deviant (-0.63), and weaker for children with CI (-0.35), and children with HA (-0.22). The lack of correlations with language tests could indicate that the simple tone pips of the paradigm did not reveal responses more relevant for complex auditory processing. The difference in responses to intensity between children with HA with a weak MMN and children with CI that responded with pMMR is noteworthy but difficult to interpret. Finally, children with NH and HA have negative going difference waves, LDN, for all contrasts in the last two time-windows, while children with CI have positive effects for many contrasts, strongest for location. Processing of the location contrast could be different in the group with CI because some participants have unilateral CI, or bilateral CI implanted with a long interval.

Summary of study III

Since study I, there has been an increased interest in semantic processing in children and adults with cochlear implants and three studies using N400 paradigms in children with CI has been published since then (Bell et al., 2019; Pierotti et al., 2021; Vavatzanidis et al., 2018), among them a partial replication of study I (Pierotti et al., 2021). Study III is a review article of these studies and study I. In the systematic search for studies of semantics among children with CI that use neuro-methods we find that only the N400 studies do focus on this issue. There are no fMRI studies on the subject, in part due to incompatibilities between typical CI's and the MR technique. There are a few oddball paradigms using word stimuli but most of these do not constrain experiments or analysis of neural responses in ways that can disentangle the general oddball effect from semantic processing. One study makes the claim that they do, by identifying a N400 component in the response (Munivrana Dervišbegović and Mildner, 2020). However, the claimed N400 effect is not presented well, and there are several methodological issues in the article, so the study is not included in the review.

In the review we group the three studies that all have image targets (study I; Bell et al., 2019; Pierotti et al., 2021). This is done because experimental design and ERP responses have important similarities. The remaining study have auditory target stimuli, using a N400 paradigm in a developmental study following small children the first years after implant (Vavatzanidis et al., 2018).

In the discussion we emphasize that N400 effects are found in all studies in participant groups that use CI, except in a group distinguished by other impairments besides HL among very young children (Vavatzanidis et al., 2018). Two studies find a larger N400 effect among children with CI compared to children with TH (study I; Pierotti et al., 2021). The third similar study found similar sized N400 effects in groups of children with CI and children with TH, despite indications of lower semantic skills in children with CI (Bell et al., 2019). Together these results invalidate the often-repeated hypothesis (study I; Bell et al., 2019; Pierotti et al., 2021) that N400 should reflect semantic skills and thus be smaller in children with CI than in children with TH.

While there are likely some conditions where N400 effects do reflect semantic skills, the present experiments and results instead point to a difference in processing. We discuss at length in study III the hypothesis that the large N400 despite lower semantic skills depend on a shifted balance from perceptual bottom-up processing towards a more semantic top-down processing, that is, a more predictive processing.

We find that many recent studies, most of them with of adult participants with CI, explore this type of processing (Pisoni and Kronenberger, 2021; Winn, 2016; Diemtrievitj et al., 2019; Dingemanse, 2019; Moberly and Reed, 2019; Moberly, 2020; O'Neill et al., 2019; Zaltz et al., 2020). While the hypothesis is supported by details in the ERP responses, such as a smaller N400 effect of related compared to unrelated mismatches (study I) and early latency semantic mismatch differences (study I; Pierotti et al., 2021), and the aforementioned studies of adults with CI, there is still a lack of conclusive causal linking between this processing mode and the large N400 effects.

Large N400 effects in children with CI have only been presented in studies with targets in the visual modality. That limitation leads to a possible alternative explanation that the effects are related to different cross-modal processing among children with CI. This alternative hypothesis has less direct support than the top-down processing hypothesis but it is important because emphasis on cross-modal or visual means of communication (including sign language), has been controversial and even discouraged for children with CI (Giraud and Lee, 2007). Earlier results seemed to indicate that visual input could overtake auditory processing areas in the brain with detrimental effects on oral language processing (Campbell and Sharma, 2016). Several studies have contested the hypothesis of maladaptive cross-modal reorganization (Anderson et al., 2017; Corina et al., 2017; Heimler et al., 2014; Mushtaq et al., 2020; Paul et al. 2022; Wallace, 2017). A recent review of the evidence concludes that the effects of cross-modal reorganization are limited and flexible, and not responsible for closing critical periods of auditory development in deafness (Kral and Sharma, 2023). This review has an extra weight since the same authors have published many of the central articles used to argue for maladaptive cross-modal reorganization. The present results suggest that clinical recommendations to avoid cross-modal communication in (re)habilitation for children with CI may need to be revised.

The literature on N400 effects in children with CI is small, both in number of studies and in number of participants. This is a central problem not easily avoided because children with CI are relatively few, and as a population very heterogeneous. There is important variation in residual hearing, language background, implantation, and also impairments besides HL. We discuss ways to overcome this problem and suggest that aggregated analysis of individual data from many studies, addition of short N400-paradigms to other ERP studies of the population, and a widening of inclusion criteria and studying of related larger populations such as children with HA might be ways to overcome the scarcity of data. Children with HA are an important population in their own right that is likely understudied. The hypothesis that large N400 effects in children with CI reflect increased top-down processing is suited for further investigation in other populations, since compensatory top-down processing in response to adverse hearing situations is likely a general phenomenon.

Further studies are needed to establish a causal link between top-down processing and larger N400 effects more firmly (Lau et al., 2013), and also to map out the boundaries of such processing and side effects, i.e., its relation to effort. The goal of understanding semantic processing in children with CI is finding ways to enhance their language and communication skills. The present results do not suggest new interventions yet, but put focus on already existing practices, especially those that help semantic processing, but possibly also cross-modal communication. Both areas are already established in recommendations to practitioners and parents (Luckner and Cooke, 2010; Luckner and Handley, 2008, Curtin et al., 2021; Nittrouer et al., 2018). We also briefly mention that EF-training and morphological reading could be helpful and in line with present results (Neville et al., 2011; Trussell and Easterbrooks, 2017).

Summary of study IV and V

Swedish preschools, like Swedish schools, are regulated in documents with learning goals and ethical and democratic principles (Skolverket, 2018. In English: Swedish National Agency for Education, 2019). Yet there is a lack of research, especially experimental research, to evaluate methods and support the achievement of those goals effectively. Study IV is the summary of the first randomized control trial (RCT) research study in preschool pedagogics in Sweden. That is, the first study using randomization of participants to evaluate intervention effects in this field. It evaluates the effects of a group-based socio-emotional learning strategy and an individual digital training of EF and early math, using a large test battery of language and cognitive tests pre- and post-intervention. A subgroup of the preschool children also participated in a selective attention experiment using ERPs. Study V is a follow-up analysis and discusses relations between individual EF measures and language measures including selective auditory attention.

Study IV

The field of preschool pedagogics in Sweden have previously not used RCT research designs and have generally avoided quantitative and experimental methods (Frankenberg et al., 2018). In part this is a prolonged response to behaviorist influences in the historical roots of preschool pedagogics in the kindergartens of the 1940s (Lenz Taguchi, 2019). In part it is influenced by a preference for participatory research (Bodén, 2021). The project was conceived as an effort to evaluate present teaching methods using experimental methods, cognitive testing and neuroscience methods. A type of socio-emotional learning is already established in many Swedish preschools, especially in the Stockholm area. A central ingredient is the social component and collaborative learning, and therefore this intervention was contrasted with an intervention based on individual activities: an early math training using digital tablets and exercises that were not collaborative.

In international research studies there are interventions in preschools and preschool ages that mainly target executive function (EF), socio-emotional skills, language and literacy and early math. All these skills and abilities can be enhanced with pedagogical interventions (Anders et al., 2013; Bleses et al., 2017; Clements et al., 2016; Koponen et al., 2013; Lonigan et al., 2017; Neville et al., 2013). At the same time there is a divergence of study results were different subgroups respond to interventions in inconsistent manners (Buysse et al., 2014; Loeb et al., 2005; Magnuson et al., 2007; National Early Literacy Panel, 2008), and also unclarity about how persistent effects are (Love et al., 2002; Department of health and human services, 2010). In most studies low socio-economic status predicts low results initially, but also higher chances of enhancement due to intervention (Barnett et al., 2008; Blair et al., 2007; Bull et al., 2011; Diamond et al., 2011; Diamond et al., 2007; Hackman et al., 2010; Hackman et al., 2019; Melby-Lervåg et al., 2013; National Early Literacy Panel, 2008; Neville et al., 2013). Another important factor that varies between studies is the quality of preschools and intervention programs (Cunha et al., 2006; Havnes et al., 2011; Rege et al., 2018; Sylva et al., 2011). Our selection of target and background variables in the study was informed by this broad literature.

In total 30 preschools of a municipality outside Stockholm were invited to participate, and 18 agreed to do so. During intervention they consisted of 29 units with a total of 431 children. Due to the group-oriented nature of the socio-emotional intervention and of most preschool activity, randomization of interventions was conducted at preschool unit level. Randomization was restricted so that each preschool could only have control units and one type of intervention. Participating children should be at least 4 years old, and there were no other restrictions on participation. Average age was 5.2 years. Preschool personnel, parents and children was informed with directed talks, pamphlets, videos etc. and constituted a hierarchy of informed consents, were personnel first had to agree to participate in the project, parents had to agree that their children could participate in testing, and finally children had to agree themselves to participate in the testing. Parents and children could opt out of testing, but could not opt out of the intervention programs as these were considered variations within the preschool curriculum. Child ethics in the project have been studied by a separate researcher (Bodén, 2021) and is further discussed in the methods section on ethics.

The socio-emotional learning strategy intervention was named SEMLA (Socio-Emotional and Material Learning) and consisted of crafting a 'city of the future' in a small group. The concentrated hands-on construction project included face-to-face interaction, creative practice, measurement, introduction of new concepts, documentation and meta-reflection. Throughout there was a focus on communication, emotional engagement and early math. The engaging explorative learning, led by children but scaffolded by teachers, was expected to enhance interest in learning, language and communication skills and EF. SEMLA was considered a more concentrated, boosted form of the type of Social-Emotional learning taught at Stockholm university and practiced in many Swedish preschools.

The individual training was named DIL, Digital Individual Learning for body-and-mind. It consisted of an early math training on digital tablets from the Education and technology group at Lund university (Haake et al., 2015), and concepts and exercises designed to enhance EF such as self-regulation and attention and were adapted from an intervention designed by the Brain Development Lab, Oregon (Neville et al., 2013).

In the control condition pedagogical work was carried out as usual.

The interventions were carried out in three waves. Before an intervention period, parents were informed and asked to give informed consent and background information regarding their children, children were informed about the project, staff was educated in how to deliver interventions and pre-testing was conducted at preschools. The intervention period was six weeks, and was followed by post-testing. In addition, preschool quality was assessed with ECERS-3 (Harms et al., 2014) and intervention implementation fidelity was scored.

The test battery is summarized in table 2 of study IV and includes standardized or adapted tests of language, communication, math, socio-emotional comprehension and executive functions and a Swedish implementation of the selective auditory attention test AudAt. AudAt is an adaptation to children of the Posner dichotic listening task where children's brainwaves are measured as ERPs to probe sounds from speakers on the left or right. In each speaker a pre-recorded story is being played and the children are instructed to attend to one story while ignoring the other. Images on a screen relating to the attended stories helps them focus according to instructions. ERPs to the attended channel are generally larger. AudAt was developed by Brain Development Lab, Oregon (Coch et al., 2005), and has been used to evaluate interventions (Neville et al., 2013) by this group. We made a new implementation of AudAt using Swedish stories.

Brainwaves were recorded at preschools using mobile equipment. Only a subset of children was tested with Swedish AudAt. We devised randomized priority lists to maintain an effective recording schedule while minimizing pressure on children to participate. If a child declined to participate, we asked the next child on the list to avoid down-time associated with individually scheduled recordings. We recorded 138 children during pre-testing, and slightly fewer at post-testing. Only 6 children declined to be recorded a second time. After processing of EEG and rejection based on quality criteria, we used 89 recordings from pre-tests, and 89 from post-tests in study IV, where 76 individuals had sufficient quality data from both pre- and post-testing.

To handle nested data, with children in units at preschools, missing data, and both categorical and continuous variables we used mixed model regressions. There was no main effect of intervention conditions. The largest pre-post difference within an intervention condition was 0.15 SD for EF, and 0.24 SD for selective attention in DIL. but the study is not designed for small differences such as these that would need over 350 or over 150 participants respectively. Furthermore, these differences between conditions are found in the pre-tests and disappear in the post tests. Part of the DIL intervention was based on earlier interventions with positive results for AudAt (Neville et al., 2013). The present result could be seen as a very weak trend in the same direction rather than evidence against similar effects. Both interventions were targeting early math, but there was no measurable progress in math.

The most important positive results are that SES predict math, EF and test of emotional comprehension (TEC) post intervention. Implementation fidelity is also a significant predictor of TEC. Family language problems (FLP) negatively predicts communication post intervention. Because of an underestimated problem with collinearity a multivariate analysis was conducted as a complement to the pre-registered analysis. Here background variables are not significant predictors (SES and FLP), instead pre-EF predicts Math, Language and TEC. Pre-Math is a positive predictor of Post-EF, while Pre-Communication is a negative predictor of Post-EF.

The selective attention ERP measure used was based on mean amplitude between 100–200ms. It was analyzed with an ANOVA. There was a main effect of attention, but no interaction between conditions and time (pre vs post). As a difference measure between attended and unattended it was analyzed with the same type of mixed model as other variables for comparison, but without any significant effects. In our overall results there was a complete lack of intervention effects, however the selective attention effect was higher after intervention in the DIL condition (see figure 2.C, study IV). Due to the small size of the effect (0.24 Std), and the fact that the attention effect was smaller in the DIL condition before intervention, and similar to other conditions afterwards, we do not consider this a genuine effect. However, it is neither a complete lack of effect. The DIL intervention was partly based on intervention practices that do show selective attention effects in ERPs (Neville et al., 2013) and the present effect, while not significant, could be seen as weak evidence in this direction.

Some unexpected ERP effects are reported: a correlation with language in pre-sessions that is one of the starting points for study V. Also, there was a significant late negative attention effect at 300–400ms. This effect is interesting because it is not expected among children this age, but is expected among older children and adults (Karns et al., 2015). These two results have relevance for comparing our results with earlier implementations of AudAt.

An important result is that SES is such a general predictor of varied abilities even in the relatively high SES area where the study was conducted. There are class differences already in preschool, and preschools have a function to ensure that socio-economically disadvantaged children are not left behind as stated in directions from Swedish National Agency for Education (Skolverket, 2018. In English: Swedish National Agency for Education, 2019). Reasons for the lack of effect of intervention are discussed, such as too short intervention period, low fidelity in implementation of SEMLA, and other factors. The SEMLA program could be too similar to current preschool practices, especially as the preschool in the control condition scored higher on the preschool quality measure. A broader explanation could be that the circumstances of the children in the study were already good enough for their general development, making it difficult for interventions to add substantial impact.

Study V

In study V we explore the relation between EF including selective auditory attention effects and language in data from the same project as study IV. In study IV EF and language test were analyzed as broad composites, and in relation to interventions. In study V we analyze individual EF and language tests. Previous studies tend to compare many EF tests with the most common measure of language skill, vocabulary. In study V seven different language measures that porbe syntax, morphology and vocabulary are compared with five EF tests of inhibition, working memory and cognitive flexibility and also selective auditory attention.

The relation between EF and language is well established, but precisely how they are causally related is under debate. Some studies have suggested that EF influence language development (Weiland et al., 2014; Woodard et al., 2016; Ten Braak et al., 2018), some that language influence EF (Kuhn et al., 2014; Miller and Marcovitch, 2015; Botting et al., 2017) and some investigate a dynamic relationship between EF and language (Friend and Bates, 2014; Bohlmann et al., 2015; Slot and von Suchodoletz, 2017).

In our data, language and EF measures did correlate, but the strongest correlation was moderate, between receptive vocabulary (PPVT-3) and backward digit span, indicating that many studies who only use vocabulary as language measure overestimate the strength of the language-EF relation. We found a female advantage in EF and language, as well as relations to SES and age.

Since selective attention is considered part of EF or a foundational/prerequisite ability for EF we were expecting a correlation with EF measures and not with language. Selective auditory attention in the early 100–200ms time window had weak correlations with morphosyntax and unified predicates and none with any EF results. None of the attention effects correlated with age, despite the unexpected late effect being associated with older children in the literature (Karns et al., 2015). A regression analysis of selective attention parental education and having Swedish as a stronger language predicted the early attention effect. In study V we included 16 children who had failed to answer the comprehension questions and were excluded in study IV. The attention effects in this group did not differ from other participants.

We discuss a difference between the original AudAt and Swedish AudAt, that might have influenced the results. In the Swedish AudAt stories were read with engaging voices, whereas voices in original AudAt were by design less engaging. This could affect the balance between bottom-up stimulus driven attention and top-down and endogenous attention, top-down, sustained and goal driven attention. We argue that the exact nature of this shift in balance is difficult to interpret since the probe sounds that elicit the analyzed ERPs attract bottom-up attention.

Discussion

The thesis present novel research and results in many areas, that contribute to understanding language comprehension in HL, how socio-economic factors predict preschool children's abilities in Sweden in contrast to the egalitarian mission of the preschool system, how EF and language interact, and by introducing RCT interventions in Swedish preschool pedagogics. The finding that N400 effects might reflect compensatory semantic top-down processing in children with CI stand out as the most mature line of investigation presented here, with follow up studies including a replication, and a related broader field of studies of semantic top-down processing in adults with CI. The results could be seen as a neural version of an insight that understanding speech is not only a matter of hearing (Nittrouer, 2002. Pichora-Fuller et al, 2016). The spoken language signal is varied to the point where the listener must bring their linguistic knowledge to be able to pick it up. Phonological knowledge is central, but also vocabulary, world knowledge and pragmatics. When hearing and phonology is compromised, processing of speech becomes less automatic, and a more active processing mode is needed where semantic context is important.

An important question that follows is how effective compensatory semantic top-down processing is in varied situations. Various results indicate that noisy environments, lack of semantic cues, effort and dependence on WM put severe constraints on semantic top-down processing. Another question is how care-takers, speech pathologists and teachers can support semantic top-down processing. In the following sections, the results underpinning these broader questions are discussed in more detail.

In the two intervention projects described in the thesis, ERP results did not show effects of intervention. Differences between pre- and post-intervention results in study I did not indicate transfer from a better phonological awareness to better semantic discrimination as hypothesized. Post-intervention results of the multi-feature MMN paradigm did not indicate a better auditory discrimination. These results are presented in more detail below. In study IV there were no positive intervention results. EF and Selective auditory attention improved somewhat in the DIL intervention group, but the effects were too small to be evaluated with the present sample sizes and were based on differences pre-intervention that disappeared post-intervention. A general conclusion based on the lack of intervention effects could be that expectations of transfer from one domain of training to effects in other cognitive domains were too high.

Semantic and auditory processing in DHH children

Semantic top-down processing in children with CI

In study I, children with CI had a larger N400 effect than other participants. They also had a graded N400 effect compared to an undifferentiated N400 effect in other participants. The graded effect was larger for unrelated mismatches compared to related "within-category" mismatches, where a smaller effect was observed, typical in the N400 literature (Kutas and Federmeier, 2011). The result was in direct contrast to our hypothesis, which was based on the notion that N400 effect amplitude should reflect ability to make semantic discriminations. In the language testing of the same children, we could see that children with TH had better expressive vocabulary skills and better lexical access skills and sentence completion skills than children with CI, indicating better semantic skills overall. In study I we discuss possible explanations: We propose that children with CI use more semantic top-down processing, thus engaging the predictive processing reflected in the N400 component more than other participants.

The main arguments for this explanation are: First, the large N400 effect in children with CI did not match their semantic skills, which points to a difference in how they approached the task. Second, N400 effects in children with HA and TH did not differ between unrelated and related conditions, something that has been found when participants are less engaged in prediction in several studies (Federmeier & Kutas, 1999; Franklin et al., 2007; Kiang et al., 2013; Wlotko et al., 2010). Third, there where early latency mismatch effects in children with CI, that was not found in other participants, and these comprise evidence for a high level of specificity of prediction (Bornkessel-Schlesewsky et al., 2016; Brothers et al., 2015; Lau et al., 2013). While not hypothesized in relation to the N400, the semantic top-down strategy was described in previous studies of children with CI by researchers in the project (Lyxell et al., 2009; Nakeva von Mentzer, 2014a). Two other possible explanations are discussed. The relatedness effect could be seen as reflecting a lack of precision in the task discrimination of congruence among children with CI. Another possible explanation is that the full N400 effect in children with TH is not seen at the scalp because of an overlapping positive component (P3b) potentially stronger among children with TH reflecting stimulus task relevance. See discussion in study I for more detailed descriptions of these alternative explanations. The explanation based on top-down processing seemed to connect better to previous literature, both regarding the N400 and literature about children with CI, and the other explanations did not account for early latency semantic effects.

Two studies reviewed in study III recreate the N400 paradigm with unrelated mismatches (but both omit the condition with related mismatches). The first of these (Bell et al., 2019) had few participants with CI, and despite having slightly larger N400 effects among children with CI compared with children with TH the difference is not significant. The second study had more CI participants than previous two studies taken together and replicated the larger N400 effect in children with CI compared to children with TH. Moreover, they predicted and found early mismatch effects, before the N400 time window, hypothesized as a consequence of predictive processing. During this period a number of studies with adults using CI also focused on semantic top-down processing (Pisoni and Kronenberger, 2021; Winn, 2016; Diemtrievitj et al., 2019; Dingemanse, 2019; Moberly and Reed, 2019; Moberly, 2020; O'Neill et al., 2019; Zaltz et al., 2020), strengthening the argument that this compensatory strategy is important for persons using CI, and also investigating its relation to WM or EF and to effort. Motivated effort is mentioned in study I and in some of the literature that we used to argue for compensatory top-down processing (Lyxell et al., 2009), but the present literature brings this issue to the forefront. In study III, the strengthened support for semantic top-down processing as an explanation for unexpectedly large N400 effects among children with CI is discussed in more detail than in previous empirical reports. In sum, despite indirect support from several sources, the support for the hypothesis is still not conclusive. Two central problems are the small numbers of participants in the studies involved, and the lack of a direct experimental manipulation of top-down processing in the population of children with CI in an N400 paradigm.

An important discussion of the large N400 effects in children with CI (study I; Pierotti et al., 2021) is how they can be expected to generalize. The original hypothesis of study I, that children with CI was expected to have smaller N400 effects compared to children with TH is a very reasonable hypothesis considering the general N400 literature (Kutas and Federmeier, 2011) and was still the main hypothesis in Bell and colleagues (2018) and a complementary hypothesis in Pierotti and colleagues (2021). Indeed, we cannot expect that compensatory top-down processing will always succeed, and discriminatory success is necessary for the N400 effect. Therefore, it is likely that these N400 effects depend on task difficulty and would be smaller in children with CI compared to children with TH, if the semantic material was difficult enough. The use of high frequency words as primes, and images as targets, might both have contributed to an optimal task difficulty for eliciting large N400 effects in children with CI.

In a recent study (Burkhardt et.al., 2022) of mostly post-lingually implanted persons with CI (N=26 including 2 prelingually implanted persons), that listened to sentences with and without background noise, found smaller N400 effects among persons with CI compared to persons with TH (N=26). Post-lingually deafened persons with CI can be expected to use semantic top-down processing, perhaps even more than children with CI, due to their history of hearing and thus on average a larger vocabulary and other semantic skills. The stimuli were sentences in German where the last word, verbs in the example sentences, were semantically congruent or incongruent. Sentence comprehension can be a task where persons with CI do well (Bell et al., 2019), likely because semantic context is necessary for semantic top-down processing. However, in the study the persons with CI did not perform as well as persons with TH. Interestingly, in a condition with background noise, the N400 was slightly larger in the NH group (though this result was not statistically significant), but not in persons with CI. The noise condition for NH could be compared to the normal hearing situation for persons with CI, promoting more semantic top-down processing to compensate for the noise. Compared with the reviewed studies of children it is possible that this study, using speech instead of visual target stimuli, more difficult language material, and in some conditions background noise may all put a limit to the compensatory semantic processing by making the task too difficult. Burkhardt and colleagues (2022) result emphasize that the effects with large N400 effects in children with CI is limited to a certain range of task difficulty.

Top-down processing and effort

In study I top-down processing is presented more or less as a semantic phenomenon, and semantic top-down processing has been the focus of many behavioral studies of adults with CI. In this literature top-down processing is related to effort. However, effortful top-down processing is not only based on semantics, it should be seen as something broader, and is needed for discrimination in the sound stream overall (Jerger, 2007). Attention towards important cues and selective attention to channels of information, such as discriminating speech in noise is also top-down processing and related to effort (Westbrook and Braver, 2015). In the MMN study, the responses to deviants are larger because they deviate from the memory trace of the expected standard stimulus (Näätänen et.al. 2007; Näätänen et.al. 2017).

In that sense, all of the studies presented in the present thesis concern top-down processing, as ERP responses to the same stimuli are changed due to expectations or attention, manipulated by experimental context or instruction. The relation of top-down processing to effort is not studied directly in the thesis, but represents a central question arising from the present research.

Listening effort is an important problem in any adverse listening situation (Jamsek et al., 2022; Pichora-Fuller et al, 2016; Salehomoum, 2020), and effort is identified as a central limitation of semantic top-down processing in study III. An analysis of cognitive effort (Westbrook and Braver, 2015) finds that the construct is often poorly defined, and can be confused with related factors such as difficulty, motivation, attention, fatigue or cognitive control. The experience of cognitive effort they suggest (Westbrook and Braver, 2015), is based on the subjective value/cost of cognitive engagement with a task, and should be analyzed economically. They present a paradigm for measuring cognitive effort using monetary rewards called Cognitive Effort Discounting (COGED). Various levels of task effortfulness are introduced, and the participant can choose between them. Higher effort is rewarded more (task success is not rewarded), but the rewards are changed during the experiment until the participant is indifferent to the different levels of effort. At this point rewards are assumed to match the subjective value of effort at different levels of cognitive load. By measuring the subjective value of effort in this way it is not conflated with load or reward, but the individual's relation between load and reward is found. This type of paradigm could be used with language tasks that require different levels of effortful processing such as levels of background noise, or varied amounts of semantic clues. N400 effects could be compared with both objective criteria such as level of noise or lexical surprisal and to subjectively defined effort. This paradigm suggests a route for investigating the role of effort in semantic top-down processing, and also a way of investigating top-down processing effectiveness at various levels of difficulty. Many questions from study I and III could presumably be answered in a similar paradigm: How effective is top-down processing in a range of language stimuli, at different difficulties? How sensitive is top-down processing to auditory distortions that simulate CI, or that simulate noisy environments? How does effort differ between groups of participants, i.e., with HL or without? Such a paradigm would also put the main limitation of semantic top-down processing, its relation to effort, at the center of investigation. Furthermore, ways to reduce effort could be investigated using the same paradigm. There are general similarities between this approach and previous listening effort research (Pichora-Fuller et al, 2016; Rönnberg et al., 2022). The topic of listening effort is broad, and concerns any adverse listening situation, including second language learners, age related HL and noisy environments. The relation between top-down processing and effort could be studied in larger studies in TH populations mapping the domain with relatively more easy access to participants. Studies of HL populations, that are typically smaller, could then be situated against better background knowledge, and make better use of the small number of participants.

Cross-modal processing

In study III cross-modal processing differences are presented as an alternative possible explanation of the large N400 effects in study I. The reasoning behind this hypothesis is simply that the examples where N400 is larger for children with CI (study I, Pierotti et al., 2022) or some adults with CI (Mehravari et al., 2017), compared to typically hearing controls, are based on targets in the visual modality. This lack of examples of large N400 with auditory targets could just reflect that there is a lack of studies with auditory target stimuli. However, it could also reflect that children with CI do have problems with hearing and that visual stimuli are relatively easier to process. In study III we bring up another possibility, that visual processing could be different in children with CI compared to children with TH due to cross-modal cortical reorganization.

Cross-modal reorganization has been seen as a colonization of the cortical hearing areas by visual processing, and has had a large impact on (re)habilitation practices in children with CI. Based on a fear that hearing areas in the temporal lobe would be tuned to visual stimuli instead of competing auditory stimuli, with maladaptive results, (re)habilitation after implantation have to various degree avoided visual aspects of language, and especially sign language. A recent review of the evidence (Kral and Sharma, 2023) state that cross-modal reorganization is not a static rewiring of hearing areas to visual inputs, but a flexible amplification of the same inputs, and without any permanent or maladaptive consequences. The hypothesis that cross-modal processing differences could influence N400 does not imply any deeper cortical reorganization, but could reflect an attentional or experiential focus on visual stimuli in line with Kral and Sharma's (2023) analysis. Children with CI can benefit from visual support to spoken language, other visual cues such as lip-reading, and from learning sign language, and such practices can likely become used more if the fear of maladaptive cortical reorganization is put to rest.

Positive mismatch responses in 5–7-year-olds

Study II describes baseline results, before intervention and the results are dominated by unexpected pMMR responses. At the time of planning, recording and early analysis of the MMN experiment in study II, the possibility of pMMR in children at an age of 5–7 years was not established, although a few such studies had been published (Shafer, 2010. See also Torppa et al., 2014 with many positive mismatch responses in similar latencies as in study II). Our hypotheses were based on expected MMN effects and the unexpected responses including pMMR were presented descriptively. Inverse correlations between (positive) amplitude and age (Figure 3, study II) suggested that the pMMR results were related to maturation. However, only children with TH had a significant correlation at group level, suggesting that maturation was not homogenous in the groups with HL or perhaps delayed. P1 amplitude was lower in children with HA, suggesting insufficient amplification in their hearing devices. As described in detail previously, there were no intervention results in the MMN study (Engström et al., 2019. Engström et al., 20209, and we did not find a clear developmental trajectory from pMMR to MMN between baseline, post-intervention and follow-up study. However, the P1 amplitude among children with HA did change over the course of several years (Engström et al., 2021).

A possible explanation for the lack of clear effects could be that children transition from pMMR to MMN and these components overlap, canceling each other out. Thus, there would be periods that are suboptimal for finding effects in either direction. The lack of consistent responses at individual level is in line with earlier conclusions (Näätänen et al., 2007) that MMN is quite replicable at group level, but not at individual level.

Later, studies of Torrpa and colleagues (2014, 2018, 2022) have found pMMR in children with CI, establishing the phenomena (see also a review in Ahmadi et al., 2022). In these studies, difficult and easy contrasts are compared and pMMR is found in response to difficult contrasts in children with CI. In the articles by Torrpa and colleagues (2014, 2018, 2022) intensity, pitch and vowel change contrasts are described as difficult, while duration and gap were considered easy. In study II intensity had the largest pMMR in children with CI, and in contrast to children with HA and NH, in line with the suggested relation of contrast difficulty and pMMR by Torrpa and colleagues (2022). Also, the duration contrast was the only contrast that resulted in an MMN in children with CI in study II, in line with suggestions that this contrast was easy to make. Torrpa and colleagues (2022) categorize pitch as difficult and gap is easy for children with CI. Gap and Pitch deviants in our study resulted in pMMR without significant differences between children with TH, HA or CI. A notable feature of the ERPs in study II is a late negativity, possibly Late Discriminant Negativity (LDN), for children with TH or HA, while the later time windows are more positive in the group of children with CI. This difference is significant in time window 3 and time window 4 for the intensity effect. It is possible that these effects reflect a P3a in children with CI in study II, similar to P3a in Torrpa and colleagues (2022).

The experimental differences between Torrpa and colleagues (2022) and study II are many despite both using variations of the multi-feature paradigm Optimum (Näätänen et al., 2004). Torrpa and colleagues (2022) used tri-syllabic language stimuli (‘tatata’) with deviant changes in the middle syllable. The stimulus onset asynchrony (SOA) was 900ms and the total number of stimuli was 2000 (5x200 deviants). In study II the original Optimum-paradigm was used (Näätänen et al., 2004) but in a shorter version with fewer events. The stimuli were harmonic tones, SOA 500ms and the total number of stimuli were 1244 (5x120 deviants). The shorter SOA in our study might have made discrimination more difficult for all children and especially so for children with CI. The lower number of stimuli (67% of the original Optimum) could have contributed to less stable response. In Torrpa and colleagues (2022) the total experiment time was 30 minutes, while in study II it was just over 10 minutes, and presented after the N400-experiment described in study I.

The main contribution of study II was demonstrating pMMR results for older children, and children with CI and HA, in a time where such results were scarce, and also descriptions of responses where children with CI stands out such as a larger pMMR response for intensity in children with CI and late positivity. At the time of analysis and publication, pMMR was an unexpected result and therefore met with some suspicion, even within the research team and by the author who collected and analyzed the data. Similar but not identical results from Torrpa and colleagues (2014, 2018 and 2022), validate the positive mismatch-responses (identified as P3a or both pMMR and P3a).

The multi-feature paradigm provides a profile of responses to many basic dimensions of sound, however since responses vary in relation to the difficulty of discrimination, I suggest that future studies also vary sizes of contrasts for each deviant type, from easy to difficult. SOA or inter-stimulus interval (ISI) should be longer than in study II in multi-feature MMN-studies with children. The longer SOA is a likely reason for the stronger and more differentiated responses in Torrpa and colleagues (2022) compared to study II.

Clinical implications

While the research in study I, II and III regard clinical populations, the type of research is basic research, and will inform the experienced practitioners and other researchers rather than give specific directions. Most importantly, the N400 results are part of a broader investigation of semantic processing and compensatory semantic top-down processing that is described in study III. This recent focus on semantics might reflect the broad insight that listening cannot be reduced to hearing thresholds, but involve important cognitive elements (Pichora-Fuller et al, 2017). The N400 results in study I and III give further weight to this general understanding, despite not being conclusively tied to function. Both the primary hypothesis, that large N400 effects in children with CI reflect compensatory semantic top-down processing, and the alternative hypothesis that the same N400 effects are related to cross-modal processing that include vision, could be synthesized in a general recommendation, that children with CI benefit from all kinds of cues, that can strengthen top-down processing of various kinds: A firm grasp of phonology, vocabulary and narrative structures, a good view of the face of a person speaking, supporting verbal messages with gestures or signs, and plenty of semantic cues in a spoken message are all ways of adding cues that can help top-down processes, be they phonological, visual or semantic. These suggestions are not new to speech therapists, teachers and care-givers (Curtin et al., 2021; Luckner & Cooke, 2010; Luckner & Handley, 2008; Nittrouer et al., 2018; Nittrouer, 2002), but the present results might give a new emphasis to them. Also important in this context, is that one of the main reasons to avoid visual communication with children with CI, the fear of maladaptive cross-modal reorganization, is being strongly contested as central researchers in this area have reinterpreted the evidence (Kral and Sharma, 2023). In this article it is stated that the evidence does not support the idea that cross-modal reorganization closes critical periods in deaf people, and that, instead, cross-modal plasticity is flexible and adaptable. The previous results (Sharma et al,, 2007b) that seemed to indicate a take-over of auditory brain areas by processing of visual stimuli are explained as results of increased gain in input from visual processing in these areas when sufficient auditory input is missing, rather than a reorganization of them for visual processing.

There are many indications that effort and reliance on EF and WM are limitations for top-down processing (Diemtrievitj et al., 2019; Dingemanse and Goedegebure, 2019; Lyxell et al., 2009; Kronenberg et al., 2013; Moberly and Reed, 2019; Moberly, 2020; O'Neill et al., 2019; Pisoni and Kronenberger, 2021; Winn, 2016; Zaltz et al., 2020). This is not because semantic processing in itself is effortful, semantic cues reduce effort (Winn, 2016;), but is likely related to keeping an auditory message online in working memory for deliberate processing. To enhance semantic top-down processing while minimizing effort there are two ways forward: One is to train the more automatic input to this process, world knowledge, concepts, vocabulary, narrative structure and also non-semantic inputs like lip reading and phonology. The other route is training WM and EF. Regarding EF there are plenty of results that seem to indicate that such training is possible (Diamond and Lee, 2011; Muir et al., 2023; Neville et al., 2013). However, despite short term effects of EF and WM training the meta-analysis evidence indicate that these results do not last and do not transfer to cognitive abilities that was not trained (Melby-Lervåg et al., 2016, Kassai et al., 2019), and not to academic skills (Melby-Lervåg et al., 2016; Sala & Gobet, 2017). It is at least not clear that WM and EF training have desired effects. Reading training based on morphology (Trussell & Easterbrooks, 2017) could align with the general emphasis on top-down processing in study I and III and with more specific results that find that reading in children and adults with CI is often more semantically oriented than TH readers (Nittrouer, 2020). The computer-assisted reading intervention with a phonics approach in the intervention context of study I and II target a weakness among children with CI, phonology, while learning to read based on morphology might instead be a reasonable adaptation to reading styles actually used in the population. Interventions need to both adapt to, and challenge children's skills. In a review of interventions that target EF in TH preschool populations successful interventions were challenging, specific, and delivered by experts (Muir et al., 2023).

Preschool interventions

Study IV indicates that neither the socio-emotional learning SEMLA, nor the digital, individual training DIL easily boost children's cognitive and linguistic development. It is possible that aspects of implementation such low fidelity have masked effects, but any such effect is likely not very strong, especially in the case of SEMLA since we do not find any trends in that direction. DIL has a trend in the selective attention results that, together with earlier results in interventions with some similarities (Neville et al., 2013) indicate that further research on cognitive training could be worthwhile, but the effect in itself is weak. Possibly children, without specific problems, are already learning and developing in ways not easily enhanced. To make interventions with measurable results one might want to focus on specific populations with specific problems rather than making preschool better for all children. Such a strategy would also align with the compensatory goal of Swedish preschool policy (Skolverket. (2018). Läroplan för förskolan: Lpfö 18.). Children in low SES areas, and children who learn Swedish as their second language could be two important populations to study. Some researchers have suggested that intervention research on children should be performed in low-income countries because effects are expected to be larger when resources are added where baseline is low and contributing to other goals (Diamond and Lee, 2011).

Muir et al. (2023) review intervention studies targeting self-regulation and EFs in preschools. Of 85 studies only one used EEG (study IV). In other ways study IV was more similar to other studies in this review: several studies evaluated Socio-emotional learning (SEL) strategies, early math, and used small group semi-structured creative play in their interventions. High-efficacy studies did use external interventionists or preschool personnel with extensive training before the intervention (compare this with discussions of implementation in study IV), and many results were stronger in groups with low baseline results (such as the results for DIL in study IV). Several SEL strategies had high efficacy, and some that used digital task training. Dosage and duration of intervention varied a lot among high efficacy studies and long intervention times were associated with problems with intervention fidelity. The review does not report clear patterns that distinguish high efficacy studies from those with less promising results, they were on the whole similar. In conclusion the review suggests that theory of change for self-regulation and EFs are not well developed, and that results do not suggest that a specific type of intervention or pedagogic strategy is especially successful, instead efficacy may depend on a combination of factors like target population, interventionist expertise, content and implementation. Successful interventions included those that had challenging cognitive tasks, that included movement and that used expert interventionists. Small group sizes fared better than both whole class and individual interventions. In the context of this review (Muir et al., 2023), the project of study IV and the lack of intervention results seems not to be the result of specific mistakes, but perhaps more an effect of being the first intervention study by this group of researchers with methods that were partly defined at the start of the project, and could only be tuned to a limited extent despite extensive piloting. The broad, diverse goals that investigated both EFs, math and language skills compared to a more specific goal like enhancing EFs only, might have contributed to a lack of results. The project was conceived as an investigation of the specific socio-emotional learning that was distilled as SEMLA, rather than an EF intervention. The evaluation is still of interest despite the lack of intervention results. Perhaps the qualities of SEMLA with its focus on communication, creativity and child agency, is not measurable as basic cognitive abilities, but in other constructs more directly related to the focus of SEMLA? Language development is very robust, and difficult to enhance with interventions if there are no specific problems. EFs could likely be targeted better with a population that have EF problems, such as a low SES population, and with a more specific intervention and highly trained interventionists. The importance of highly trained experts that interact with children directly is interesting in a broader preschool and school perspective, and suggest that it is important with experts, such as speech therapists, in child environments.

It should be noted that intervention research is difficult (Hansen et al., 2016) and very few studies have been able to produce experimental results that generalize and have lasting effects on child development. To measure an effect directly in a short experiment is much easier than having a similar effect effectively implemented in pedagogical, therapeutic, economic, environmental or medical practice.

Auditory selective attention

In a review of EEG studies of EF and selective attention in 2–5 years-old children (Bhavnani et al., 2021) nine studies of auditory selective attention are presented. In three of these studies, a positive attention effect starting at 100ms is found (Sanders et al., 2006; Sanders and Zobel, 2012; Karns et al., 2015), but one (Sanders and Zobel, 2012) saw an indication of a negative effect as well. Two studies reported no attention effects (Bartgis et al., 2003; Strait et al., 2014) where one (Strait et al., 2014) was a non-significant negative effect. One study reported changes in P3a (Pesonen et al., 2010) as a function of selective attention. Three studies reported differential results related to SES, with larger effects for high SES children (Hampton-Wray et al., 2017; Giuliano et al., 2017) or for low SES children with higher nonverbal IQ (Isbell et al., 2016). In this review we find two negative attention effects for preschool children, precedents of the late negative effect in study IV, however both of them were non-significant. It is likely that our large number of participants is the reason for finding a significant negative effect. Our results, in terms of a relation between SES and selective attention, are in line with earlier studies, and even the more unexpected negative attention effect had precursors. The lack of selective attention effects in children with selective language impairment (Stevens et al., 2006), could be seen as a precursor to the unexpected correlation between selective attention and language skills in study V.

The selective attention measure seems to be more sensitive to experimental manipulation than our behavioral test battery, however its direct interpretation is discussed and problematized in study V. A possible difference between our and previous versions of AudAt is the level of engagement in the reading of stories that could have reduced the amount of effortful attention needed to focus on only one story. The COGED paradigm introduced previously could be used to measure effort in combination with AudAt. The AudAt paradigm could be combined with levels requiring different amounts of effort, and attention requiring more effort could be compared with attention requiring less effort. Another way of further investigation of the issues raised in study V is to analyze the same data with a very different method used in a recent paper (Phelps et al., 2022). Instead of comparing responses to attended and unattended probe sounds, the speech envelopes of the attended and unattended stories are reconstructed from the EEG using regression methods (Smith and Kutas, 2015a; Smith and Kutas, 2015b). The reconstruction quality is considered a measure of attention. The reconstructed speech envelope could be considered a more ecologically valid processing measure compared to probe sound responses, since they reflect attention to stories themselves, rather than probes in the same broadly defined channel. The reconstructed speech envelope could provide more detailed measures of changes in attention over time, and in relation to language features and narrative. Finally, the reconstructed speech envelope would provide a partly independent measure of attention, derived from the same data as the selective attention effect, that would be suitable for further analysis with respect to the influence of language vs EF skills, the theme of study V. Using the regression-based ERP approach is also suitable for extracting N400 responses from continuous data, based on words in the stories. That could be a way of connecting two branches of ERP research presented in study I and III and in study IV and V. That way, the relation between N400 effects and selective attention could be studied. The variation in stories and probe sounds could make such an analysis cumbersome, each child's set of stimuli would have to be modeled individually, but it is feasible.

General discussion points

Automatic language processing, and effortful EF

Semantic top-down processing of children with CI as described in study I and III is linked to effort and EF-measures in the discussion of behavioral results. Effort is directly linked to working memory (Westbrook and Braver, 2015), but not to semantic processing in general (Winn, 2016). It is likely not the semantic processing itself that is effortful, but the extended use of working memory to keep material online, having predictions based on semantics but also being able to revise those predictions. In contrast, the bottom-up processing of children with TH does not require much working memory, word meaning is retrieved automatically as soon as words are identified and revisions are only needed when specific problems or ambiguities appear. Effortful speech processing due to HL is potentially hindering deeper processing of linguistic material because cognitive resources, semantic top-down processing included, are needed just to decode the basic message.

In study V we find a lack of correlations between auditory selective attention and behavioral EF measures, while we do find weak correlations with language measures. A possible underlying factor in the N400 and selective attention studies of this thesis, that may contribute to unexpected results, are the relations between language processing, attention, EF and effort. Semantic processing can be highly automatic, and should lower effort in language processing. Attention can be modulated both by salience of the stimuli and motivated effort. In the P300 literature P3a is related to automatic attention capture, and P3b to task dependent and thus motivated attention (Polich, 2007). Working memory and effort are strongly linked. In the original AudAt stories were deliberately read with a non-engaging voice. In the Swedish AudAt the readings were highly engaging, as part of an effort to make the experiment fun and child friendly.

Tasks in both experiments are situated in a continuum between automatic salience and effortful deliberate attention including working memory processing.

It is possible that the correlations between language skills and selective attention in study V reflects that the task of attending one story and ignoring the other was helped more by automatic highly trained language skills, than by deliberate, effortful, focus. Similarly, TH children in study I may have found the unrelated mismatches so easy that they failed to pay attention to them but focused on the more difficult related mismatches. While N400 itself is not that sensitive to attention (Kutas and Federmeier, 2011), the late N400 effects for children with TH in study I could be a large long lasting N400 with a peak diminished by a P3a or P3b peaking at 400ms. This possibility is discussed in study I. Variation in processing effort, related to working memory demands, could be underlying some of our unexpected results across studies I, III, IV and V.

Linguistic ecological validity

In experimental settings such as study I, the language materials used are presented as a word game, rather than in a communicative task. That is, the participant should not think of the words presented as a message from the experimenters or another communicator. This is true for many experiments: real, relevant forms of communication are often sacrificed in favor of experimental control.

In study IV and V stories are used to capture children's attention. Stories represent communicative acts that have a message that the child can engage with just as well under experimental settings as in other situations. Despite the presence of probe sounds in the stories, in study IV and V, they can be said to have a strong ecological validity for language processing, because the language material is communicative. Experiments like study I, with rather low ecological validity from a language perspective, run a risk that participants make up their own interpretation of the experimental task, in ways that affect ERPs, for instance by inducing the task-related component P3b. Stories or other stimuli that prompt a more typical processing mode could be important to ensure that effects studied have a broad relevance.

The cost of ecologically valid language stimuli is often longer experiments since experimental manipulations, such as incongruent words, need to be used sparsely to avoid making the material strange, and once again risking that the participants respond to experimental manipulations as something that deviate from the communicative intent.

The sensitivity of ERPs, a double-edged sword

The use of ERPs in the studies of the thesis indicate that ERPs are sensitive: all empirical studies have had major unexpected features of the studied components: pMMR in surprisingly old children, larger N400 in children with CI despite lower semantic skill, selective attention effects typical for older ages and correlations to language measures rather than EF measures. ERPs are sensitive to experimental manipulations within the recording session, and between recording sessions, in some cases to age, likely also to learning the task over sessions and to interventions. The broadest conclusions from these results are that ERP measurements may respond to details that are not easy to predict, but that these surprising responses can be very valuable. Rather than resolving a research question quickly with hard data on actual brain processing, which is sometimes the reason for measuring brain responses, brainwaves add new dimensions, reflecting the true complexity of issues at hand. The long-term value then depends on repeated studies that can understand the unexpected results. Among the present results, the N400 effects in children with CI has been investigated to a point where the unexpected first result is now a more stable hypothesis about semantic processing. The pMMR results in older children, and children with CI is now described as a repeated pattern of results (Ahmadi et al., 2022; Torrpa et al., 2014, 2018, 2022), with a possible functional interpretation that pMMR is related to difficult contrasts, and MMN to easy discriminable contrasts. The selective attention results, when compared with earlier non-significant findings in small N studies, are less unique, but do raise questions about population differences between Swedish and American children of the same age, and about selective attention relation to language skills in stories read with different levels of engagement.

The discussion in study IV on lack of correlations between ERPs and standardized tests is based on the assumed sensitivity of ERPs. Researchers use standardized tests because they produce stable rankings, but do not always realize that the stability can be problematic. Standardized tests are optimized for test-retest reliability of variation at individual level and may sometimes be too insensitive to capture changes relating to interventions or experimental manipulations. In contrast experimental paradigms become popular in part due to low variability between individuals (Hedge et al., 2017). ERP paradigms and measures are examples of this principle; they are selected for their ability to show group level effects of experimental manipulations, but may not produce stable rankings of participants. All of the three ERP-paradigms reported in this thesis have experimental effects in the predicted component. The intervention effect of study IV was not large enough to be evaluated with a feasible number of participants, but it was still the largest effect of intervention in the study. The weak correlations between ERP results and language tests in study I, II, IV and V should be interpreted with this background.

Future studies, summary

The hypothesis that compensatory top-down processing led to large N400 effects needs to be better established causally (like Lau et al., 2013) and its importance in facilitating language comprehension needs to be investigated in HL populations. The hypothesis should also be investigated with auditory target stimuli in children with CI, and it should be investigated in adverse listening situations in broader populations such as adults with CI, children with HA and persons with TH.

Existing data on children with CI should if possible be collaboratively re-analyzed to investigate sub-groups and distributions of N400 effects. Existing types of N400 paradigms (Study I) should have auditory target conditions added, and be made freely available to facilitate more studies. Semantic top-down processing should also be investigated in naturalistic stories or with other more ecologically valid forms of language material. The relation between semantic top-down processing and effort should be investigated, perhaps by implementing aspects of COGED (Westbrook and Braver, 2015).

Auditory discrimination studied in multi-feature paradigms need to be better optimized for child populations, likely by using longer SOA and by varying difficulty of the contrasts involved. However, it is still possible that the simultaneous presence of MMN and pMMR will overlap and make effects difficult to measure.

Selective auditory attention effects in AudAt could be studied with variations that contrast engaging and neutral reading of stories, to investigate the effects of motivated and likely more effortful attention. AudAt data should be analyzed based on speech envelope using regression-based ERPs, to investigate attention effects directly in the responses to speech, rather than to inserted probe sounds. That kind of analysis could reveal other dimensions of the attention effect and what features of the speech signal that drive it.

Interventions in preschools should focus on areas with low SES, where the needs are largest, and the probability of measurable effects are highest.

Ethical reflections on cognitive sciences near past and uncertain future

My time as a PhD student started well before the replication crisis (Open Science Collaboration, 2015), in a research culture that was utterly uninterested in null results, and often rebranded unexpected results as hypothesized. It took a small crisis to disrupt this unethical ‘business as usual’. The many published null results and unexpected results that are part of this thesis I take to be a sign of a more ethical, and more scientific research culture.

The unfolding climate crisis put other ethical pressures on cognitive sciences. What research tells us is that planetary boundaries and tipping points are already passed or will be in the near future (Armstrong McKay et al., 2022; Richardson et al., 2023; Rockström et al., 2023). Society itself is under pressure and might collapse (Gowdy, 2020; Kemp et al., 2022). Resources and time for research cannot be taken for granted in our lifetimes.

Many of the results presented in this thesis are only relevant in a stable and reasonably rich society where there are resources for further investigation of themes such as semantic processing, tests of pedagogical interventions, and habilitation of deaf and hard-of-hearing children. In the future our best science predicts such stability does not exist. The climate crisis has ethical implications in every field, and may change priorities in what should be studied. From a perspective of resilience for children with CI, learning sign language could be considered to ensure communication also in situations when access to health care is compromised. Like the rest of society, cognitive sciences need to contribute to adaptation and mitigation related to climate change (Thierry et al., 2023). The ethical deliberation of what kind of research, education, information and other action the cognitive sciences can contribute with need to start now!

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Study I

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Semantic Processing in Deaf and Hard-of-Hearing Children: Large N400 Mismatch Effects in Brain Responses, Despite Poor Semantic Ability

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Difficulties in auditory and phonological processing affect semantic processing in speech comprehension for deaf and hard-of-hearing (DHH) children. However, little is known about brain responses related to semantic processing in this group. We investigated event-related potentials (ERPs) in DHH children with cochlear implants (CIs) and/or hearing aids (HAs), and in normally hearing controls (NH). We used a semantic priming task with spoken word primes followed by picture targets. In both DHH children and controls, cortical response differences between matching and mismatching targets revealed a typical N400 effect associated with semantic processing. Children with CI had the largest mismatch response despite poor semantic abilities overall; Children with CI also had the largest ERP differentiation between mismatch types, with small effects in within-category mismatch trials (target from same category as prime) and large effects in between-category mismatch trials (where target is from a different category than prime), compared to matching trials. Children with NH and HA had similar responses to both mismatch types. While the large and differentiated ERP responses in the CI group were unexpected and should be interpreted with caution, the results could reflect less precision in semantic processing among children with CI, or a stronger reliance on predictive processing.

Keywords: children, cochlear implants, hearing aids, semantics, N400 evoked potential

INTRODUCTION

In a spoken language environment, impaired hearing can limit the development of words, concepts and ultimately language comprehension and communication in children. Indeed, deaf and hard-of-hearing children (henceforth, DHH) children have, on average, a more limited vocabulary than their peers (e.g., Luckner and Cooke, 2010 for a review; Blamey et al., 2001; Geers et al., 2003;

Le Normand et al., 2003; Kenett et al., 2013; Walker and McGregor, 2013). With a small vocabulary, an underdeveloped semantic structure (i.e., the taxonomic, associative or similarity-based relations between words) could also be expected, but research indicates a large heterogeneity among DHH children (Peterson et al., 2010; Löfkvist et al., 2012; Kenett et al., 2013; Li et al., 2013; Nakeva von Mentzer, 2014). In fact, semantic and other cognitive cues may play a more important role in linguistic processing of DHH children, as a means to compensate for poor phonological skills (Lyxell et al., 2009; Nakeva von Mentzer et al., 2014a). What cannot be extracted from the speech signal bottom-up might be inferred using top-down processes (Wingfield and Tun, 2007). Thus, predicting semantic content might be of importance for DHH persons, due to their difficulties in extracting semantic content from speech input.

Children who are DHH are characterized by widely varying etiologies and symptoms. The most common mitigation for hearing deficits in DHH children is hearing aids (HAs) and/or cochlear implants (CIs). Traditional HAs amplify sounds and optimize the auditory input for the children's residual sensory function. In contrast, CIs convert sounds to coded electrical signals that are transmitted to the auditory nerve in the cochlea, enabling access to sound. Cochlear implants have shown to recover auditory function also in profoundly deaf individuals (Henkin et al., 2003; Sullivan, 2013).

Listening through HAs or CIs is associated with specific limitations (Moore, 2008; Nittrouer et al., 2012). For example, the limited temporal and spectral resolution of the CI signal can lead to difficulties in perceiving segments in consonant clusters and other aspects of speech. Phonological skills involve the decoding of speech into linguistically relevant information such as phoneme combinations that are central for learning, storing and accessing words (Ramus and Szenkovits, 2008; Stoel-Gammon, 2010; Dillon et al., 2012). Poor phonological skills might explain DHH children's poor performance in many cognitive and linguistic tests, such as those assessing lexical access and lexical variation (Lyxell et al., 2009; Asker-Árnason et al., 2010).

The present study investigated cortical processing of semantics before and after a computer-assisted reading intervention with a phonics approach (Nakeva von Mentzer et al., 2013, 2014b). The intervention focus is on strengthening the connection between graphemes and phonemes, which was hypothesized to boost phonological awareness skills, which in turn could enhance lexical access and vocabulary development. The intervention did have effects on phonological processing, in particular for DHH children starting with low phonological skills (Nakeva von Mentzer et al., 2013). There were also effects on reading skills (Nakeva von Mentzer et al., 2014b), however semantic tasks such as lexical prediction was not affected. Children with CI performed worse than controls on auditory lexical prediction tasks (Nakeva von Mentzer et al., 2013). This is in apparent contrast to recent results using picture naming that show semantic performance et al. with controls (Löfkvist et al., 2014; Wechsler-Kashi et al., 2014), but this difference might be explained by varying difficulty in processing speech stimuli.

Semantic processing can be investigated using the event related potential (ERP) component N400, and the N400 is arguably the most studied brain response in language processing research (Kutas and Federmeier, 2011). The typical N400 component is a negative peak at centro-parietal electrodes around 400 ms after event onset, elicited by meaningful stimuli such as spoken or written words (Kutas and Federmeier, 2011), but also pictures (West and Holcomb, 2002; Franklin et al., 2007; Proverbio and Riva, 2009). Semantically improbable or incongruent stimuli elicit large negative N400 responses compared to probable or congruent stimuli. The N400 is modulated by semantic structure; when primes are semantically related, but mismatching, to targets, the N400 amplitude is reduced (Kutas and Federmeier, 2011). This relatedness effect might be due to an increased use of predictive processing (Franklin et al., 2007; Kutas and Federmeier, 2011). In study designs using picture targets, the N400 is typically preceded by the N300, a more frontal negative component that responds to very distinct semantic deviations such as unrelated or between-category mismatches (Barrett and Rugg, 1990; McPherson and Holcomb, 1999; Hamm et al., 2002).

Research on CI routinely uses ERP assessment, but the focus is often on processing of auditory stimuli in cortical auditory evoked potentials (CAPS) and auditory oddball paradigms (Groenen et al., 2001; Martin et al., 2008; Peterson et al., 2010). Traditional ERP components such as the P1-N1-P2 complex, acoustic change complex (ACC), mismatch negativity (MMN), and P3 have been used to assess auditory discrimination, maturation and intervention effects in persons with CI (Kraus et al., 1993; Okusa et al., 1999; Eggermont and Ponton, 2003; Beynon and Snik, 2004; Kral and Sharma, 2012; Näätänen et al., 2012; Timm et al., 2012; Vavatzanidis et al., 2016) and with HA (Thai-Van et al., 2010). Studies of N400 responses are scarce, in particular among DHH-children, leaving their semantic processing changes relatively unexplored on a biological level (Johnson, 2009). We are aware of only one study of N400 conducted on a child with CI. In this study (Key et al., 2010), N400 responses were recorded from a 6-year-old girl with unilateral CI from 2 years of age. Assessment before and after activating the CI resulted in a dramatic increase of the N400. A few studies report N400 results among adult CI-users with post-lingual deafness. One study (Hahne et al., 2012) assessed 13 CI-users (mean age 51 years) and found N400 effects for both semantic violations and cloze probability manipulations in an auditory sentence comprehension test. The N400 effects consisted of later and more long-lasting peaks among CI-users than controls. Another study (Finke et al., 2016) with 13 CI-users (mean age 60 years) found an N400-like effect in an oddball task with word stimuli, although the authors described it as an N2 component. Here, ERP latencies were associated with listening effort and intelligibility in the CI group. A third study (Henkin et al., 2015) assessed 9 CI-users (mean age 66 years) in a voice gender discrimination task with auditory word stimuli. Results showed nominally longer N400 latencies among CI-users compared to controls, however, the difference was not tested for statistical difference.

In the present study, we investigated semantic processing in DHH children using an N400 paradigm with spoken primes and picture targets. The spoken primes were either fully congruent with targets (matching), unrelated to the target (between-category mismatch), or a mismatching prime that was related to the target by category membership (within-category mismatch). Participating children were asked whether the picture target matched the word prime or not. The task challenged semantic processing, and allowed us to compare DHH children to matched controls with normal hearing (NH). We compared results from the two mismatch types to investigate effects related to semantic structure. We hypothesized differences in brain responses between normal hearing children (NH), children with HA and children with CI, reflecting increased semantic difficulties related to the severity of hearing impairment. Presumably this would be reflected in smaller mismatch effects overall (NH > HA > CI), or smaller response to within-category mismatches relative to between-category mismatches, due to a less fine-grained semantic structure in DHH children. We also investigated effects of a reading intervention with the phonics approach directed at beginning readers (Lovio et al., 2012). This intervention was hypothesized to strengthen phonological awareness by training grapheme-phoneme correspondence. We hypothesized that better phonological awareness among DHH children would make words more distinct and thereby easier to process semantically, resulting in larger N400 mismatch effects after training.

MATERIALS AND METHODS

Participants

This study was based on data from 42 children (21 girls) aged 5–7 years. Thirty of them were deaf or hard-of-hearing (DHH) and 12 were normal hearing controls (NH; 3 girls). Of the DHH children, 15 had bilateral hearing aids (HAs) and 15 had at least one cochlear implant (CI). In each of these groups 9 were girls. Nine children (7 girls) had bilateral cochlear implants, and six children (2 girls) had CI in one ear and hearing aid in the other. Participants were grouped based on their type of hearing amplification: NH, HA, and CI (at least one implant). Seventeen children (9 girls) had a severe/profound hearing impairment with a pure tone average (PTA) at > 70 dB Hearing Level unaided. Eleven children (7 girls) with hearing aids had a moderate HI (PTA 40-60 dB) and two children (girls) had a mild HI (PTA < 40 dB). The mean age at diagnosis was 1 year and 2 months, ranging from 0 weeks to 5 years. Seven children were diagnosed with a progressive hearing impairment, where one child was born with unilateral deafness and later developed progressive hearing impairment on the other ear. The mean age for receiving HA was 2 years and 8 months (ranging from 3 months to 6 years) and the mean age for first CI-operation was 1 year and 7 months (ranging from 11 months to 5 years). Aided thresholds with CI or HA were at 20–40 dB, with higher values in the high frequencies for children with hearing aids. Three children had another spoken language besides Swedish, two children used sign language as their first mode of communication at home and used spoken Swedish in school and two children used sign support to their spoken language. All children performed within normal limits on nonverbal intelligence as assessed by Ravens colored matrices, and there was no significant difference between the groups regarding nonverbal intelligence (see **Table 1** and Nakeva von Mentzer et al., 2013). Four more children participated in the study but were excluded from the present analysis (one control did not meet inclusion criteria, one control did not participate in the training intervention, and two children with CI were excluded due to ERP-recording issues). The DHH children were found through clinical records of the participating hospitals. All children were invited who fulfilled the criteria; 5–7 years old with bilateral hearing aids and/or CIs, speaking Swedish in their educational setting, and with no known disability affecting language development. Invitations were sent to 90 families and approximately one third of those accepted to participate. The controls were recruited from preschools and schools in the Stockholm area. Written informed parental consent was obtained for all the participants. The study was approved by the Regional Committee of Medical Research Ethics in Stockholm.

Language Testing, Intervention, and ERP Recording

Participation started 1 month before the first ERP-recording, with a set of assessments of language and cognitive skills, conducted in a quiet room in the children's homes or in their educational setting. The same tests were repeated on the day of the first ERP recording, and on the day of the second ERP recording following a month of intervention training. Tests, scores and behavioral effects of the intervention were described previously, i.e., the phonological composite variable was described in Nakeva von Mentzer et al. (2013), and a reading composite variable and lexical expectation test were described in Nakeva von Mentzer et al. (2014b). Scores on key tests are presented in **Table 1**. The N400 procedure was identical across the two ERP sessions. Participants sat in front of a monitor at a distance of approximately 1 m. Each trial started with a fixation cross

TABLE 1 | Selected test results (from first ERP session) presented as means and standard deviations for each hearing amplification group.

Hearing amplification groups, selected test results			
Hearing amplification group	**Normal hearing (NH)**	**Hearing aid (HA)**	**Cochlear implant (CI)**
	Mean (Std)	**Mean (Std)**	**Mean (Std)**
Age (months)	81 (12.0)	76 (11.9)	76 (11.0)
Raven colored matrices (%)	85.8 (24.0)	76.3 (18.7)	75.3 (24.5)
Phonological composite	86.7 (7.9)	68.6 (10.8)	59.3 (17.4)
Lexical access	14.8 (1.8)	13.6 (4.3)	9.3 (6.6)
Reading skill composite	0.111 (0.126)	0.044 (0.07)	0.083 (0.131)
Auditory ERP response	2.66 (0.66)	1.69 (0.76)	2.19 (1.32)
N	12	15	15

The auditory ERP response is the average amplitude at 6 fronto-central electrodes at a latency of 80–220 ms in response to both standards and 4 deviant types in a MMN paradigm (see Uhlén et al., in preparation).

followed by a spoken word presented after 1 s. Word primes consisted of recorded spoken words (in Swedish) naming base-level common objects like foods, animals, clothes, body parts, vehicles, furniture, baby supplies, kitchen utensils and outdoor objects. Word primes were delivered at 75 dB (SPL). Picture targets were presented 2.3 s after word onset. After picture presentation participants indicated if the picture matched the word by pressing buttons on a response box corresponding to "yes" or "no." This procedure was repeated for 120 trials. The procedure was introduced by a short training session including trials similar to those of the experimental paradigm, but without time limits for the response. When these trials were successfully completed, further trials included time limits for the response. Each stimulus pair consisted of a spoken prime followed by a picture target. The pairs were of three types, constituting the semantic conditions of the experiment: matches, where the target is a typical illustration of the prime word (e.g., "wolf" followed by a picture of a wolf), within-category mismatches, where the target is an illustration of another object than the prime, but from the same category or domain (e.g., "wolf" followed by a picture of a bear) or between-category mismatches where there is no apparent semantic link between prime and target (e.g., "wolf" followed by a picture of a car). There were 40 stimulus pairs in each condition, in total 120 pairs that were presented in mixed and random order. The pictures consisted of simple color drawings, depicting familiar objects in a cartoon-like or realistic manner. Pictures were presented on the screen against white background (width 12–18 cm and height 12–20 cm). Presentation and randomization of stimuli was handled by E-prime 2.0 software (Psychology 370 Software Tools Inc., 2012[1]; Pittsburgh, PA). Note that while the targets were pictures, the mismatch effects depend entirely on perceiving and deriving meaning from the spoken primes. A speech pathologist with experience working with DHH children prepared the words and pictures used as stimuli, the prime-target pairings, and recorded the spoken word stimuli. There was no quantitative matching of lexical, auditory or visual features of stimuli between conditions, as they were all very familiar base-level nouns and objects, chosen with intelligibility in mind. Stimulus pairs are described further in the Supplementary Materials.

The behavioral procedure was slightly revised after 10 of the included participants were tested (4 CI, 6 HA, 0 NC), after concerns that that use of the response box was confusing for some participants. Visual feedback was added in each trial, and a visual prompt for responses was omitted. All participants are included in the present analysis, but a complementary analysis excluding the first 10 participants is provided in the Supplementary Materials. This analysis reveals highly similar results and suggests that this subtle methodological change had no effect on outcomes.

EEG Recordings and Processing

We recorded EEG at Department of Linguistics at Stockholm University, and at Humlab, Lund University using identical equipment from EGI (Electrical Geodesics Inc.), net amp 300 amplifier, electrode nets of the hydrocel 129 channel type (EOG channels were removed leaving 125 channels), using Cz as a reference channel and a ground channel positioned between CPz and Pz. In this system recordings are sampled at 20,000 Hz, low pass filtered online with a cut off at 4000 Hz and resampled to 250 Hz. The impedance of the channels was kept below 50 Ohm as recommended by the manufacturer. Hearing aids were refitted after the net was applied.

Recordings were filtered offline with a 1–40 Hz band pass FIR filter, resampled to 125 Hz and epoched. Only responses to picture targets were considered for the present study. Epochs with extreme amplitudes (exceeding $\pm 500\ \mu V$) were rejected. Epoched data was subjected to preprocessing procedures in EP toolkit (Dien, 2010). Blink artifacts were removed with an automatic procedure, where independent component topographies are matched to a blink template. Movement artifacts were isolated using PCA and an amplitude criterion (i.e., principal components of single trial data with more than 200 μV amplitude change were removed). Channels with poor signal quality were identified globally (by means of correlation: correlation with neighboring channels should be above 0.4 but not perfect) and per epoch (amplitude differences within the epoch should be below 200 μV). Data from these channels were interpolated. A negligible number of artifacts could be attributed to CIs (Gilley et al., 2006; Debener et al., 2008; Viola et al., 2012) and did not demand special treatment. In total, 6% of all trials were rejected, and each subject retained on average 220 trials (*SD* = 28) of 240.

RESULTS

First, we established the presence of semantic mismatch effects in the EEG data. Thus, data (collapsed across groups and intervention conditions) were visually inspected, and showed a large negative fronto-central peak in responses to pictures in all semantic conditions. Difference waves, produced by subtracting responses to matching pictures from responses to mismatching pictures, showed a broad negative deflection and polarity shift at lateral sites. A broad electrode window was used to capture these effects (all electrodes except edges and lateral sites, see **Figure 1A**). Only one electrode region was used, in order to reduce number of factors in the ANOVA (Luck, 2014). To obtain information about the time course of this semantic differential, average amplitudes of these electrodes were tested for semantic mismatch effects in series of T-tests, using 50 ms bins, from 0 to 650 ms after stimulus onset. Between 350 and 500 ms, both mismatch types differed significantly from congruent responses (see **Table 2B**), constituting an overall semantic mismatch effect in line with typical N400 descriptions (Picton et al., 2000; Kutas and Federmeier, 2011). T-values over time bins are presented in **Figure 1B** with separate lines for within-category and between-category mismatches, each compared to the congruent responses. While significance levels presented in **Table 2B** are uncorrected, the N400 difference results remain significant at the 0.05 level (one-tailed) also with Bonferroni-correction (corrected p-value $0.05/26 = 0.002$ and critical t-value at 3.05).

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[1] Psychology Software Tools Inc. (2012). *Retrieved from* http://www.pstnet.com.

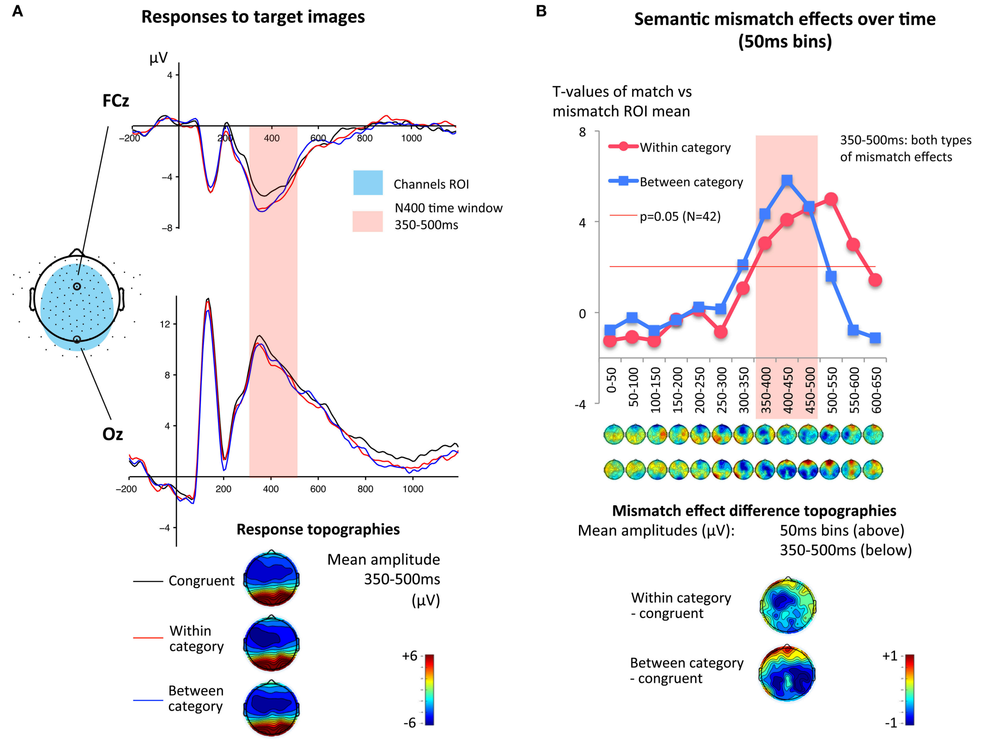

FIGURE 1 | (A) Overview of ERP responses: average responses at FCz and Oz, and topographic maps for the N400 time window 350–500 ms. Averages include all participants, collapsed across pre- and post-intervention. **(B)**. Within- and between-category mismatch effects (mismatches compared to matches) over time. *T*-tests based on amplitude averages in 50 ms time windows in the Region of Interest (ROI). Both effects were found in the time window 350–500 ms, which was used for the main analysis. Topographic maps show the mismatch effect amplitude differences, in 50 ms time windows and in the critical 350–500 ms interval.

The 350–500 ms time window was used for the main analyses to assess group differences in the N400 response in relation to semantic difficulties among DHH children. To this end, three factors were analyzed in a repeated-measures ANOVA: semantic incongruence (within-category, between-category, and congruent), intervention (before and after) and hearing amplification group (CI, HA, and NH). There was a main effect of semantic condition (**Figure 2A**, **Table 2A**), again confirming an overall semantic N400 effect among the participants, where the congruent condition differed from both mismatch types. There was also an interaction between semantic condition and group: Whereas between-category vs. congruent trials displayed the largest mismatch effect for the CI group, within- and between-category mismatch types were similar for the NH and HA groups. The HA group had less pronounced mismatch effects overall (**Figure 2B**). There was no meaningful main effect of intervention, or of the intervention factor interacting with semantic condition. A three-way interaction between group, semantic condition and intervention reached significance (**Figure 2C**). In the pre-training session, responses were similar among groups except for between-category responses (where the response was largest for the CI group and smallest for NH children). In the post-training session, groups were more different, with both mismatch responses larger than before for NH, almost no differences among children with HA and essentially the same response to congruent and within-category incongruent for CI-users (still with a large between effect). This pattern does not fit predictions of improved semantic processing for DHH children due to the intervention. Rather, it indicates that group differences in the first session were somewhat enhanced in the second. In sum, the analysis confirmed typical N400 incongruence effects, and show differences in semantic processing among groups. Smaller mismatch effects overall for HA-users, and little within-category

TABLE 2 | (A) Main effects and interactions of semantic conditions, training and group. Significant effects, and the nonsignificant effect of training is included. (B) Mismatch effects were assessed in 50 ms time windows across all participants, to establish the time-window of the effects (dotted square). Group-specific tests explored the semantic condition × group interaction over time. (C) Explorative correlation of peak mismatch effects and language test variables.

Results summary

(A) Repeated measurements ANOVA (*N* = 42)	**Variables**	**DF, error DF**	**F**	**Sig.**	**Partial eta squared**
	Semantic conditions	2, 78	19.41	<0.001	0.332
	Semantic × group	4, 78	3.42	0.012	0.149
	Training (pre, post)	1, 39	3.71	0.061	0.087
	Training × Semantic × group	4, 78	2.49	0.05	0.113

(B) *T*-values of within and between category mismatch ERP effects in time bins			**Time bin latency (ms)**												
Participant group	**Mismatch type**	**DF**	**0–50**	**50–100**	**100–150**	**150–200**	**200–250**	**250–300**	**300–350**	**350–400**	**400–450**	**450–500**	**500–550**	**550–600**	**600–650**
All	Within-category	41								3.05**	4.10***	4.60***	4.99***	3.00**	
	Between	41								4.35***	5.82***	4.68***			
NH	Within	11									2.65*	4.37***	4.38***	4.21***	3.28**
	Between	11									2.20*	2.81**			
HA	Within	14								2.22*		2.43*	3.98***		
	Between	14									2.36*				
CI	Within	14								2.61*	2.91*				
	Between	14					2.17*		2.56*	4.87***	6.49***	4.74***	2.58*		

(C) Pearson correlations between ERP effect amplitudes and other variables	**ERP mismatch effects**		**Language test variables (from first ERP session)**			**Age (months)**
		DF	**Phonological Composite**	**Lexical Access**	**Reading Composite**	
	Between-category 400–450 ms	41	0.23	0.26	0.06	0.12
	Within-category 500–550 ms	41	−0.33*	−0.34*	−0.08	0.08

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ uncorrected *P*-values.

mismatch effect for CI-users, despite a large between-category effect, is broadly in line with predictions of less semantic sensitivity among DHH children. However, the result that the between-category mismatch response was larger for children with CI than for NH was unexpected and might suggest differences in processing mode rather than a lack of semantic competence in the NH group.

In order to understand the time courses of semantic processing, we explored group differences further by reapplying the serial *T*-test analysis to each group separately (**Figure 3**). In the original series of *T*-tests, presented in **Figure 1B**, a difference was present in the time courses of within- and between-category mismatch effects. The between-category mismatch effect peaked at 400–450 ms whereas the within-category mismatch peaked at 500–550 ms, 100 ms later. As showed in **Figure 3**, mismatch effects in the group of children with CI peaked at 350–500 ms (in the time window of our main analysis) with much larger effects for between-category mismatches. In contrast, children with NH and HA showed larger effects for within-category mismatches, peaking after 500 ms. The effects showed small to moderate positive correlations with behavioral tests of semantic and phonological skills. The within-category mismatch effect at 500–550 ms was negatively correlated with test scores of lexical expectations and phonological skills. The between-category effect at 400–450 ms showed smaller positive correlation to the same variables. The within-category correlations, but not the between-category correlations, were statistically significant (see **Table 2C**). Two other potentially interesting variables, participant age and reading composite score, were tested for significant correlations, but none were found. The exploratory analysis highlighted the distinct cortical response pattern of the CI group, seen in the main analysis, and showed that response patterns among children with NH and HA were similar, with an extended within-category effect that was associated with lexical processing skills. These exploratory *T*-tests and correlations were presented without correction for multiple comparisons.

DISCUSSION

Semantic processing in DHH children has been largely unexplored at the neural level. In our word-picture matching design, both DHH children and NH controls showed large negative deflections for mismatching target pictures, consistent

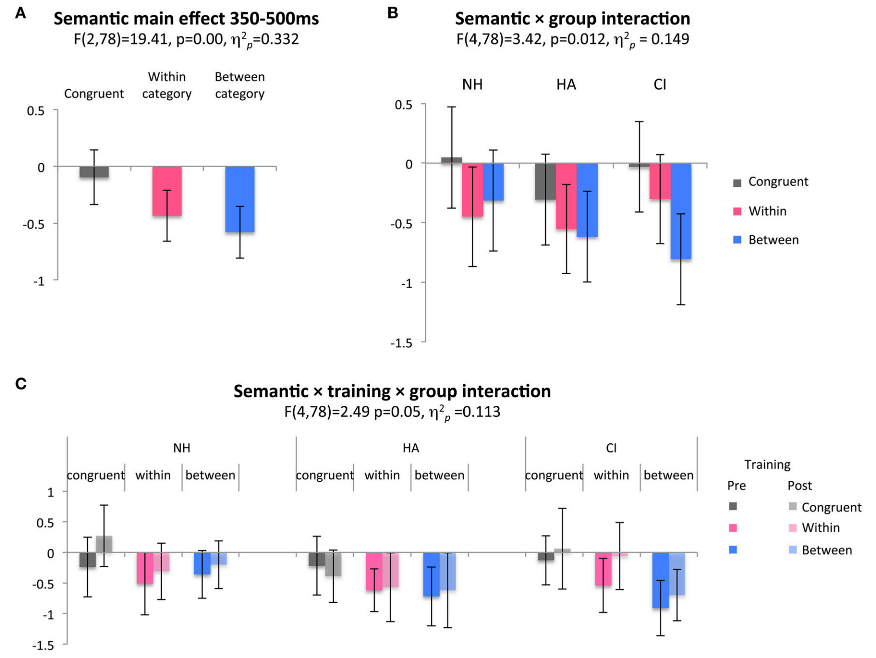

FIGURE 2 | (A) Main ERP effect of semantic condition revealing less negative responses to congruent images, and more negative responses in mismatches of both types. **(B)** Group interaction showing similar responses to both mismatch types in controls and children with HA, while children with CI show a distinct response. **(C)** The three-way interaction shows differences in the group pattern before and after training. However, mismatch effects for DHH children are not emphasized after training, so no positive effect of intervention can be inferred from this interaction.

with typical N400 effects. This group study of N400 responses in children with CI, support the observations in a previous case report (Key et al., 2010). In our results, based on N400 responses to visual stimuli, we did not observe the prolonged N400 latencies previously reported among adult CI users in response to speech (Hahne et al., 2012; Henkin et al., 2015; Finke et al., 2016), perhaps due to stimulus modality differences across studies. At a more detailed level, we observed differences between controls, children with HA and children with CI. Children with HA had nominally smaller mismatch effects than those of other groups, especially post-intervention (see **Figure 2C**). It is possible that the group with HA did not hear the primes as well as other participants, because they had smaller ERP responses to tones also in a subsequent auditory mismatch negativity paradigm (see **Table 1** and Uhlén et al., in preparation). The fact that ERP mismatch effects declined between recording sessions might, however, be more consistent with a diminishing motivation specifically for this group, although this was not apparent during interaction with the children. Future studies will ultimately show if this result is reproducible or, as we suspect, was a spurious finding.

Unexpectedly, children with CI had a larger between-category mismatch effect than the other groups. In some settings, a large mismatch effect would indicate better semantic discrimination, but given that the participants with CI did not perform well on a lexical prediction test (Nakeva von Mentzer et al., 2014b) this is unlikely. In contrast, children with preserved hearing and semantic ability had smaller ERP mismatch effects, with similar responses to both mismatch types. The exploratory *T*-tests revealed how the between-category effect had an early maximum and was largest for children with CI, while the within-category effect was largest among children with NH and HA and had a later maximum for these groups. The amplitude of the latter effect was correlated with better phonological and lexical skills (see **Table 2C**). The differences in timing and magnitude of N400 effects might indicate that children with CI engage in the task with different processing modes or strategies than children with NH and HA.

Prior work has found that lack of predictive processing might affect ERPs such that semantic within-category and between-category effects become more alike (Federmeier and Kutas, 1999; Franklin et al., 2007; Wlotko et al., 2010; Kiang et al., 2013).

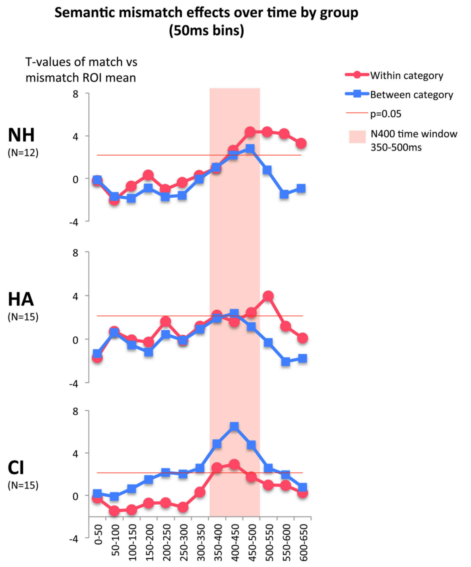

FIGURE 3 | Within- and between-category mismatch effects (mismatching trials compared to congruent trials) over time. *T*-tests based on ERP amplitude averages in 50 ms time windows in the Region of Interest (ROI). Positive threshold for $p = 0.05$ is shown for $N = 12$ (NH group) or $N = 15$ (HA and CI groups). A strong between-category mismatch effect is seen in children with CI, and a late within-category effect in children with NH and HA. Only the positive threshold is plotted, but one point with a negative *T*-value does reach the negative threshold for significance (the second red dot, 50–100 ms for NH children).

Effects of semantic relatedness on ERPs are typically smaller or absent when semantic processing results from passive, bottom-up processing, when motivation is lower (Kiang et al., 2013), at older age (Wlotko et al., 2010), or when the stimulated visual field favors processing outside of the language-dominant left-hemisphere (Federmeier and Kutas, 1999). Although our results are not conclusive, we speculate that children with CI might rely on more predictive processing than controls when performing this task. Predictive processing is a successful strategy used by this group to solve auditory tasks (Lyxell et al., 2009; Nakeva von Mentzer, 2014). Furthermore, the task design included only one-third matching trials, and one-third of trials were semantically challenging, within-category mismatches. It is possible that controls soon realize that primes do not accurately predict targets except in a minority of cases, and switch to a more passive, bottom-up mode. As the task is much more challenging for children with CI, they might be less likely to identify the low proportion of matches, and more likely to stay in a predictive mode even if it is more effortful. Children with CI have less structured semantic relations between word meanings (Kenett et al., 2013), which means that within-category mismatches will be mistaken for matches to some extent, and possess features that are overlapping with the predicted match, leading to a reduction of N400 amplitude. In sum, one possible explanation of our observed group differences is that children with CI rely on a predictive processing mode that reflects motivated effort. In everyday communication this might be an adaptive strategy, but in the present experiment it is not. Controls, in contrast, might use a more passive bottom-up processing mode that is more adaptive in this context.

The differentiated mismatch effects among CI children might be interpreted as a reflection of lower semantic precision, in line with prior work (Kenett et al., 2013). However, we find this interpretation unsatisfactory, because a lack of mismatch differentiation could also reasonably be interpreted as a lack of semantic precision. A third possible explanation for the absence of relatedness effects among NH children is that the mismatch response to between-category targets are influenced by a P3b component (Polich, 2007) that overlaps with the N400. As our results were unexpected, we encourage future studies to investigate whether predictive processing, an overlapping P3b response, or other interpretations could account for the deviating between-category mismatch effect in the N400 responses of individuals with CI.

In conclusion, our findings indicate that the ERP-responses of semantic processing in DHH children share similarities with those of controls. However, there are differences that seem to reflect different responses to task demands. The relatively large and differentiated N400 mismatch effects among children with CI could reflect predictive, top-down semantic processing. If we accept this interpretation, our results, together with the lack of positive effects of the phonics training intervention on the N400, emphasize the role of top-down semantic processing, and would highlight strategies such as perspective guiding in teaching reading comprehension to DHH individuals (Luckner and Handley, 2008). Further studies could use paradigms similar to ours to link top-down semantic processing closer to specific patterns of brain responses and behavioral results. Ways of supporting an adaptive use of such processing strategy should be investigated, perhaps by investigating the role of feedback on performance and ERP responses.

AUTHOR CONTRIBUTIONS

PK adapted the experiment, collected and analyzed ERP data and wrote the manuscript. JO supervised writing and analysis. ML, BS, BL, IU, MO conceived and designed the experiment. MO, EE, CN collected and managed the data. CN, PK, and BL analyzed behavioral data. CN, ML, BS, IU, EE read and commented on manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2016.01146

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Study II

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Health and Disability

Using a multi-feature paradigm to measure mismatch responses to minimal sound contrasts in children with cochlear implants and hearing aids

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Our aim was to explore whether a multi-feature paradigm (Optimum-1) for eliciting mismatch negativity (MMN) would objectively capture difficulties in perceiving small sound contrasts in children with hearing impairment (HI) listening through their hearing aids (HAs) and/or cochlear implants (CIs). Children aged 5–7 years with HAs, CIs and children with normal hearing (NH) were tested in a free-field setting using a multi-feature paradigm with deviations in pitch, intensity, gap, duration, and location. There were significant mismatch responses across all subjects that were positive (p-MMR) for the gap and pitch deviants ($F(1,43) = 5.17$, $p = 0.028$ and $F(1,43) = 6.56$, $p = 0.014$, respectively) and negative (MMN) for the duration deviant ($F(1,43) = 4.74$, $p = 0.035$). Only the intensity deviant showed a significant group interaction with MMN in the HA group and p-MMR in the CI group ($F(2,43) = 3.40$, $p = 0.043$). The p-MMR correlated negatively with age, with the strongest correlation in the NH subjects. In the CI group, the late discriminative negativity (LDN) was replaced by a late positivity with a significant group interaction for the location deviant. Children with severe HI can be assessed through their hearing device with a fast multi-feature paradigm. For further studies a multi-feature paradigm including more complex speech sounds may better capture variation in auditory processing in these children.

Key words: Mismatch negativity (MMN), hearing impairment, cochlear implant, hearing aid, children, multi-feature paradigm.

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INTRODUCTION

The introduction of cochlear implants (CIs) has dramatically improved the quality of life for children with congenital deafness and severe hearing impairment (HI) and has opened the door to oral communication. However, clinical experience has clearly shown that long-standing congenital deafness cannot be reversed into normal hearing (NH) because sensory deprivation in the prenatal period can have a profound and permanent effect on the development of the entire central auditory system (Kral & Sharma, 2012; Moore & Linthicum, 2007; Moore & Shannon, 2009). Cochlear implantation after the age of 3 years is associated with a functional delay as seen by latency of the P1 component. The latency of the cortical evoked potential P1 reflects functional maturation through the peripheral and central auditory pathways (Eggermont, Ponton, Don, Waring & Kwong, 1997) P1 latencies in congenitally deaf children after early CI implantation show rapid developmental changes, demonstrating the plasticity of the young brain (Sharma, Dorman & Spahr, 2002b). However, Sharma et al. showed significant differences in P1 development between children implanted early, before 3.5 years of age, or later. This sensitive period ends at around 7 years of age, after which fully functional auditory pathways may never develop (Ponton & Eggermont, 2001; Sharma, Dorman & Spahr, 2002a; Sharma, Martin, Roland *et al*., 2015). Despite spoken language development at near age level in children with early implantation, deeper investigation of their language abilities shows deficits in many aspects. Several studies (Löfqvist, Sahlén, Ibertsson, 2010; Lyxell, Wass, Sahlén *et al*., 2009; Geers, Davidson, Uchansk, Nicholas, 2013a; Geers & Nicholas, 2013b; Nakeva von Mentzer, Lyxell, Sahlén *et al*., 2013; Wass, Lyxell, Sahlén *et al*., 2010) have shown that phonological development is particularly hampered in children with CIs. Children with moderate to mild HI wearing hearing aids (HAs) are less well studied, but the importance of early intervention for language and social-emotional development has been documented for this group (Ching, Day, Seeto, Dillon, Marnane, Street, 2013a; Ching, Hill, Dillon, 2008; Ching, Dillon, Marnane *et al*., 2013b; Yoshinaga-Itano, 2003; Yoshinaga-Itano, Baca, Sedey, 2010). The phonological and lexical development in children with HAs has shown significant differences both compared with NH children and children with CIs (Nakeva von Mentzer *et al*., 2013). Hearing development in children with HI is not only delayed, but might be permanently distorted, hampering the ability to perceive the fine structures of speech.

Event-related potentials (ERPs) offer a way of exploring the neural auditory processes that underlie speech development. Children with HA or CI constitutes a rather small and heterogeneous group. A traditional oddball protocol gives limited information. The new multi-feature paradigm is a very interesting possibility to test deviants of different physical profile in the same test session. The Optimum 1 (Näätänen, Pakarinen, Rinne & Takegata, 2004) includes the typical basic features of sound, that may at least in part, be difficult to perceive through a hearing device.

Mismatch responses in children

Mismatch negativity (MMN) as described by Näätänen, Gaillard and Mäntysalo (1978) is generated by the brain's automatic response to any discriminable change in auditory stimulation irrespective of the attention being paid to the stimulation. This is a great advantage in studying children, who can enjoy their favorite cartoon while their auditory processing is being assessed. MMN develops early in infancy (Cheour, Alho, Ceponiené *et al*., 1998) and is relatively mature by the age of 5–7 years (Lovio, Pakarinen, Huotilainen *et al*., 2009; Glass, Sachse & von Suchodoletz, 2008; Shafer, Morr, Kreuzer & Kurtzberg, 2000). The MMN response has been shown to correlate with psychometric test scores of language development in children (Datta, Shafer, Morr, Kurtzberg & Schwartz, 2010; Huotilainen, Lovio, Kujala, Tommiska, Karma & Fellman, 2011; Lovio *et al*., 2009; Mikkola, Kushnerenko, Partanen *et al*., 2007; Shafer *et al*., 2010). suggesting that the MMN paradigm has the potential to acquire information on auditory processing capabilities in addition to or instead of psychometric testing. The MMN has therefore also been used in studies on children with central auditory processing disorder (CAPD) (Bauer, Burger, Kummer, Lohscheller, Eysholdt & Doellinger, 2009), with or at risk of dyslexia (Bruder, Leppänen, Bartling, Csépe, Démonet & Schulte-Körne, 2011; Lachmann, Berti, Kujala & Schröger, 2005; Lovio, Halttunen, Lyytinen, Näätänen & Kujala, 2012), learning impairment (Kraus, McGee, Carrell, Sharma & Nicol, 1995), Asperger's syndrome (Korpilahti, Jansson-Verkasalo, Mattila *et al*., 2007; Kujala,Lepistö, Nieminen-von Wendt, Näätänen & Näätänen, 2005), and autism (Gomot, Giard, Roux, Barthélémy & Bruneau, 2000; Gomot, Blanc, Clery, Roux, Barthelemy & Bruneau, 2011; Lepistö *et al*., 2005).

In addition to, or instead of, adult-like MMNs, positive mismatch responses (p-MMR) have been found in infants and children (Ahmmed, Clarke & Adams, 2008; Gomot *et al*., 2000; Lee, Yim & Sim, 2012; Leppänen, Guttorm, Pihko, Takkinen, Eklund & Lyytinen, 2004; Liu, Chen & Tsao, 2014; Ponton, Eggermont, Kwong & Don, 2000b; Partanen, Torppa, Pykäläinen, Kujala & Huotilainen, 2013b; Shafer *et al*., 2000, 2010). Shafer *et al*. (2000) found robust adult-like MMNs for pure tone contrasts in 4 year olds, whereas younger children often had a p-MMR instead of, or preceding, the adult-like MMN. In a later study by Shafer using vowel sounds (Shafer *et al*., 2010), most of the children younger than 5.5 years and some of the older children showed a p-MMR peaking between 100 ms and 300 ms. According to Shafer (Shafer *et al*., 2010), the p-MMR amplitude typically decreases with increasing age and is generally absent by 8 years of age, indicating an age-dependent transition from p-MMR to MMN.

This transition also seems to be affected by stimulus characteristics such as the size of the deviant and the interstimulus interval (ISI). In children with specific language impairment (SLI) a p-MMR was seen in response to small contrasts and shorter ISI, but a MMN to larger deviants or longer ISI (Ahmmed *et al*., 2008). In a study by Lee of 4–6-year-old children (Lee *et al*., 2012), Mandarin Chinese speech sounds MMN was only seen in response to larger deviants, while p-MMR was found in response to smaller deviants, and this effect was more pronounced in the younger subjects. Similar to these findings Liu (Liu *et al*., 2014) found p-MMR to small consonant contrasts in preschool- and school children as opposed to MMN to lexical tone contrasts. Partanen *et al*. (2013b) found p-MMR to speech sounds in young children predicting lower language comprehension scores. These results indicate that p-MMR can coexist with MMN in young children in response to sound stimuli that would normally only elicit MMN in older children and adults. However, the relationship between MMN and p-MMR is not yet fully understood.

The multi-feature paradigm

A multi-feature paradigm (Optimum-1) for eliciting mismatch responses (MMR) from five different deviant stimuli in one short test session and with the same accuracy as in the standard oddball paradigm was introduced by Näätänen in 2004 (Näätänen *et al*., 2004; Näätänen *et al*., 2007; Pakarinen *et al*., 2009). The deviant types in the original multi-feature paradigm represent small contrasts in pitch, intensity, duration, location, and gap detection, so that every other tone is a standard and every other is one of the five deviants. This time-saving protocol is particularly useful in studies of young children who do not tolerate long testing sessions. The multi-feature paradigm has been shown to elicit MMRs in newborns (Partanen, Pakarinen, Kujala & Huotilainen, 2013a; Sambeth, Pakarinen, Ruohio, Fellman, van Zuijen & Huotilainen, 2009) and in very young children aged 2–3 years (Putkinen *et al*., 2012). In infants the amplitudes were more positive for the frequency, intensity, and gap deviants than for standard stimuli, whereas the duration deviant elicited more negative responses (Sambeth *et al*., 2009). Also in the 2-3 years old duration and gap generated the most prominent MMN but also a positivity named P3a (Putkinen *et al*., 2012). In infants and children the multi-feature paradigm has been compared with a standard oddball paradigm using semisynthetic speech sounds (vowel and wovel duration), showing similar MMNs in the two conditions (Lovio *et al*., 2009; Partanen *et al*., 2013a, 2013b). A significant stimulus effect was seen with larger MMN amplitude to the wovel duration deviant compared to all other deviants. Further studies have shown a correlation between MMRs and psychometric language scores (Lovio *et al*., 2012; Partanen *et al*., 2013b). A recent study of 6-year olds using the multifeature paradigm, support larger MMN amplitudes to verbal versus non-verbal stimuli (Kuuluvainen, Alku, Makkonen, Lipsanen & Kujala, 2016), the results also indicating a relationship between establishment of cortical memory traces (MMN, LDN) and cognitive and language test scores. There are only a few studies using the multifeature paradigm in HI subjects. Studies of musical perception in subjects with CI, adults (Sandmann, Kegel, Eichele *et al*., 2010) and children (Torppa, Salo, Makkonen *et al*., 2012), elicited MMN responses in both groups. Smaller MMN amplitudes indicated reduced auditory discrimination accuracy in adult CI subjects, but for children there was no significant group interaction. There are no studies from subjects with HA to our knowledge. From a clinical point of view, the multi-feature paradigm seems promising as an objective means of evaluating different rehabilitation approaches.

Mismatch responses in CI and HA users

In reviewing his earlier studies of CI users, Ponton *et al*. (2000a) concluded that compared to the N1 component, MMN is a better measure of the basic auditory processes that are a prerequisite for the development of spoken language perception skills in profoundly deaf children and adults with CIs. Recordings of MMN might therefore serve as an objective index of sound discrimination ability. Studies in adults show that MMN is similar in good-performing CI users and NH listeners, but it is absent or abnormal in poor-performing CI users (Groenen, Snik & van den Broek, 1996; Kraus, Micco, Koch *et al*., 1993; Ponton *et al*., 1996; Roman, Canévet, Marquis, Triglia & Liégeois-Chauvel, 2005; Zhang, Hammer, Banks, Benson, Xiang & Fu, 2011). MMN amplitudes also correlate with speech perception in adults and children with CIs (Gordon, Tanaka & Papsin, 2005; Kileny, Boerst & Zwolan, 1997; Lonka, Kujala, Lehtokoski *et al*., 2004; Lonka, Relander-Syrjänen, Johansson, Näätänen, Alho & Kujala, 2013; Singh, Liasis, Rajput, Towell & Luxon, 2004; Turgeon, Lazzouni, Lepore & Ellemberg, 2014), suggesting that CI users can encode acoustic differences. Studying musical perception in adult CI users with a multi-feature paradigm, Sandmann *et al*. (2010) found reduced auditory discrimination accuracy. Accordingly, MMN reflected reduced accuracy in detecting changes in musical sounds in children with CIs (Torppa *et al*., 2012).

There is not much documentation on MMN from subjects wearing their HAs. The varying profile of hearing loss at different frequencies (which is often more severe at high frequencies) and the complexity of HA technology present a certain challenge when interpreting cortical responses in this group. The changes in stimulus characteristics modified by HAs might affect cortical responses, and these changes do not always reliably reflect HA gain (Billings, Tremblay & Miller, 2011). However, increased detectability of obligatory responses and MMN in the aided condition has been described in adults (Korczak, Kurtzberg & Stapells, 2005) and adolescents (Glista, Easwar, Purcell & Scollie, 2012). In children, the clinical potential of obligatory responses (P1) to evaluate whether acoustic amplification has provided sufficient stimulation for development of central auditory pathways, has been demonstrated (Chang, Dillon, Carter, van Dun & Young, 2012; Sharma *et al*., 2005).

Late discriminative negativity

The multi-feature mismatch paradigm applied to small children (Putkinen *et al*., 2012) has been shown to elicit a second negativity known as the late discriminative negativity (LDN). LDN, also named 'late MMN' by Korpilahti, Krause, Holopainen and Lang (2001), is described as a prolonged period of negativity occurring around 300–550 ms post-stimulus onset (Ceponiene *et al*., 1998; Shestakova, Huotilainen, Ceponiene & Cheour, 2003). LDN might reflect further, higher-order processing of the deviant sounds that follows the initial change detection (Ceponiene *et al*., 1998, 2002). The LDN component has been linked to an event-related desynchronization of oscillations extending across the delta, theta, and alpha ranges. Bishop, Hardiman and Barry (2010) found that children with speech-and-language-impairment failed to show the expected event-related desynchronization during the LDN time window that was seen in typically developing controls. Unlike MMN, LDN was found to be larger for small rather than large deviants and might reflect additional processing of auditory stimuli that occurs when the salient features of the stimulus are difficult to discriminate (Bishop, Hardiman & Barry, 2011). Further studies of LDN in children with dyslexia indicate that the difficulties these children experience in processing deviations in auditory information might arise at a relatively late stage of processing, that is, following the initial detection and discrimination of the stimulus (Halliday, Barry, Hardiman & Bishop, 2014; Hämäläinen, Leppänen, Guttorm & Lyytinen, 2008). Larger LDNs elicited to speech sounds versus non-speech sound have been found to associate with language and cognitive performance in children, also suggest that LDN is related to higher order neurocognitive processing (Liu *et al*., 2014, Kuuluvainen *et al*., 2016).

Aim of the study

Our aim was to explore whether a multi-feature paradigm (Optimum-1) for eliciting MMN can objectively capture difficulties in perceiving small sound contrasts in children with HI listening through their HAs and/or CIs. The deviant types in the multi-feature paradigm represent small contrasts in pitch, intensity, duration, location, and gap detection, all of which are basic features of speech that are necessary for building phonological representations. Our hypothesis was that the children with HI would show deficits in building these representations and that this would be reflected by absent or deviating mismatch responses (MMRs). The specific research question was whether this time-saving paradigm captures relevant variation in auditory processing that would correlate with the severity of HI and the delay in language development.

MATERIALS AND METHODS

Children with HI aged 5–7 years and using CIs, HAs, or a combination of both constituted the study group. The inclusion criteria were mild, moderate to severe, or profound bilateral sensorineural HI and full-time use of CIs and/or HAs. No other disability that could affect their speech and language development should be present. They should speak Swedish at preschool or school, but could use another language at home. Medical case notes were studied by audiologists and speech language pathologists in Stockholm, Uppsala, and Lund, Sweden. Ninety families had a child who met the criteria for the study. Approximately one third agreed to participate and were given written and spoken information.

Children of the same age with NH constituted the reference group. The inclusion criterion for the reference group was NH as reported by their parents in a written consent form. They should speak Swedish in their educational setting and should have no disability that could affect their speech and language development. Children with NH were recruited from preschools and schools in the Stockholm area.

Written parental informed consent was obtained for all the participants. Ethical approval was obtained from the Regional Committee for Medical Research Ethics in Stockholm, Sweden.

Participants

This study is based on data from 46 children (24 girls), including 30 (19 girls) with HI and 16 (5 girls) with NH. Among the 30 children with HI, 9 (7 girls) had bilateral CIs, 15 (9 girls) had bilateral HAs, and 6 (2 girls) had a combination of CIs and HAs (CI/HA). Seventeen children (10 girls) had a severe/profound HI with a pure tone average (PTA) of >70 dB unaided, 11 children (7 girls) had a moderate HI (PTA 40–60 dB), and 2 girls had a mild HI (PTA <40 dB) (Tables 1 and 2). Children with bilateral CIs and children with CI/HA formed one group (CI) in the data processing (CI). They all had a severe HI and relied mainly on their CIs, and together they formed a group of the same size as the HA and NH groups, respectively. Aided thresholds in children with CIs or HAs were between 20 and 40 dB, except for children with HAs and a steep high-frequency loss where HAs could not reach these levels.

The mean age at diagnosis was 19 months and ranged from 2 weeks up to 5 years of age. Approximately half of the children were diagnosed before one year of age. Four children were diagnosed with a progressive HI, and one child was born with unilateral deafness and later developed HI in the other ear. The mean age at diagnosis for children in the CI group was 10 months (range 2–19 months) with a mean age for implantation at 19 months (range 11–36 months). All children with profound HI were first fitted with bilateral conventional HAs until they could undergo CI surgery. Children with CI/HA were diagnosed at an average age of 14 months (range 1–31 months), received HAs at an average age of 25 months (range 4–48 months), and were implanted at an average age of 36 months (range 15–67 months). Children with bilateral HAs were diagnosed at an average age of 27 months (range 1–64 months) and received HAs at an average age of 3 years and 1 month (range 8–67 months).

Three children had another spoken languages besides Swedish. Two children with CIs used sign language as their first mode of communication at home but used spoken Swedish in school, and two other children used sign-supported speech. In the NH group, there was one child who spoke another language besides Swedish. All children performed within normal limits on nonverbal intelligence as assessed by Raven's colored matrices (Raven, 1995), and there was no significant difference between the groups for nonverbal intelligence. Another two children participated in the study but where excluded from the present analysis (one NH child did not meet the inclusion criteria, and one child with CIs was excluded due to ERP-recording issues).

Stimuli and procedure

The multi-feature paradigm Optimum-1 designed by Näätänen *et al.* (2004) was used, where MMN is elicited by contrasts in pitch, duration, intensity, gap, and location under passive conditions. The standard stimuli were harmonic tones composed of three sinusoidal partials of 500, 1000, and 1500 Hz that were 75 ms in duration, including 5 ms rise and fall times. The intensities of the second and third partials were lower than that of the first partial by 3 dB and 6 dB, respectively, for all stimuli. After 10 standard tones, there followed a sequence where a deviant tone stimulus was inserted between each standard with a pseudo random variation of deviant type. The deviant tones differed from standards either in frequency, duration, intensity, perceived sound source location, or by having a gap inserted in the middle of the tone. The frequency deviants were 10% higher (partials: 550, 1100, 1650 Hz) or 10% lower (450, 900, 1350 Hz), half of each, than the standard. The intensity deviants were 10 dB higher or 10 dB lower, half of each, than the standard. A change in perceived sound-source location of approximately 90° was created by an interaural difference time of 800 μs to the right or left channel, half of each. The duration deviant was 25 ms instead of the standard 75 ms. A silent gap of 7 ms (including a 1 ms fall and rise time) in the middle of the standard stimulus constituted the gap deviant (see Näätänen *et al.* 2004 for more details). Because the memory trace of the standard tones is also reinforced by overlapping features in the deviants, more deviant stimuli can be inserted than in a typical MMN paradigm. The stimuli were presented at a stimulus-onset asynchrony (SOA) of 500 ms in two 6-minute sequences (1244 stimuli in total) with a total recording time of 12 minutes. Because every second stimulus was a deviant, there were about 120 (622/5) of each stimulus deviant type.

The participating children were seated in a chair – where height and seating position could be adjusted to give comfortable support – and were instructed to watch an animated movie (silenced) and not to pay attention to the sound stimuli. The stimuli were presented through two loudspeakers in front of the child at an angle of 45 degree on each side at 70 dB HL. All children were listening through their hearing device with which 70 dB was a subjectively well-heard level. (This free-field stimulation was different from that in the study by Näätänen *et al.* 2004, in which the stimuli were presented via headphones at 60 dB above the individual subject's hearing threshold.)

EEG recordings and processing

EEGs were recorded at the phonetics lab of the Department of Linguistics at Stockholm University and at Humlab at Lund University. Recordings were obtained from 40 participants in Stockholm and 6 HI subjects (4 HA and 2 CI) in Lund with nearly identical procedures and the same EEG equipment (Net Amp 300, Electrical Geodesics Inc.), including a hydrocel electrode net with 128 channels, Cz as the reference channel, the ground channel positioned between CPz and PZ. Minor differences between the labs included different chairs, speakers, and monitors. In the Stockholm lab, horizontal and suborbital electrodes for eye movements had been removed from the electrode nets. EEG was recorded at 250 Hz sample rate using a EGI Net Amp 300 (Electrical Geodesics Inc.). The impedance of the channels was kept below 50 kΩ as recommended by the manufacturer. HAs were put in place after the electrode net was applied.

Recordings were filtered offline with a 1–40 Hz bandpass FIR filter, resampled to 125 Hz, and epoched at 100 ms pre-stimulus and 500 ms post-stimulus. Epochs with extreme amplitudes (exceeding ±500 μV) were rejected before submitting the data to the automatic preprocessing procedures in the EP toolkit (Dien, 2010). The EP toolkit first applied rejection criteria for the channels. Bad channels were identified globally by means of correlation, and correlation with neighboring channels should be above 0.4. The remaining channels were decomposed by independent components analysis (ICA) (Bell & Sejnowski, 1995), for identifying blink artifacts, and components whose topographies closely matched a topographic blink template were removed. Next, large irregular artifacts such as movement artifacts were identified and removed by using principal component analysis (PCA) and an amplitude criterion. Principal components of single trial data were removed if the principal component contained amplitude changes larger than 200 μV. Finally, the remaining channels with amplitude differences within the epoch above 300 μV were rejected as well as epochs with 25% or more bad channels. The rejected channels where then interpolated. On average, 73% of all epochs where retained through this procedure, with an average of 91 trials per deviant type and 454 standard trials per subject.

Data with CI artifacts were treated with an additional ICA-based procedure in EEGLAB (Delorme *et al.*, 2004; Jung, Makeig, Humphries *et al.*, 2000a; Jung, Makeig, Westerfield, Townsend, Courchesne & Sejnowski 2000b,). This procedure was inserted after blink removal in the overall processing scheme. The CI artifact was attenuated by rejecting independent components with comparatively good isolation of CI artifact features from brain source features, in an iterative manner. CI artifact components were first identified by sorting ICA components based on their contribution to a peak at 0–50 ms after stimulus onset – the time of the largest CI artifact – originating in the CI magnetic pulse. Topographic and spectral characteristics of these components were noted. Components with the highest loadings specifically in this period and little or no spectral features typical of brain sources were rejected as CI artifacts, other components with similar characteristics and high power was also considered and in some cases rejected.

After preprocessing, ERPs were re-referenced to linked mastoids and baseline corrected with a baseline period starting 100 ms before stimulus onset. In total, recordings were obtained from 30 children with HI and 16 children with NH. All individual waveforms were visually evaluated by two of the authors, accepting only data with a broad positive P1 peak characteristic for the children's auditory responses (Sharma *et al*., 2005).

Time windows and electrode selection

ERPs were roughly similar across the scalp, changing smoothly with maximal amplitudes at the fronto-central sites, which is typical for mastoid-referenced responses (Yao, Wang, Oostenveld, Nielsen, Arendt-Nielsen & Chen, 2005). In line with these maxima and earlier MMN findings (Duncan, Barry, Connolly *et al*., 2009; Näätänen *et al*., 2007), a fronto-central group of seven electrodes between Fz and Cz (channel numbers 5, 6, 7, 12, 13, 106, and 112 in an EGI 128-channel HGS net) was chosen and used for all further analysis (see Fig. 1). Due to the lack of a distinct negativity peak for the MMN difference wave, the analysis was based on four time windows (TW1, TW2, TW3 and TW4) set according to the major positive and negative waves in the standard average response waveform (Fig. 1). TW1 (samples within 0–80ms from onset) captures the time between sound onset and before the large positive response in TW2 (samples within 80–220ms). A pronounced negativity follows in TW3 (samples within 220–400ms) ending in a positive slope in TW4 (samples within 400–500ms). TW2 is considered the window of most interest for MMN, but because it is fitted to the broad positive peak it starts and ends about 40 ms earlier than other studies with similar paradigms (Pakarinen *et al*., 2009, Putkinen *et al*., 2012). However, there is still a considerable overlap with typical MMN latencies of 150–250 ms (Näätänen *et al*., 2007).

Table 1. *The 30 children with hearing impairment constituted a heterogeneous group. Etiology was unknown in 16 cases. In 10 children the hearing impairment was classified as hereditary, two verified (Cx26 and X-linked hearing loss). Others were diagnosed with congenital CMV-infection, neonatal complications, CNS disorder and ototoxic medication. Subject 6, 12, 14 and 19 had a progressive hearing loss with better hearing the first years of life. Subject 19 later received CI. Visual inspection showed a distinct P1 in most subjects and a mismatch response of varying polarity. Traces of CI-artifact remained in some recordings*

	Hearing device Right/Left	Age years; months	Sex	Cause of impairment	Hearing at diagnosis Right/Left	Age at diagnosis yrs;mths	Age at HA: yrs;mths	Age at CI: yrs;mths	Raven matri-ces	ERP (visual inspection)
1	CI bilat	7;05	F	Cx26	80-90	0;02	-	0;11	50	P1, MMN
2	CI bilat	7;06	F	Otosclerosis in family	85-90	0;09	-	1;01	75	P1, MMN, CI artifact
3	CI bilat	4;11	F	CMV	Deaf	1;07	1;07	1;11	75	P1, MMN
4	CI bilat	6;04	M	Unknown	Deaf	1;00	-	1;07	75	P1, MMN
5	CI bilat	6;00	M	Unknown	70-100	1;07	1;08	1;09	95	P1, pMMR? CI artifact
6	CI bilat	7;07	F	Unknown	Profound, progress	0;09	-	1;06	75	P1 low ampl, pMMR
7	CI bilat	6:10	F	Unknown	Deaf	1;06	1;07	1;10	90	P1, MMN?
8	CI bilat	5;06	F	Hereditary*	Deaf	0;02	-	3;00	75	P1 low ampl, pMMR, CI artifact
9	CI bilat	7;08	F	Hereditary	85/85	0;03	0;03	1;00	95	P1, MMN
10	HA/CI	4,10	M	X-linked hearing loss	75-90/ Deaf	1;10	1;11	2;03	95	P1, MMN
11	CI/HA	6,10	F	Hereditary	D/70-80	2;07	2;08	3;02	95	P1, pMMR?, CI artifact
12	HA/CI	6;05	F	Neonatal, CNS sequale	40/50 Progress	1;11	2;02	4;07	50	P1 low ampl. pMMR
13	HA/CI	6;09	M	Unknown	59/Deaf	0;01	4;10	5;7	90	P1, pMMR
14	HA/CI	5;04	M	Unknown	80/80 Progress	0;01	0;05	1;09	90	P1, noisy rec, pMMR?
15	CI/HA	6;05	M	Hereditary	Deaf/58	0;09	0;10	1;03	50	P1 low ampl, pMMR
16	HA bilat	5;02	F	Unknown	42/42	4;03	4;07	-	50	P1, MMN
17	HA bilat	5;07	F	Neonatal	52/57	4;07	5;00	-	95	P1, pMMR(?)
18	HA bilat	7;08	M	Hereditary	53/55	4;05	4;06	-	95	P1, pMMR
19	HA bilat	7;04	M	Unknown	78/83 Progress**	4;11	6;07	-	75	P1, pMMR
20	HA bilat	5;00	F	Unknown	41/48	0;01	2;08	-	50	P1, MMR(?)
21	HA bilat	6;05	M	Hereditary	80/74	0;04	0;09	-	75	P1, MMN
22	HA bilat	7;06	M	Unknown	46/53	0;02	1;08	-	95	P1 low ampl, MMN(?)
23	HA bilat	7;07	F	Unknown	39/35	4;04	4;05	-	75	P1, MMN
24	HA bilat	5;10	M	Ototox.med.	46/54	2;05	2;09	-	95	P1, pMMR
25	HA bilat	5;11	F	Unknown	48/50	1;04	3;04	-	50	P1, pMMR
26	HA bilat	6;04	F	Hereditary	45/45	1;02	1;02	-	75	P1, MMN
27	HA bilat	6;10	F	Unknown	59/63	0;00	2;06	-	50	P1, pMMR
28	HA bilat	6;10	F	Unknown	29/30	5;04	5;06	-	95	P1, MMN
29	HA bilat	5;00	F	Unknown	46/46	0;02	0;08		75	P1, pMMR
30	HA bilat	5;01	F	Unknown	61/50	0;03	1;03		95	P1, pMMR

Note: *Deaf parents, **Received CI later.

Table 2. *Fifteen children with normal hearing constituted the control group. Visual inspection showed a P1 in all subjects and mismatch responses of varying polarity*

Controls	Sex	Age yrs;mths	ERP
1	M	4;11	P1, pMMR
2	M	5;03	P1, pMMR
3	F	5;11	P1, MMN
4	F	6;00	P1, pMMR?
5	M	6;00	P1, pMMR
6	M	6;00	P1, MMN
7	M	6;03	P1, pMMR
8	M	6;05	P1, pMMR?
9	F	6;07	P1, MMN
10	F	6;11	P1, MMN
11	M	7;00	P1, MMN
12	M	7;00	P1, MMN
13	M	7;10	P1, MMN
14	F	8:00	P1, pMMR
15	M	8;01	P1, MMN

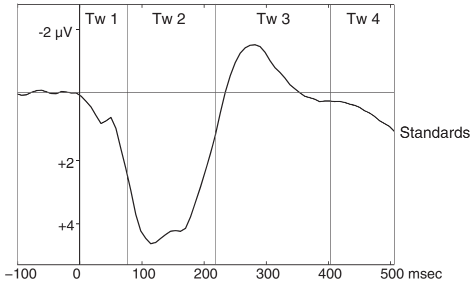

Fig. 1. The average responses to standards from a fronto-central group of seven electrodes. The 500 ms post-stimulus period is divided into four time windows that are set according to the major positive and negative deflections in the standard condition.

Statistical analysis

The average amplitudes over selected channels and samples were compared in a repeated-measurement ANOVA with simple contrasts between standards and deviant types as within-subject tests. Thus, six stimulus type levels are tested as five contrasts. Hearing type group was entered as a between-subject factor with three levels (HA, CI, NH). With this approach tests for mismatch effects over all participants, as well as group interactions with mismatch effects, and group interactions with responses over all stimulus types (standards and deviants) were combined in one test. The analysis of TW2 is considered the primary test of MMN effects. However, the same ANOVA design was used for exploratory analysis of the other three time windows.

RESULTS

All results are summarized in Tables 3 and 4. An overall display of responses is shown in Fig. 2.

Obligatory responses to both standard and deviant tones

Responses to all stimuli (both standards and deviants) differed between groups in TW1 ($F(2,43) = 3.58$, $p = 0.036$) and TW2 ($F(2,43) = 3.81$, $p = 0.030$). Post hoc testing indicated that the NH and the CI group had significantly larger responses than the HA group in TW1 (Fisher's LSD: NH − HA, mean difference = 0.5, $p = 0.045$; CI − HA, mean difference = 0.6, $p = 0.016$). In TW2, which corresponded to the P1 component, the response amplitudes in the NH group were larger than the response amplitudes in the HA and CI groups; however, only the difference between the NH and HA groups was significant in post hoc testing (Fisher's LSD: mean difference = 0.9, $p = 0.009$).

Mismatch responses to the deviant types and group interactions

In TW1, only the gap deviant response was significantly more positive than the response to the standards ($F(1,43) = 5.26$, $p = 0.027$). Mismatch differences did not interact with participant group in TW1.

In TW2 (80–220ms) there was a significant MMR across all subjects for the gap and pitch deviants that was more positive compared to the standards ($F(1,43) = 5.17$, $p = 0.028$ and $F(1,43) = 6.56$, $p = 0.014$, respectively), and more negative for the duration deviant than the responses to standards ($F(1,43) = 4.74$, $p = 0.035$). Our results thus show a p-MMR for the gap and pitch deviants and a MMN for the duration deviant. These mismatch responses did not interact with participant group.

The intensity deviant showed a significant group interaction with MMN in the HA group and p-MMR in the CI group ($F(2,43) = 3.40$, $p = 0.043$). Post hoc tests confirmed this difference (Fisher's LSD: mean difference HA − CI = −0.7, $p = 0.013$). This effect was still significant when the difference waves were converted to absolute values (Fisher's LSD: mean difference HA − CI = −0.4, $p = 0.036$). NH did not differ significantly from other groups in post hoc testing.

In TW3 and TW4, the difference wave showed negative slopes for the HA and NH groups, while the CI group showed positive discriminative responses in these time windows. This pattern was found for several deviants, but only the location deviant showed a significant group interaction (TW3: $F(2,43) = 3.58$, $p = 0.037$, TW4: $F(2,43) = 4.48$, $p = 0.017$) (see Table 4 and Fig. 2). Post hoc tests confirmed that the CI group differed from the two other groups in both TW3 and TW4 (Fisher's LSD: mean differences and p-values for TW3: CI − NH = 0.5, $p = 0.032$; CI − HA = −0.5, $p = 0.03$. Mean differences and p-values for TW4: CI − NH = −0.6, $p = 0.036$; CI − HA = −0.7, $p = 0.014$). TW4 corresponds to the LDN response occurring around 300–550 ms post-stimulus onset (Bishop *et al.*, 2011; Ceponiene *et al.*, 1998; Korpilahti *et al.*, 2001; Shestakova *et al.*, 2003).

Exploring correlations to p-MMR

Three variables were used to explore correlations with p-MMR, including age and two language variables measuring phonological and lexical development. The two language variables, a composite phonetic score and lexical expectations are described in (Nakeva von Mentzer *et al.*, 2013). Mismatch amplitude in TW2 correlated negatively with age for the intensity (Pearson correlation, –0.35, P = 0.022) (Fig. 3) and location deviant (Pearson correlation, −0.34, P = 0.030) with a transition to MMN in older subjects. This correlation was significant also in the NH group separately (Intensity deviant: Pearson correlation, –0.63, P = 0.021; Location

Table 3. *ERP responses to standards and deviants in hard of hearing children and controls: means and effects for each time window*

Repeated Measurements ANOVA tests	Participants	Stimulus Type	Tw1 0-80ms			Tw2 80-220ms			Tw3 220-400ms			Tw4 400-500ms		
			Mean	(SD)	*F*	Mean	(SD)	*F*	Mean	(SD)	*F*	Mean	(SD)	*F*
Between-subjects effects (df 2, Error df 43)	NH	All	0.62_{a}	(0.56)	$3.58^{1}*$	2.60_{a}	(0.66)	$3.81^{1}*$	−0.36	(0.66)		−0.25	(0.63)	
	HA	All	0.12_{ab}	(0.52)		1.69_{a}	(0.78)		−0.27	(1.07)		−0.22	(0.57)	
	CI	All	0.73_{b}	(0.87)		2.05	(1.25)		−0.18	(0.64)		0.07	(0.39)	
Simple effects of Stimulus Type: Standards vs. each deviant (df 1, Error df 43)	All (N=46)	Standard vs.	0.34_{cd}	(0.68)		2.00_{bcde}	(1.11)		−0.27	(0.70)		0.21	(0.74)	
		Duration	0.45	(1.04)		1.57_{c}	(1.24)	4.74*	−0.20	(1.10)		−0.20	(1.23)	
		Gap	0.62_{d}	(0.97)	5.26*	2.32_{d}	(1.18)	5.17*	−0.27	(1.28)		−0.15	(1.34)	
		Intensity	0.48	(0.97)		2.17	(1.24)		−0.38	(1.40)		−0.27	(1.20)	
		Location	0.54	(1.10)		2.23	(1.42)		−0.21	(1.25)		−0.27	(1.27)	
		Pitch	0.51	(1.01)		2.37_{e}	(1.25)	6.56*	−0.30	(1.15)		−0.15	(1.14)	
Interactions: Type x Group (df 2, Error df 43)	(N=16)	Standard vs.	0.47	(0.63)		2.51	(0.63)		−0.15	(0.75)		0.42	(0.77)	
		Duration	0.51	(1.00)		1.82	(1.24)		−0.01	(1.00)		−0.32	(1.21)	
		Gap	0.48	(0.71)		2.96	(0.85)		−0.23	(1.07)		−0.36	(1.51)	
		Intensity	0.81	(0.70)		2.66	(0.88)	$3.40^{1}*$	−0.72	(0.90)		−0.52	(1.01)	
		Location	0.74	(1.03)		2.71	(1.25)		-0.48_{a}	(1.20)	$3.58^{1}*$	-0.55_{a}	(1.08)	$4.48^{1}*$
		Pitch	0.67	(1.02)		2.80	(1.16)		−0.51	(1.30)		−0.15	(1.44)	
	Hearing Aid (N=15)	Standard vs.	0.17	(0.61)		1.65	(0.93)		−0.16	(0.61)		0.29	(0.70)	
		Duration	0.14	(1.07)		1.65	(1.13)		−0.13	(1.14)		−0.13	(1.35)	
		Gap	0.35	(1.05)		1.74	(0.98)		−0.16	(1.78)		−0.27	(1.46)	
		Intensity	−0.03	(0.82)		1.45_{f}	(0.82)		−0.43	(1.57)		−0.15	(1.39)	
		Location	0.11	(0.83)		1.85	(1.35)		-0.39_{b}	(1.35)		-0.70_{b}	(1.08)	
		Pitch	0.02	(0.86)		1.78	(1.04)		−0.36	(1.25)		−0.38	(0.96)	
	Cochlear Implant (N=15)	Standard vs.	0.38	(0.81)		1.80	(1.48)		−0.51	(0.71)		−0.10	(0.68)	
		Duration	0.69	(1.04)		1.21	(1.35)		−0.48	(1.18)		−0.15	(1.22)	
		Gap	1.03	(1.04)		2.22	(1.39)		−0.42	(0.91)		0.20	(1.00)	
		Intensity	0.64	(1.18)		2.35_{f}	(1.60)		0.03	(1.64)		−0.13	(1.23)	
		Location	0.77	(1.32)		2.10	(1.59)		0.26_{ab}	(1.13)		0.47_{ab}	(1.37)	
		Pitch	0.84	(1.02)		2.49	(1.37)		−0.02	(0.87)		0.07	(0.96)	

Notes: ^{1}F-values for group effects and interactions are reported at control group rows. $*p < 0.05$. Subscripts$(_{abcdef})$ indicate means for significant contrasts. For group effects subscripts indicate significant contrasts in LSD post hoc tests, described in the results.

Table 4. *Exploring MMR correlation with age, phonetic and lexical scores*

Mismatch-amplitudes Tw2	Duration	Gap	Intensity	Location	Pitch
All					
Age (n = 46)	–0.193	–0.208	–0.352*	–0.335*	–0.189
Phonetic composite scores (n = 42)	–0.15	–0.025	–0.056	–0.164	–0.117
Lexical expectations (n = 41)	–0.093	–0.115	–0.033	–0.083	0.037
Groups: Age					
Normal hearin g (n = 16)	–0.227	–0.486	–0.629*	–0.581*	–0.411
Hearing aid (n = 15)	0.106	0.106	–0.216	–0.08	–0.166
Cochlear implant (n = 15)	–0.361	–0.311	–0.345	–0.328	–0.039

Notes: $*p < 0.05$ Correlation (Pearson), two-tailed.

deviant: Pearson correlation, –0.58, P = 0.037). None of the language variables did correlate with p-MMR.

Summary of the results

The overall response amplitudes were smaller for the HA group in comparison with the CI and NH groups. There were significant mismatch responses across all subjects that were positive (p-MMR) for the gap and pitch deviants ($F(1,43)$ = 5.17, p = 0.028 and $F(1,43)$ = 6.56, p = 0.014, respectively) and negative (MMN) for the duration deviant ($F(1,43)$ = 4.74, p = 0.035). Only the intensity deviant showed a significant group interaction with MMN in the HA group and p-MMR in the CI group ($F(2,43)$ = 3.40, p = 0.043). The p-MMR correlated negatively with age, with the strongest correlation in the NH subjects. In the CI group, the late discriminative negativity (LDN) was replaced by a late positivity with a

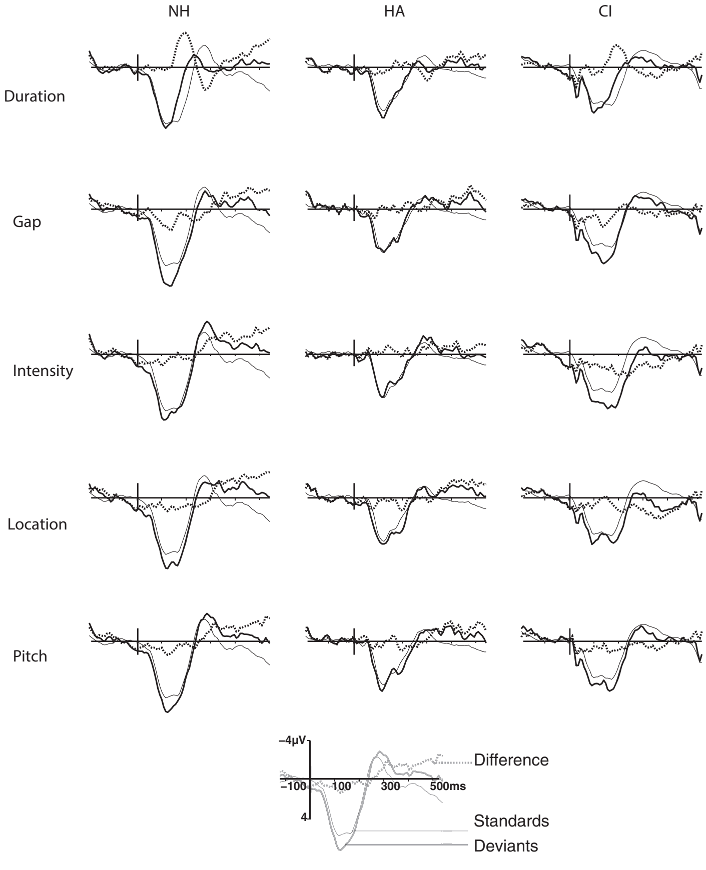

Fig. 2. The average responses to standard (thin line), the deviants (thick line) and the MMRs (dotted line), separated by deviant type and by group. Negative values are towards the top of the figure. A mismatch negativity (MMN) is elicited by the duration deviant. A late discriminative negativity (LDN) can be observed in the NH and HA groups, but not in the CI group. Responses are generally larger in NH children compared to hearing-impaired children.

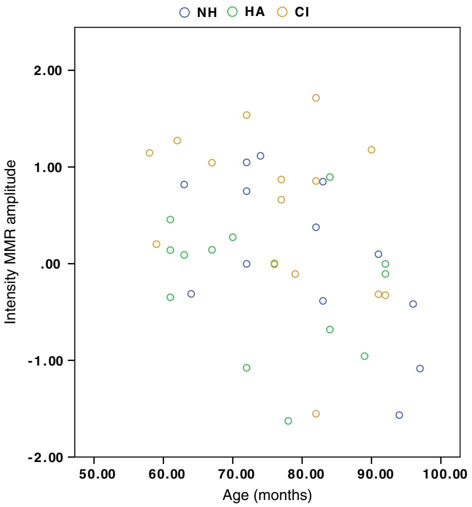

Fig. 3. Mismatch amplitude in TW2 correlated negatively with age for the intensity deviant (Pearson correlation, −0.35, P = 0.022) with a transition to MMN in older subjects. This correlation was significant also in the NH group separately (Pearson correlation, −0.63, P = 0.021).

significant group interaction for the location deviant. The results in all groups did show a high degree of interindividual variability with both positive and negative difference waves. We consider the analysis of TW2 to be the primary analysis thus without need for Bonferroni correction. However, effects in other time windows should be treated as exploratory, with correction. The location deviant group interaction effect in TW3 and TW4 would only survive in TW4 with Bonferroni-correction for 3 tests (P = 0.017). The effect of gap deviant in TW1, would not survive correction (P = 0.027).

DISCUSSION

There are only a few studies of ERP in which subjects with HI have been tested when they are listening through their hearing device. In our study, the main purpose was to obtain a measure of the brain's response to the signals at user settings that were typical for that hearing-impaired individual. The deviant types in the multi-feature paradigm represent small contrasts in pitch, intensity, duration, location, and gap detection that form the basic features of speech that are necessary for building phonological representations. Our hypothesis was that the hearing-impaired children would show deficits in building these representations as reflected by absent or deviating MMR compared to normal hearing children. However, our results do not support any major between-group differences in discrimination of these small sound contrasts

Obligatory responses

The obligatory responses to standard and deviant in our age group is dominated by the positive wave (P1), later maturing into the typical P1-N1-P2 complex. The standard and deviant waveforms showed a similar pattern in all groups, but with significantly lower amplitudes in the HA group. Because amplitude is an effect of loudness, the lower response amplitudes may indicate lower perceived loudness for these subjects. When sensation levels increase, the P1 response amplitude becomes larger and latency shorter in NH subjects (Dinces *et al*., 2011). Smaller P1 amplitudes in the HA group might thus be the effect of insufficient amplification through their hearing device. Aided thresholds with HAs are mostly lower than hearing thresholds in NH subjects (Korczak *et al*., 2005), especially in the high frequencies. CI audibility thresholds are in general at 20–35 dB because amplification is often limited by comfort and side effects. This can explain the lower amplitudes seen in this and other studies (Torppa *et al*., 2012) where subjects are wearing their hearing device. In our subjects, we did not assess the aided thresholds in the test booth. Thus, we can only speculate that lower response amplitudes reflect lower input stimulus levels in our children with HAs or CIs. The peak of P1 in the CI subjects was also less sharp and more like a plateau, which might partly be the result of the CI artifact rejection procedure. In all, our results support that HAs and CIs do not fully compensate for the hearing impairment in these children.

Mismatch responses and p-MMR

Our results, showing a MMN elicited by the duration deviant, while for the other deviants the MMRs were less distinct or replaced with a positivity followed by a late negativity, are very similar to other studies using the Optimum-1 paradigm in children (Lovio *et al*., 2009; Putkinen *et al*., 2012; Sambeth *et al*., 2009). In 5–7-year-old children, the auditory pathways are still maturing and the MMN might not be present, or there might be an overlapping p-MMR that dominates or cancels out the MMN (Ahmmed *et al*., 2008; Leppänen *et al*., 2004; Shafer *et al*., 2010). The positivity seen in our results is likely such a p-MMR. The significant negative correlation between the p-MMR and increasing age in our children might thus reflect maturation of the auditory system.

However, the major contribution to this age effect was seen in the NH group. In the hearing-impaired children, other factors than age might affect the mismatch response. The change from p-MMR to MMN is not only influenced by age but also by stimulus-related factors such as the size of stimulus contrast and the ISI (Ahmmed *et al*., 2008). In young children, small deviants might elicit p-MMRs whereas larger deviants might elicit an adult-like MMN, as shown by Lee *et al.* (2012). Partanen *et al.* (2013b) also found p-MMR to speech stimuli in young children in contrast to MMN in response to other non-verbal stimuli. A child with a HI might perceive many of the sound contrasts in an oddball paradigm as small compared to a NH child, thus producing a p-MMR. The p-MMR seen here may thus reflect immaturity in the auditory system both because of age and hearing impairment.

All HI children in this study have developed spoken language, but with lower phonological processing skills (Nakeva von Mentzer *et al*., 2013), indicating inadequate perception of speech in many situations. Studies in NH children using speech stimuli suggest that p-MMR may predict poorer language scores (Partanen *et al*., 2013b). The lack of correlation between MMR and language variables in our study may indicate that the non-verbal stimuli in the present paradigm are too simple to reveal difficulties in more complex sound processing underlying speech development. Previous studies have also shown that central auditory processing might compensate for deficits in fine structure representation (Anderson *et al*., 2013).

Group effects

The group effect for intensity, with MMN in the HA group and p-MMR in the CI group, indicates differences in how intensity is perceived through a HA compared to a CI. Location showed a significant group effect in TW3 and TW4, as described for LDN below. The waveforms in Fig. 2 indicate group effects for duration, although our results did not reach statistical significance. There were no significant group effects for gap and pitch, thus there was no support for any major between-group differences in discrimination of these small sound contrasts. This difference between stimulus types is hard to explain and need further studies. A paradigm with different levels of contrast between standard and deviant or, once again, more complex verbal stimuli may better disclose deviating auditory processing in the HI group. On the other hand, young children have problems to endure long test sessions and with many deviants the number of accepted epochs per deviant may become low.

The heterogeneity of our study group regarding degree, duration and etiology of HI and various experience with a hearing device, are other possible explanations for the considerable within-group response variability that might obscure group effects.

LDN and late positivity in CI subjects

The negative slopes (LDN) for NH and HA and a weak positivity for CI, is striking in the averages of Fig. 2, but the differences were only statistically significant for the location deviant. Processing of the location of sound is dependent on binaural hearing and may be affected by asymmetry in amplification between the ears (Asp, Mäki-Torkko, Karltorp *et al*., 2012). Some CI children had a CI in one ear and a HA in the other. Others had two CIs with a long interval between implantations. At least one earlier MMN study has shown a late positivity for CIs compared to NH (Zhang *et al*., 2011), and this late positivity was similar for good performers with distinct MMN and poor performers with absent MMN. The significance of LDN in our study is unclear because it does not involve any complex sounds or higher-order processing, but might reflect additional processing of auditory stimuli that occurs when the stimulus is difficult to discriminate (Bishop *et al*., 2011). LDN in infants (Putkinen *et al*., 2012) and in children but not in adults (Liu *et al*., 2014) indicate a maturational process and the LDN might eventually become an important index of auditory learning and development alongside the MMN.

Future directions

Our results show that the multi-feature paradigm using tone stimuli can capture the way hearing-impaired subjects process small sound contrasts through their HA or CI, that is, the very foundation of their acoustic perception capacities. The multi-feature paradigm is reasonably easy for a child to endure and could be developed into a sensitive tool where MMRs could reflect the development in the child′s auditory perception at an earlier age. However, for further studies a multi-feature paradigm including speech sounds may be a better choice for investigating more complex auditory processing in hearing impaired children.

Conflict of interest statement

No conflict of interest is declared, including financial, personal, or other relationships with other people or organizations for any of the authors in this study. All authors have approved the final article.

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Review

Semantic processing in children with Cochlear Implants: A review of current N400 studies and recommendations for future research

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ABSTRACT

Deaf and hard of hearing children with cochlear implants (CI) often display impaired spoken language skills. While a large number of studies investigated brain responses to sounds in this population, relatively few focused on semantic processing. Here we summarize and discuss findings in four studies of the N400, a cortical response that reflects semantic processing, in children with CI. A study with auditory target stimuli found N400 effects at delayed latencies at 12 months after implantation, but at 18 and 24 months after implantation effects had typical latencies. In studies with visual target stimuli N400 effects were larger than or similar to controls in children with CI, despite lower semantic abilities. We propose that in children with CI, the observed large N400 effect reflects a stronger reliance on top-down predictions, relative to bottom-up language processing. Recent behavioral studies of children and adults with CI suggest that top-down processing is a common compensatory strategy, but with distinct limitations such as being effortful. A majority of the studies have small sample sizes ($N < 20$), and only responses to image targets were studied repeatedly in similar paradigms. This precludes strong conclusions. We give suggestions for future research and ways to overcome the scarcity of participants, including extending research to children with conventional hearing aids, an understudied group.

1. Introduction

Hearing loss is one of the most common childhood disorders, affecting 1–3 out of 1000 newborn infants, and many more in some developing countries (World Health Organization, 2010; Neumann et al., 2020). Around 730,000 children around the world are estimated to have severe or profound hearing loss (Stevens et al., 2013) and could benefit from a cochlear implant (CI). Access to CI varies however. High access is reported in Australia and many European countries (De Raeve et al., 2020; Sorkin & Buchman, 2016), and access within countries are often related to household income (Omar et al., 2022). Low access to hearing (re)habilitation is often reported in developing countries (Harris & Dodson, 2017). CI gives deaf people access to sound, but not at the level of an intact human ear (Henkin et al., 2003; Sullivan, 2013). Outcomes of cochlear implantation are diverse (Pisoni et al., 2017) and children with CI lag behind their peers on central measures of spoken language skills such as vocabulary (Lund, 2016; Wang et al., 2021). For children growing up using CI, limitations in sound transmission makes it difficult to extract phonological details, which in turn hampers building of vocabulary, language comprehension and participating fully in spoken communication. Previous research on neural responses in children with CI have focused on responses to sound (Ahmadi et al., 2022; Martin et al., 2008; Näätänen et al., 2017; Peterson et al., 2010; Ponton et al., 2000; Sharma et al., 2015; Vavatzanidis et al., 2015; Vavatzanidis et al., 2016) while higher level processing such as comprehension has not been studied widely (Johnson, 2009). Little is yet known about the cortical processing of semantics in this group, although it may reveal central aspects of their language comprehension. In this review, we summarize and integrate the emerging research literature on the cortical responses of semantic processing among children with CI. Integrating the existing research may contribute to the development of evidence-based intervention designs and pedagogic programs, help understand and mitigate the variability in outcomes following implantation (Pisoni et al., 2017).

The N400 component is observed as a negative peak at around 400 ms after stimulus onset, with a centroparietal topographic maximum

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when words, written or spoken, are used as prime stimuli (Kutas & Federmeier, 2011), and a more frontal distribution when images are used as stimuli (Hamm et al., 2002; Proverbio & Riva, 2009). N400 is modulated by deviations relating to meaning, reflecting *semantic processing*. It was discovered in relation to unexpected, incongruent sentence endings such as "He spread the warm bread with socks" (where "butter" would have been the most expected ending) (Kutas & Hillyard, 1980). Incongruent or unexpected targets result in a large N400 amplitude, while semantically expected targets result in a reduced N400 amplitude. The difference in amplitude between these types of conditions is called the N400 effect. In the present review most experiments use auditory presentation of prime words, followed by image targets of the same word in congruent conditions (i.e. the spoken word "bear" followed by an image of a bear). In incongruent conditions image targets are unrelated to the prime word (i.e. the spoken word "bear" followed by an image of a car). Semantic processing is a broad concept in cognitive neuroscience, encompassing processing of both lexical semantics (i.e., linguistic word meaning), and nonverbal conceptual world-knowledge (i.e. semantic memory; Binder & Fernandino, 2015). In a recent account (Federmeier, 2022) semantic processing of the N400 is conceptualized as *semantic access*, when information about a new stimulus is fused with a broader pre-activated semantic network. While the linguistic concept *lexical access* is understood as an instant event when a word is recognized and its meaning accessed, Federmeier's *semantic access* refers to a fusing over time of new and old information in a distributed network of both linguistic and non-verbal conceptual knowledge (Federmeier, 2022).

N400 effects have been demonstrated in infants as young as 6 months of age (Friedrich & Friederici, 2011) and at 9 months of age (Junge et al., 2012; Parise & Csibra, 2012; Reid et al., 2009). In a review of N400 and other ERP components in infants and toddlers (Morgan et al., 2020), N400 effects, and thus semantic processing was observed at younger ages than ERP components related to grammatical processing. A systematic review of N400 in ages 0–2 years by Junge and colleagues (2021) found a lack of methodological consistency in the literature, precluding the establishment of a clear developmental trajectory of latency and topography of the component in the first 2 years. Some studies found positive correlations between N400 amplitudes and vocabulary sizes, or differences between subgroups related to language proficiency; low proficiency groups did not show N400 effects at all, or did so at later latencies (Junge et al., 2021). A study of N400 in children and young adults found decreasing latencies and amplitudes in ages 5–16 years and the ERP effects stabilized between 17 and 26 years of age (Holcomb et al., 1992). Another study found decreased latency, but not amplitude, between 6 and 10 years of age (Hahne et al., 2004). A study of typically developing (TD) 3–4-year-old children also found effects of semantically incongruent spoken sentence endings in the typical N400 time-window (300–500 ms) with further peaks until 1000 ms (Silva-Pereyra et al., 2005). Importantly, all three studies found N400-like effects of semantic violations in all age groups. In a study of typically developing (TD) preschoolers and preschoolers with specific language impairment (SLI) N400 effects were later, weaker and had less clear topography in children with SLI (Pijnacker et al., 2017). A study comparing groups with relatively high and low IQ within the normal range in TD children at 7 and 8 years of age, found earlier latency N400 effects in the high IQ group but similar amplitudes in both groups (Hampton Wray & Weber-Fox, 2013). Studies of children in preschool ages or older have demonstrated N400 effects at all ages, sometimes with later latencies of the effects in younger or disadvantaged children.

A long-standing discussion in the literature on the N400 component relates to what extent it reflects *predictive processing* (Kutas & Federmeier, 2011). There are results indicating that the N400 is more predictive in left hemisphere processing compared to right hemisphere processing (Federmeier & Kutas, 1999), and that the N400 reflects more predictive processing in young compared to old adults (Wlotko et al., 2010). In a recent paper (Broderick et al., 2021), young adult participants (mean age 27 years) displayed large N400 effects based on pre-activated semantic features of predicted words, whereas older participant's (mean age 64 years) N400 effects were smaller and based on word probability rather than semantic features.

Relatedness effects, where N400 amplitudes are reduced in response to mismatching but semantically related targets, were also linked to predictive processing in paradigms with long duration between prime and target (Brothers et al., 2015; Federmeier & Kutas, 1999; Lau, 2013; Wlotko et al., 2010). The reduction in N400 amplitude is thought to be mediated by activation of overlapping semantic features in prime and target, and require prime concepts to be actively kept online until target presentation. Top-down processing has also been directly manipulated. Larger N400 effects were shown in conditions where predictions were encouraged (Lau et al., 2013). Early cortical responses to semantic incongruence, prior to the N400, has been related to prediction, as it may reflect responses to deviations from very specific expectations (Bornkessel-Schlesewsky et al., 2016; Brothers et al., 2015; Lau et al., 2013). Responses in various N400 paradigms may thus reflect predictive processes in general, but also the level of detail of active predictions, such as conceptual detail or expectations of a specific word.

2. Spoken language knowledge in children listening through CI

Limitations in hearing through a CI can be better understood when understanding the technology. A CI consist of two parts. An external part with a microphone, a sound processor and an electromagnetic transmitting coil, and an internal part, the implant, with a receiving coil and a stimulator under the skin, and an electrode array in the cochlea (Wolfe et al., 2014). The external part signals to and powers the implant with radio frequency (RF) signals through electromagnetic induction. The sound processor enhances the speech signal and reduces background noise, and decompose the sound to frequency bands based on the number of electrodes in the array. High frequency band activity is sent to basal electrodes, and low frequency bands to more apical electrodes, following the tonotopic organization of the cochlea. Sound processing depends on stimulation strategy: a common stimulation strategy, Continuous Interleaved Sampling (CIS), represents the envelope of each frequency band by matching stimulation amplitude to the energy present in each frequency band, while stimulation rate is fixed (Wolfe et al., 2014). Other strategies are Spectral Peak (SPEAK) and Advanced Combination Encoder (ACE) that select frequency bands for stimulation based on amplitude. Despite differences, the strategies have similar performance (Wolfe et al., 2014). In typical devices, the array has 12–22 electrodes. In comparison, a typically hearing child has 15,000–18,000 hair cells with different roles in receiving and transmitting the sound signal from the basilar membrane to the cochlear nerve (Madell & Flexer, 2008). As expected, spectro-temporal resolution is limited listening through a CI (Jahn et al., 2022; Moore, 2008; Nittrouer et al., 2012) making for example discrimination of speech sounds such as consonants in clusters more difficult for children with CI compared to those with typical hearing (TH) (Nakeva von Mentzer, 2014). For a child depending on CI to learn language, this limitation can be conceptualized as impoverished phonological processing. Studies have shown that segmental phonological properties (vowels and consonants) are particularly challenging compared to suprasegmental phonological properties (stress and intonation of speech) (Nakeva von Mentzer, 2014). Learning phonology is an essential factor for vocabulary development (Dillon et al., 2012; Ramus & Szenkovits, 2008; Stoel-Gammon, 2011) and as mentioned, children with CI have smaller expressive and receptive vocabularies than peers with TH (Lund, 2016; Wang et al., 2021). Reading seems to have a positive influence on phonological awareness in children with CI, based on a cross-lagged analysis where reading skills predicted later phonological awareness, but phonological awareness did not predict later reading skills (Nittrouer et al., 2018). Overall, phonological development for children with CI during elementary school lag behind that of children with TH (Nittrouer et al., 2018). When learning to read, children with TH use phonology and semantic knowledge as largely independent skills (Nittrouer, 2020). This reflects a basic structure of language called "duality of patterning": Meaningful semantic units of words and morphemes are patterned separately from their building blocks of meaningless phonemic elements, i.e. speech sounds. Children with CI however, have difficulties in using phonology independently. The result is a reading skill where phonology and semantics are less differentiated, that fails to capitalize on the dual structure of language (Nittrouer, 2020). A recent N400 study of adults reading sentences, with semantic or grammatical deviations, compared adults who were deaf to adults with TH (Mehravari et al., 2017). N400 amplitudes were similar between groups. However, the best deaf readers had the largest N400 amplitudes of all participants, while the best TH readers had the largest P600 responses. This was interpreted as a successful reliance on semantics among the best deaf readers, a successful but different strategy from the one used by best TH readers.

Duration of auditory deprivation, i.e., the period when the child has an untreated hearing loss, is a critical factor for spoken language development. There is a large bulk of research findings acknowledging the negative effects of auditory deprivation on spoken language processing, both in early studies in the prelingually deaf population who received CI as adults (Nishimura et al., 1999) and in more recent studies of DHH children who received CI or HA in childhood (Karltorp et al., 2020; Persson et al., 2022; Sharma et al., 2002; Sharma et al., 2005). What these studies tell us is that early detection, early fitting and full-time use of technical hearing devices are positively associated on both receptive and expressive spoken language skills in deaf and hard of hearing (DHH) children. Furthermore, verbal short-term memory (STM) and working memory (WM) were found to predict language development in children with CI (Kronenberger et al., 2013). A recent study (Pisoni & Kronenberger, 2021) used an anomalous sentence task to identify prelingually deaf children with CI and children with TH that performed on the same level on word recognition in this task, and then compared the two groups in various other tests. The best performing children with CI and the worst performing children with TH performed at the same level, however within these groups the children with CI had higher nonverbal fluid intelligence, and nominally higher executive functions (EF), but lower rapid phonological coding compared to the children with TH. Based on these differences the authors suggest that the two groups solved the word recognition task in different ways. In the anomalous sentence task, semantically nonsensical sentences with correct grammar and word order, such as *Crackers reach gray and rude in the paint*, are used to block word identification based on semantic context. Target words have to be decoded by actively engaging with bottom-up processing of sensory evidence. The children with TH managed the task using rapid phonological coding skills, as evidenced by better non-word repetition scores, while children with CI that successfully processed anomalous sentences engaged in slow, effortful processing, inhibiting automatic processing and maintaining incompletely understood words in memory to fill in and restore gaps in bottom-up processing (Pisoni & Kronenberger, 2021).

There is, to our knowledge, no review of the empirical research regarding N400 effects in children with CI. Our present work aims at summarizing this literature and drawing general conclusions based on published results.

3. Method

We reviewed the emerging research literature on the cortical responses of comprehension processing among children with CI. Inclusion criteria were studies of children with CI that reported results from the N400 component to investigate semantic processing. We also searched for semantic processing studies of children with CI using other ERP components or fMRI, but none of the results of this search were considered relevant, so we did not expand our inclusion criteria to include other neural responses than the N400. All searches were made at the pubmed.gov on the same day (March 1, 2022). The searches are summarized in Table 1. The search terms "CI"/ "Cochlear implant" and "N400" generated few matches but identified five hits that met the inclusion criteria. Two wider searches "child cochlear implant ERP" and "child cochlear implant ERP comprehension" generated very few hits.

Six studies met the inclusion criteria. Of these six, one was a case study (Key et al., 2010) that was omitted from further review, though it may have historical interest as the first N400 recording in a child with CI. A second study (Munivrana Dervišbegović & Mildner, 2020) was omitted due to methodological problems: The N400 effect is not clearly identified and described, and the oddball design used is not suitable for comparison with other studies. The remaining four studies are summarized in Table 2. We first present studies with image targets. These studies are rather homogenous in terms of experimental paradigms and provide accumulated evidence regarding N400 in children with CI. Some detailed results are compared in thematic sections. In the second section, a study that use auditory targets is presented. In all our summaries, the experimental paradigm is described first, together with participant information and main results. Results are then interpreted in relation to the authors' predictions and proposed explanations. Finally, more detailed results and general notes are presented.

4. Results

4.1. Studies with image targets

The three studies with image targets all use auditory or audiovisual (video) word primes followed by an image target at a relatively long stimulus onset asynchrony (SOA): 2300 ms (Kallioinen et al., 2016), 1000 ms (Bell et al., 2019a), and 1430 ms (Pierotti et al., 2021). A SOA of a second or more makes automatic priming unlikely, as studies of automatic priming typically use 200–250 ms SOA (Heyman et al., 2016; Neely, 1976). All studies describe the lexicon used in the experiment as high frequency words that have a high likelihood to be known by all participants. The three studies all have in common a semantically congruent condition where the word prime is exactly matched by the image, and an unrelated incongruent condition where target and prime have no semantic relation. The difference between ERP amplitude in the congruent and incongruent conditions in the relevant time window constitutes the N400 effect. In one of the studies (Kallioinen et al., 2016) an additional condition is also used where incongruent images are

Table 1
PubMed article search summary.

Search terms	N, matching search terms	N, matching inclusion criteria	Articles matching criteria[1]	Method of identification[2]
CI N400	13	5	2, 3, 4, 5, 6	1
Cochlear implant N400	7	5	2, 3, 4, 5, 6	1
Deaf and hard of hearing child N400	4	2	2, 3	1
Child cochlear implant ERP	473	2	1, 3	2
Child cochlear implant ERP comprehension	27	2	2, 4	2
fMRI cochlear implant semantic	4	0	-	1

[1] *Key to article abbreviations. 1:* Key et al., 2010. *2:* Kallioinen et al., 2016. *3:* Vavatzanidis et al., 2018. *4:* Bell et al., 2019a. *5:* Munivrana Dervišbegović & Mildner, 2020. *6:* Pierotti et al., 2021

[2] Method of identification. 1: Abstracts and full text were read to verify inclusion criteria. 2: Abstracts and full text were read to verify inclusion criteria when semantic or cognitive processing was indicated in the title.

Table 2
Overview of N400 studies of children with Cochlear Implants.

Study, description	n, CI	n, Bil. CI	n, TH	Age, yr. (range)	CI use, yr.	First implant, months	Selected behavioral testing	Stimuli	N400 effect results
Studies with image targets Kallioinen et al., 2016 Incongruence and relatedness effects tested before and after phonics intervention	15	9	12[1]	CI: 6.3 TH: 6.8 (5–7)	4.7	19	TH better than CI in lexical access (auditory sentence completion test)	Auditory word prime - Image target	Amplitude: CI>TH CI: Early latency effect and semantic relatedness effect
Bell et al., 2019a Incongruence effects tested with children with CI in mainstream schools	12	10	30	CI: 8.1 TH: 7.7 (6–9)	6.1	24	TH better than CI at closed set word comprehension test (PPVT) and sentence comprehension (concepts and instructions), but not spoken paragraph comprehension	Auditory word prime - Image target	Amplitude: CI=TH
Pierotti et al., 2021 Incongruence effects tested with audiovisual prime	29	23	19	CI: 6.7 TH: 6.2 (2–10)	4.6	27	TH better than CI at closed set word comprehension test (ROWPVT)	Audiovisual (video) word prime - Image target	Amplitude: CI>TH. CI: Early latency effect
Study with auditory target Vavatzanidis et al., 2018 Incongruence effects in developmental study of children with CI at 12, 18 and 24 months after implantation	32	32	-	2.7[2] (1–5)	-	21	Spoken word comprehension, spoken word production, spoken sentence comprehension, spoken sentence production (SETK-2). Comprehension groups[3]: Low, Norm, High	Image prime - Auditory word target	Effect at 900–1300 ms (after 12 months) and 500–700 ms (after 18 and 24 months) for the whole group. Group effects in norm- and high- but not low-comprehenders

[1] 15 children with HA also participated, mean age 6.3(5–7).

[2] Age at first ERP recording.

[3] Low - two subtests below norm, High - two subtests above the norm, otherwise Norm.

semantically related to the prime. In the following, each of the four studies are described in chronological order:

Kallioinen et al. (2016) used congruent and unrelated incongruent image targets and an additional condition of incongruent but semantically related image targets. The semantically related incongruent images were from the same category as the auditory prime (i.e., animals, vehicles etc.). An example of the semantically related condition is the auditory prime *"anka"*, Swedish for duck, followed by an image of an owl, both belonging to the bird category. An example from the unrelated, incongruent condition is the prime *"apa"*, Swedish for monkey or ape, followed by an image of a hat. Two N400 effects were obtained, an unrelated incongruence effect and a semantically related effect. Among participating children with CI (n = 15) 9 had bilateral implants, 6 combined one CI with HA, two used Swedish sign language at home, and two used signed support for their spoken Swedish. Also participating were children with hearing aids (HA; n = 15) and children with TH (n = 12). They were all within the normal span of Raven's test with colored matrices, and did not have known disabilities affecting language development besides HL. The unrelated incongruence N400 effect appeared earlier and was larger in children with CI (350–500 ms), and appeared later and was smaller for children with TH (400–500 ms) and in children with HA (400–450 ms). The semantically related incongruence effect was peaking later for children with TH (400–650 ms) and children with HA (450–550 ms) compared to children with CI (350–450 ms). The amplitudes of the two N400 effects differed in children with CI with larger effect in the unrelated condition, and smaller effect of the related condition, while children with TH and children with HA had similar amplitudes in the two N400 effects. The authors argue that children with TH and children with HA adapt to the low proportion of congruent targets (1/3) by being less predictive, while children with CI keep using a more predictive mode that is adaptive in typical communication situations, perhaps encouraged by mistaking some semantically related images for congruent images. The N400 effect was hypothesized to increase after phonics training that was part of the study (Nakeva von Mentzer et al., 2013; Nakeva von Mentzer et al., 2014). There was, however, no increase of the N400 effect after training, and contrary to the hypothesis, N400 effects were larger in children with CI compared to children with TH, and smallest in children with HA. For the children with CI, but not for children with TH or children with HA, the unrelated incongruence effect started early, already at 200–250 ms. A phonological composite measure and a measure of lexical access were both negatively correlated to the N400 effect for semantically related targets. The effect was weak but statistically significant. Age and a reading composite measure was not correlated with any N400 effect.

Bell and colleagues (2019a) used congruent and incongruent images, and found similar N400 effects for children with CI (n = 12) and TH controls (n = 30). Among children with CI, 10 had bilateral CI, two had CI and HA, and none had diagnosed developmental disorders or intellectual disabilities. All participants in Bell and colleagues (2019a) communicated only through spoken English, and attended mainstream schooling (for hearing). This inclusion criteria is in contrast to Kallioinen and colleagues (2016) and Pierotti and colleagues (2021) where some participants used sign language or sign support to their spoken language. The authors hypothesized that children with CI would have a smaller N400 effect compared to controls and N400 effect size or latency would correlate with spoken language skills among children with CI. Inspection of grand averages revealed effects in the group of children with CI that were somewhat larger than in the control group, more positive response to congruent targets and negative response to incongruent targets, but there was no difference in the statistical analysis. N400 effect amplitude and latency was weakly correlated with comprehension measures at word-sentence- and passage-level, and also reading measures word reading and reading comprehension, but no significant correlations were found. Children with TH scored significantly higher on word- and sentence-level comprehension, but there was no significant difference between the groups in passage-level comprehension.

Pierotti et al. (2021) used audiovisual primes and image targets, and compared responses to congruent and incongruent images and found larger N400 effects for children with CI (n = 29) compared to controls (n = 19). The main difference compared to previous studies is the use of video primes where both auditory signals of speech and lipreading signals (visemes) are provided, instead of only sound. Pierotti et al. (2021) also had more participating children using CI than the previous three studies taken together (see Table 2). Among participating children with

CI, 23 had bilateral CI, 6 unilateral, 7 had experience with American Sign Language (ASL). The authors hypothesized that strategic or attentional differences between children with CI and controls would lead to differences in both the N400 effect and at earlier latencies. As hypothesized, the N400 effect was preceded by an effect of congruency in the P2 time window that was larger for children with CI compared to controls. There is a large age span in this study, 2–10 years, however only one participant is younger than 4 years. In the CI group the P2 effect was related to chronological age and time with CI. The N400 effect did not have significant correlations with age, time with CI, age of implantation or vocabulary.

4.2. Early latency incongruence effects

In the studies with image targets, there is some evidence for earlier ERP responses, before the N400 peak, in semantic incongruence conditions among children with CI compared to controls. We summarize those effects here. Visual inspection of the ERPs shows that in all studies the peak of the N400 wave is similar between children with CI and controls. N400 peaks in Kallioinen et al. (2016) and Bell et al. (2019a) are between 350 and 400 ms, and in Pierotti et al. (2021) somewhat later, around 400 ms. Grand average ERPs in all studies show larger differences between congruent and incongruent conditions before the N400 time window in children with CI compared to controls. This effect was tested with consecutive t-tests in Kallioinen et al. (2016) and was present from 200 ms for children with CI, while for controls the effect did not start until 400 ms. Pierotti et al. (2021) analyzed P2 amplitudes between 175 and 275 ms, and found a main effect of condition, and an interaction of condition with group, reflecting more negative amplitudes in the unrelated condition among children with CI compared to controls. Bell et al. (2019b) did not analyze time windows before the N400, but visual inspection of the ERP averages shows somewhat larger differences between conditions in children with CI compared to controls at the second negative peak around 200 ms (see Fig. 1). The effect of the semantically related incongruence in Kallioinen et al. (2016) was later for controls and extended to 650 ms in this group, later than any significant effects for children with CI or children with HA. Early semantic effects among children with CI could reflect stronger expectations i.e. prediction as hypothesized by Pierotti and colleagues (2021).

4.3. A study with auditory targets

One of the studies used auditory targets. Vavatzanidis and colleagues (2018) studied 32 children longitudinally at three intervals 12, 18 and 24 months after activation of their CI with 20–22 recordings obtained at each interval. Ages were from 21 to 65 months, all had bilateral CI. Among them were 6 children from signing families that were divided evenly between the three performance groups. In this study an image prime was followed by a spoken target word that was either congruent with the prime or an unrelated incongruent target. When analyzing all participants as a group a late congruency effect (900–1300 ms) was found at 12 months, and effects at typical N400 latencies (300–700 ms) were found at 18 and 24 months. Participants were divided into three groups, low, norm, and high performance, based on a spoken language test conducted at 24 months: The low performance group had no incongruence effect at all while norm and high-performance groups together had effects at 12 months (300–1300 ms) including typical N400 latencies. Effects at 18 months were at 300–500 ms and at 24 months at 300–900 ms. Norm performers and high performers as separate groups were small (n = 8 each), and the results at 12 months were only significant for norm performers at late latencies (900–1300 ms). There were no significant effects at 18 months, and effects for high performers were only significant at 24 months (300–900 ms). Furthermore, in the subgroup congenitally deaf, only norm performers had

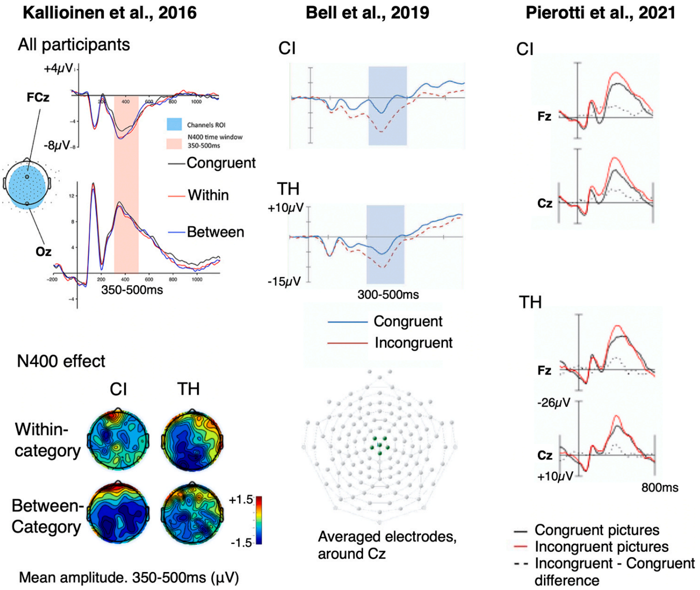

Fig. 1. Studies with image targets. Kallioinen et al. (2016): Grand average, all participants (positive polarity up), and topographic maps with related ("Within-category") and unrelated ("Between-category") N400 effects. Bell et al. (2019a): N400 at Cz and adjacent electrodes (positive polarity up). Pierotti et al. (2021): N400 at Fz and Cz (positive polarity down).

effects at 12 months (900–1100), and only high performers at 24 months (300–700 ms). These effects are seen as similar to effects in other participant groups by the authors, and they contradict the authors hypothesis that congenitally deaf would have slower semantic development. N400 effects at 12 months of hearing age, found among high and norm performers, also among congenitally deaf, is interpreted as evidence for faster learning compared to typically hearing children, probably due to more mature cognition at a higher chronological age. Fig. 2 shows responses and time windows with significant N400 effects for all participants together, and separately for low, norm and high performers. The N400 effect amplitude was not correlated to language performance or age of implantation. Seven of the nine participants in the low performance group developed additional cognitive or language impairments after inclusion in the study (general developmental delays, low non-verbal ability or language specific delays). One of the two participants without additional impairments was implanted relatively late at 39 months of age. No additional impairments were developed in the norm and high-performance groups during the time of the study.

5. Discussion

5.1. Image N400 effects and semantic top-down processing

The present systematic literature review indicates that, in contrast to a recurring hypothesis (i.e. in Kallioinen et al., 2016, Bell et al., 2019a, and Pierotti et al., 2021), lower semantic skills among children with CI compared to children with TH are not reflected in lower amplitudes of N400 effects. Instead, two studies show the largest N400 effects in children with CI (Kallioinen et al., 2016; Pierotti et al., 2021) and others show similar amplitudes as in children with TH (Bell et al., 2019a).

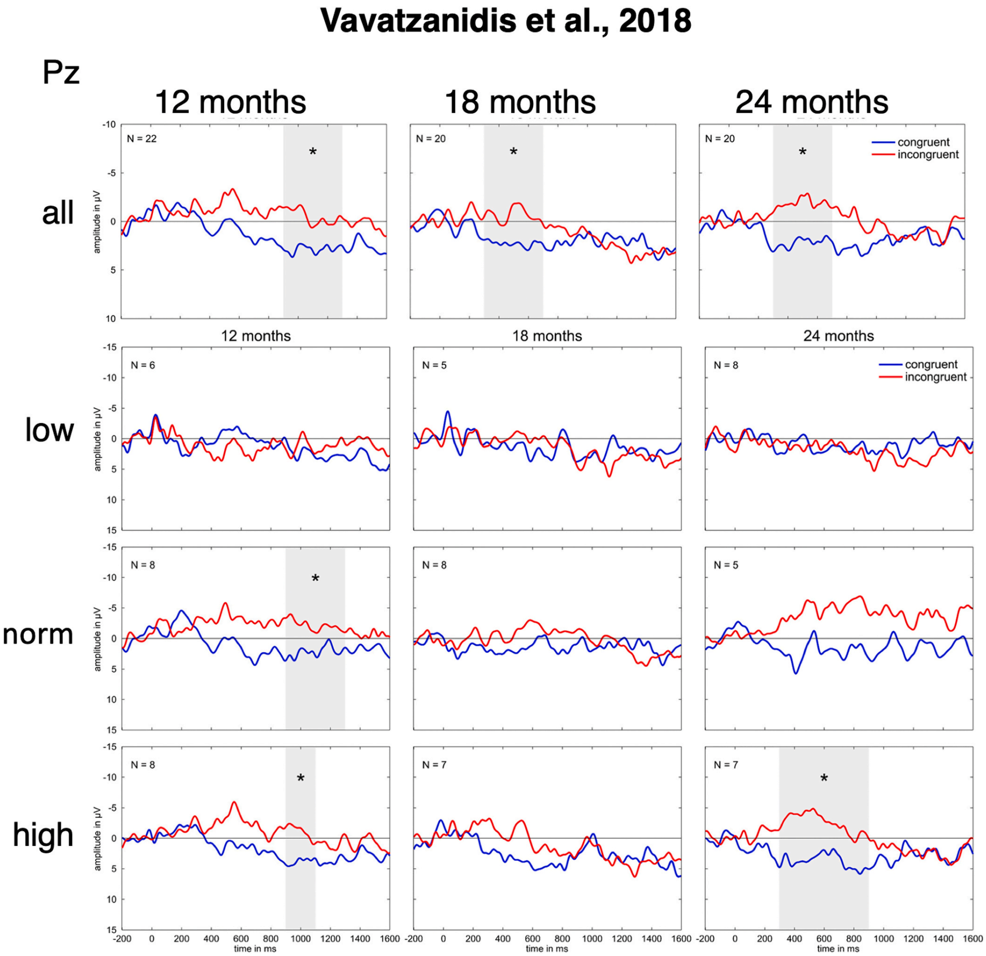

Fig. 2. Auditory targets. Vavatzanidis et al. (2018): N400 responses at Pz at 12, 18 and 24 months after implant (positive polarity down). Grand average, all participants (top row). Group averages for low, norm and high comprehenders (following rows).

While based on only two positive findings, this unexpected result is intriguing. In many other patient populations with various challenges in semantic processing, as in schizophrenia, temporal lobe epilepsy, ALS and young children with SLI, the N400 effect is indeed smaller compared to healthy controls (Jaimes-Bautista et al., 2015; Joyal et al., 2020; Kiang and Gerritsen, 2019; Royle & Courteau, 2014). These N400 effects in children with CI are not explained by their semantic skills, but rather by underlying processing characteristics.

We suggest, as previously hypothesized (Kallioinen et al., 2016; Pierotti et al., 2021), that children with CI may adopt a predictive processing mode when processing speech, tipping the balance from bottom-up processing toward relatively more top-down processing compared to children with TH, and that this processing mode is reflected in unexpectedly large N400 effects. It is notable that N400 effects are diminished in healthy aging, without any decline in semantic competence, due to a less predictive processing mode compared to young adults (Wlotko et al. 2010; Joyal et al., 2020). Recent behavioral studies have described successful semantic processing among children and adults with CI as an effortful top-down processing dependent on EF skills, while language comprehension in listeners with TH is more automatic, bottom-up and based on phonology (Pisoni & Kronenberger, 2021; Winn, 2016; Dimitrijivic et al., 2019; Dingemanse and Goedegebure 2019; Moberly & Reed, 2019; Moberly, 2020; O'Neill et al., 2019; Zaltz et al., 2020). Experimentally induced focus on top-down processing has been related to larger N400 effects (Lau et al., 2013) in TH populations. Some results specific to children with CI, including early incongruence effects (Kallioinen et al., 2016; Pierotti et al., 2021) and a graded N400 effect of relatedness (Kallioinen et al., 2016) also indicate a more predictive processing in this group as they are thought to reflect specific perceptual expectations (Bornkessel-Schlesewsky et al., 2016; Brothers et al., 2015; Federmeier & Kutas, 1999; Franklin et al., 2007; Kiang et al., 2013; Lau et al., 2013; Wlotko et al., 2010). Together, we believe that these results strengthen the case that increased top-down semantic processing can result in unexpectedly large N400 effects among children with CI under some conditions. More studies are needed to establish that large N400 effects are recurrent or even typical of the population of children with CI, and to map under which conditions they may occur. Further N400 studies with direct experimental manipulation of top-down processing are needed to investigate the effects of processing mode on N400 outcomes.

If compensatory top-down processing effects on N400 was a general phenomenon, we should find similar effects in other studies using degraded speech. N400 amplitude in listening to degraded speech, tested in populations with TH, has sometimes been smaller compared to less degraded speech (Aydelott et al., 2006; Obleser & Kotz, 2011), and sometimes larger (Devaraju et al., 2021; Drijvers and Özyürek 2018). One study measured processing effort using pupillometry and found that while degraded speech in general led to smaller N400 effects, increased effort as measured by pupil size recovered the N400 effect in semantically constrained sentences (Silcox & Payne, 2021). These heterogenous results indicate that N400 responses to degraded speech are highly dependent on experimental context and degree of degradation and also point to a specific link between effort, use of semantic context and N400.

Several recent studies find that top-down processing in adults with CI is related to effort (Dimitrijevic et al., 2019; Dingemanse and Goedegebure, 2019; Winn, 2016), and to EF variables including WM (Moberly & Reed, 2019; Moberly, 2020; O'Neill et al., 2019; Zaltz et al., 2020). Participants with CI in these studies are predominantly post-lingually deafened, with the exception of one study of older children and young adults where a majority was pre-lingually deafened (Zaltz et al., 2020). While sharing the same type of technical hearing device, pre- and post-lingually deafened persons represent very different populations. Most post-lingually implanted adults have used hearing to develop spoken language. Thus, they have built up a long-term memory store of phonological representation based on natural speech acoustics that they, when receiving the stimulation of the speech signal of the cochlear implant as adults, have the possibility to bring to life. Growing up listening and acquiring spoken language through a cochlear implant is a much different situation. Here, the modification and amplification of the inner ear's is not possible since the electrodes of the CI are placed here, replacing their function and stimulate the auditory nerve directly. This means that pre-lingually deaf children with CI have built their phonological representations (which are based on a number of distinctive features as voice, place and manner of articulation) on an impoverished signal both related to temporal and spectral resolution. Indications of semantic top-down processing as a compensatory processing mode in both adults and children with CI, despite the differences between these populations, and also in TH populations under degraded sound conditions (O'Neill et al., 2021) could indicate that compensatory top-down processing is a general phenomenon under adverse hearing conditions.

Semantic top-down processing is not a panacea. Old people with hearing loss do use contextual cues more than young people with TH, but they also make more perceptual errors ("false hearing". Lesicko & Llano, 2017). The presence of semantic top-down strategies does not mean that this strategy can fully compensate for hearing deficits as semantic cues are not always present. Language use is economical (Jaeger, 2010), and speakers do not insert a lot of semantic cues in their communication unless they understand that this is needed. As a compensatory strategy, top-down semantic processing is limited by the extent of semantic cues available, by sound quality and by EF capacity of the listener.

5.2. N400 effects and cross-modal processing

Larger N400 effects for persons with CI compared to persons with TH have only been demonstrated in the visual modality, in studies with children using image targets (Kallioinen et al., 2016; Pierotti et al., 2021). Large N400 was also found among deaf adults in a study of reading in adults, where the best deaf readers had the largest N400 while the best readers with TH had the largest P600 (Mehravari et al., 2017). Differences in visual or cross-modal auditory and visual processing among persons with CI is therefore a possible alternative explanation to the large N400 effects reviewed. Children with CI could integrate speech with visual stimuli differently than children with TH through experience or attentive factors. Deaf individuals have advantages in some visual tasks, especially in peripheral vision (Alencar et al., 2019), that does not imply however, that deaf persons are superior in general visual tasks (Marschark et al., 2015). There is evidence that post-lingually deafened adults with CI have much stronger visual influence on the McGurk-effect, a type of experiment where sound and lip formation suggest different vowels simultaneously, compared to TH listeners (Rouger et al., 2008), and also evidence that cross-modal EEG activation related to the McGurk effect is related to audio-visual integration (Stropahl & Debener, 2017). Experience with signs or sign language as some of the participants in the studies of Kallioinen et al. (2016) and Pierotti et al. (2021) could influence how the visual modality is integrated in language processing. Differences between children with CI and children with TH in terms of cross-modal processing could depend on a more specific cross-modal reorganization of cortex in children with CI. Lack of auditory input could reorganize the auditory cortex making it more responsive to visual stimuli (see Campbell & Sharma, 2016). Cross-modal reorganization has been viewed as primarily maladaptive (Campbell & Sharma, 2016) and have been used to argue against visual communication methods, such as sign language, with children with CI (Giraud & Lee, 2007). However, the presence of maladaptive cortical reorganization in children with CI has been contested (Corina et al., 2017; Heimler et al., 2014) and adaptive effects have been demonstrated (Anderson et al., 2017; Mushtaq et al., 2020; Paul et al., 2022. See also Wallace, 2017 for a theoretical perspective). A recent review of the evidence conclude that cross-modal reorganization effects are limited and flexible, and not responsible for closing critical periods of auditory development in deafness (Kral & Sharma, 2023). Previous clinical recommendations to avoid cross-modal communication in (re)habilitation for children with CI may need to be revised. Cross-modal processing as an alternative hypothesis for large N400 effects in children with CI (Kallioinen et al., 2016; Pierotti et al., 2021) is based on the present lack of similar effects in studies with auditory targets.

5.3. Auditory N400 latency

The study with auditory targets both found longer N400 latencies and small or even no N400 effect for the group with weak CI outcomes. N400 effects at long latency effects were observed in children that received their implant recently (Vavatzanidis et al., 2018). The results from Vavatzanidis and colleagues (2018), suggest a development towards earlier latencies with longer CI use that can be compared to TH children of the same hearing age, or even faster. Toddlers with TH have N400 effects at similar latencies (700–1400 ms) at an age of 19 months (Friedrich & Friederici, 2004). The results (Vavatzanidis et al., 2018) suggest typical latencies of N400 effects for children with CI who have language outcomes in the norm or higher range after 2 years with implant. There are studies of postlingually deafened adults with CI with N400 at delayed latencies of about 100 ms (Hahne et al., 2012; Finke et al., 2016). In sum, the present data does not provide strong evidence about what N400 latencies could be considered typical in response to auditory target words in children with CI, but they do show that long latency N400 effects exist close to implantation. There is a relative lack of studies with auditory target stimuli.

5.4. Lack of N400 effects

In the present review, N400 effects at group level are found in studies encompassing in total 79 children with CI: all CI participants in Table 2 except the low performance group ($n = 9$) in Vavatzanidis and colleagues (2018). The complete lack of incongruence effects in the low language performance group in Vavatzanidis and colleagues (2018) is likely related to cognitive and language impairments found among most of the children in this group in combination with their young age.

5.5. Small studies and heterogeneity of the population

The present literature on semantic processing of children with CI is small, in number of studies and in number of participants, and describe a heterogenous population. The conclusions made are therefore tentative. The conclusion that N400 effects can be elicited in children with CI that do not have other impairments besides HL is based on similarities between the few studies existing and the literature on children with TH. It could be argued that the conclusion has high prior probability, given that N400 effects are found from early ages (Morgan et al., 2020, Junge et al., 2021) and also among children with language difficulties (Pijnacker et al., 2017). Semantic top-down processing and cross-modal processing are both suggestions that could explain the present data, but it is too early to draw firm conclusions.

Small sample sizes are especially problematic in relation to the heterogeneity of the population along many dimensions: hearing, language background, implantation, and also impairments besides HL. Hearing conditions are very different in bilateral CI compared to CI with contralateral HA (bimodal hearing). In the latter group, the phonological representations may be partly based on natural speech acoustics which could be advantageous in some cases. None of the studies with image targets presented separate data for children with unilateral and bilateral CI (Bell et al., 2019a; Kallioinen et al., 2016; Pierotti et al., 2021). Children with congenital deafness, with no experience of sound except through CI is another group of special interest that was not separately presented in these studies. In Vavatzanidis et al. (2018) all participants had bilateral CI and congenitally deaf children were presented separately. Congenitally deaf children with CI had overall similar responses to other children with CI in this study, in contrast to the complete lack of N400 effects in the low performing group. Two of the 19 congenitally deaf children in this study came from signing families, a further aspect of heterogeneity in the population. In total, 6 children from signing families were included in the study to increase numbers in subgroups and because they were distributed equally in the three performance-based subgroups. Signing children, or children using sign support for spoken Swedish constituted nearly a third of participants with CI in Kallioinen et al. (2016) and a fourth of the children in Pierotti et al. (2021) had exposure to American Sign Language (ASL). Participants Bell et al. (2019a) only used spoken communication. Age, implant age and types of implant are further sources of heterogeneity. Bell et al. (2019b) did not find larger N400 effect in children with CI compared to children with TH, but differ from studies that did find such an effect (Kallioinen et al., 2016; Pierotti et al., 2021) in both inclusion of signers, mean age of the participants, and number of participants. By presenting individual results (perhaps as supplementary data), a better comparison between studies would have been possible despite differences in populations.

Considering Vavatzanidis et al. (2018) results, the present studies reviewed might still not reflect the total heterogeneity among children with CI. All studies had inclusion criteria that exclude children with impairments besides HL. Despite this criterium, and because participants were too young to be evaluated fully, seven of nine in the low performance group in Vavatzanidis et al. (2018) were diagnosed with further impairments during the study. The division into subgroups based on language performance, that include children with other impairments besides HL led to the finding that some children with CI completely lack N400 effects, arguably one of the most important results in the present literature. As the large heterogeneity among children with CI is central in descriptions of this population, one could consider embracing heterogeneity of participants, relaxing inclusion criteria in further studies but present results of subgroups and, if possible, make individual data available. An aggregated analysis, based on shared data or joint publications, might be the only feasible way to collect a large enough sample for investigations of subgroups, important predictors and distributional results that are lacking in the existing literature.

5.6. Recommendation for future research

Top-down semantic processing, we have argued, is the most likely cause of N400 effects among children with CI that are large relative to controls. However, studies that directly manipulate prediction strategies are needed, as they could clarify if there is a causal influence of semantic top-down prediction on N400 amplitudes among children with CI, as well as differences compared to children with TH, and other characteristics of this strategy. Effort and dependence on WM and other EF abilities should be studied in relation to top-down processing. Experimental studies that both control top-down processing, and investigate ways of making it more successful, thereby providing useful tools for future intervention studies, could be the most valuable type.

We conclude that there is a lack of N400 studies with auditory target stimuli. The choice of image target stimuli (and auditory primes) may initially have been a good methodological choice, to pinpoint semantic processing, avoiding CI sound artifacts in the ERP and variability related to hearing loss. However, using image targets means avoiding the modality that is most problematic in this population, and by extension most important to understand. Experiments using similar designs and participant ages as the studies reviewed with image targets (Kallioinen et al., 2016; Bell et al., 2019a; Pierotti et al., 2021) but with an additional auditory target condition would allow direct comparisons of cross-modal and unimodal auditory processing while building on earlier results.

In research on cortical reorganization, electrophysiological measures are used to detect cross-modal responses, and relate them to maladaptive or adaptive outcomes in language comprehension tasks. By combining such paradigms with N400 paradigms in the same recording session, or by studying cross-modal effects within modified N400 paradigms using meaningful stimuli, such studies could evaluate cross-modal responses effects in higher-level semantic processing directly, avoiding some problems with earlier studies of cross-modal reorganization that focus on the most basic perceptual components (Corina et al., 2017).

More naturalistic speech stimuli such as sentences, everyday conversations, or stories have not been studied with electrophysiology among children with CI, despite becoming more common and feasible in neuro-cognitive studies in general (Alday, 2019). Studying N400 responses to naturalistic spoken material with lots of semantic cues for prediction compared with speech lacking those cues could give a more ecologically valid overview of semantic processing as well as details about how cues are integrated as sentences unfold. Paragraph comprehension is often better than single word comprehension in children with CI (see for instance Bell et al., 2019a and Bell et al., 2019b).

Compensatory top-down processing in difficult listening situations could be studied in other populations than children with CI. Some results in studies of adults with CI indicate that the benefit from this strategy decline rapidly with added auditory noise (Patro & Mendel, 2020). The scope of useful compensatory top-down processing could be investigated in broader populations such as adults with CI, children and adults with HA or persons with TH if auditory challenges are manipulated experimentally (similar to O'Neill et al., 2019; O'Neill et al., 2021; Patro & Mendel, 2020). The present N400 results come from experiments that likely have been optimized for participating children with CI. In the one study that include children with HA (Kallioinen et al., 2016), we suspect that hearing conditions were not good enough for children with HA based on their small responses to auditory stimuli in an MMN study with the same participants (Uhlén et al., 2017). Children with HA are likely understudied. To the best of our knowledge there are no N400 studies in this population except Kallioinen et al. (2016) despite being a larger population than children with CI. We do not have strong reasons to believe that top-down processing as compensation for less clear auditory input would be unique for children with CI, rather we think that optimal conditions could vary between groups depending on hearing situation, language material, and cognitive resources. Therefore, studies of broader populations could be informative.

For more studies in the specific population children with CI, we would like to advise researchers to consider adding simple N400 studies to other electrophysiological studies that are already conducted within the population. N400 paradigms can provide both a fast and fun assessment when using active responses from participants.

Given the scarcity of studies and participants, and the heterogeneity of the population, individual data should be presented or shared if possible. As mentioned in the previous section, important questions regarding subgroups and distributions of effects among the reviewed studies could perhaps be answered through quantitative aggregation of similar studies (i.e. Kallioinen et al., 2016; Bell et al., 2019a; Pierotti et al., 2021). Differences in recording equipment and processing may be daunting, but could be handled at level of statistical analysis or even through a new streamlined processing of the original EEG.

The primary goal of studying semantic processing in children with CI is finding ways of supporting language development in this population. Although the present results do not support specific recommendations for interventions, both semantic top-down processing and cross-modal communication are areas where there are already many recommendations for caregivers and teachers. Strengthening semantic top-down processing can involve training vocabulary, concepts, and general world knowledge, as well as direct training in prediction, making connections between concepts and structuring material such as a story (Luckner & Cooke, 2010; Luckner & Handley, 2008). Based on discussed behavioral results, EF training could be way to boost top-down processing, and make it less effortful. There are intervention studies targeting EF in children with success (Neville et al., 2013). Morphological reading training, focusing on units of meaning rather than units of sound, could benefit DHH children (Trussell & Easterbrooks, 2017). Cross-modal strategies is also a broad field, from communicating face to face for maximizing communication cues, and reading as an input to phonological awareness to sign supported speech (Curtin et al., 2021; Luckner & Cooke, 2010; Luckner & Handley, 2008; Nittrouer et al., 2018). Given that these areas are already among the methods used for enhancing communication in deaf and hard of hearing children, we hope that this review will map out paths for intervention research, especially with a semantic processing focus, despite many remaining uncertainties.

6. Conclusion

Until recently, the N400 was not studied at all in children with CI (Johnson, 2009). However, the results of our review indicate that, with exception of young children with impairments besides HL, N400 effects are now routinely found in children with CI, using standard experimental paradigms. Our review of existing studies of N400 in children with CI suggests that in this population, the N400 is sometimes larger than expected based on their semantic skills. We propose that these results could reflect a shift of balance from more perceptual bottom-up towards more semantic top-down processing compared to children with TH. An alternative explanation of the same results is that they reflect stronger cross-modal processing.

If children with CI are engaged in semantic processing as a compensatory strategy it is likely important to strengthen semantic skills such as vocabulary and conceptual knowledge, narrative skills etc. However, there are also limitations to this strategy. Spontaneous speech does not come with vast untapped reservoirs of semantic clues, but is adapted economically to typical listeners, that is TH listeners. Semantic skills are important to make use of existing predictive opportunities in the language signal, but such redundancy is limited. We conclude that the study of cortical semantic processing in children with CI have led to unexpected results, suggesting adaptive mechanisms, rather than merely illustrating deficiency.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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Study IV

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A randomized controlled trial to examine the effect of two teaching methods on preschool children's language and communication, executive functions, socioemotional comprehension, and early math skills

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Abstract

Background: During the preschool years, children's development of skills like language and communication, executive functions, and socioemotional comprehension undergo dramatic development. Still, our knowledge of how these skills are enhanced is limited. The preschool contexts constitute a well-suited arena for investigating these skills and hold the potential for giving children an equal opportunity preparing for the school years to come. The present study compared two pedagogical methods in the Swedish preschool context as to their effect on language and communication, executive functions, socioemotional comprehension, and early math. The study targeted children in the age span four-to-six-year-old, with an additional focus on these children's backgrounds in terms of socioeconomic status, age, gender, number of languages, time spent at preschool, and preschool start. An additional goal of the study was to add to prior research by aiming at disentangling the relationship between the investigated variables.

Method: The study constitutes a randomized controlled trial including 18 preschools and 29 preschool units, with a total of 431 children, and 98 teachers. The interventions lasted for 6 weeks, preceded by pre-testing and followed by post-testing of the children. Randomization was conducted on the level of preschool unit, to either of the two interventions or to control. The interventions consisted of a socioemotional and material learning paradigm (SEMLA) and a digitally implemented attention and math training paradigm (DIL). The preschools were further evaluated with ECERS-3. The main analysis was a series of univariate mixed regression models, where the nested structure of individuals, preschool units and preschools were modeled using random variables.

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Results: The result of the intervention shows that neither of the two intervention paradigms had measurable effects on the targeted skills. However, there were results as to the follow-up questions, such as executive functions predicting all other variables (language and communication, socioemotional comprehension, and math). Background variables were related to each other in patterns congruent with earlier findings, such as socioeconomic status predicting outcome measures across the board. The results are discussed in relation to intervention fidelity, length of intervention, preschool quality, and the impact of background variables on children's developmental trajectories and life prospects.

Keywords: Intervention, Preschool, Language skills, Communication skills, Executive functions, Auditory selective attention, Socioemotional comprehension, Early math skills, Group-based learning, Digital learning

Background

A comprehensive preschool system has the unique possibility to enhance social, emotional and cognitive skills, as well as fostering general behaviors deemed important by society, such as participative, democratic citizenship. Preschools are not available worldwide and where they exist, differences can be great in a number of ways, such as whether they are subsidized or not. In countries like Sweden, where 84% of the one- to three-year-old children and 95% of the four- and five-year-olds [1] are enrolled in whole-day preschool services, the system reaches close to all children, regardless of socioeconomic status (SES), languages or family situation, during years essential for learning. In order for preschools to enhance children's abilities and skills, the educational services provided need to be of a "good enough" quality in terms of teacher/child ratio, educated staff, meaningful activities including time for play, positive interactions between children and adults, access to inspiring learning materials and environments, etc. [2].

For a long time, intervention studies have been the main way to investigate the use and effectiveness of early education internationally [3, 4]. The skills most often targeted, since they have proven essential for later outcomes in children and adolescents [5, 6], are executive functions (including auditory selective attention, [4]), socioemotional skills, language and literacy, as well as math [7–11]. Evidence from intervention studies from different parts of the world indicate that all of these skills, together with IQ and self-regulation, can be enhanced through pedagogical training [12–14]. In an RCT study of 759 preschool children, Blair and Raver [13] concluded that not only did the intervention have an effect on the targeted ability self-regulation, but the children also improved in mathematics, reading and vocabulary with results increasing into first grade. Neville et al. [4] found significant effects in an ERP-paradigm of auditory selective attention in a sample of 33 Head Start children following 8 weeks of intervention. In an RCT study also targeting Head Start children, Nix et al. [15] showed that socioemotional skills could be enhanced through a REDI (Research-Based, Developmentally-Informed) enrichment intervention. A couple of studies have also been able to demonstrate effects from preschool self-regulation training that lasted well into adulthood [16, 17].

In Sweden and the Scandinavian countries, intervention research performed with children prior to compulsory school is less common. This is an important observation, as the different circumstances for preschool services worldwide make comparisons between intervention studies potentially skewed. Nemmi et al. [18] showed in a sample of 55 six-year-olds that grit predicts significant improvements in working memory, as a result of an eight-week training program including working memory and early math tasks. Thorell et al. [19] investigated working memory and inhibition in a sample of 65 Swedish preschool children aged four to five, using an intervention with 5 weeks of either visuo-spatial training or inhibition training for 15 min a day using computer games. The results showed significant improvement in working memory as well as transfer effects on attention for these children, whereas inhibition training did not yield results. There was no follow-up to check for long-term effects in this sample, however, Klingberg et al. [20] could show effects at least 3 months after a completed study on school-aged children's working memory. In Denmark, a country that is similar to Sweden in many ways, in particular as it comes to preschool attendance and a general focus on socialization and play in the preschool curriculum, Bleses et al. [21] enrolled 5,436 children aged three to six in an RCT study targeting pre-literacy skills and language and found significant results for pre-literacy skills, albeit not for language, after a 20-week intervention.

This said, many studies, both internationally and in the local Scandinavian context, also come to diverging results when investigating the same or similar skills [22, 23]. Long-term effects of intervention studies have also been hard to find [24, 25]. However, adding children's backgrounds as a variable resolve some of the divergences and accounting for preschool quality could help explain yet others.

Starting with child background, the evidence has long been piling up that socioeconomic status plays a key role in how a child will develop through the preschool years and beyond [26, 27]. For example, Blair and Raver [13], who found effects on self-regulation, literacy, mathematics and science learning through using the educational approach Tools of the Mind [28], could also conclude that the effect was most prominent in the group of children starting out in low-SES environments. Similar findings stem from Neville et al. [4] who, in their intervention study using ERP-responses and targeting Head Start schools, found a significant increase in the children's results on auditory selective attention. Other intervention studies have come to the same conclusions on executive functions and academic abilities [5, 6, 12, 29–31]. Further, intervention studies performed in preschools including high-SES children as well, have not been able to replicate the findings [32].

Socioeconomic background is a complex concept, which calls for some caution in interpreting intervention results. Whereas most interventions appear to have a larger effect on children from low-SES backgrounds, there is also evidence pointing the other way. When targeting specific skills like language and literacy, low-SES children benefited less than their more fortunate peers from interventions in studies by Buysse et al. [33] and Marulis and Neuman [34]. Adding to the confusion, a meta-analysis of the National Early Literacy Panel [35] reported the opposite results on pre-literacy, as low-SES children showed larger outcome effects than high-SES children. Bleses et al. [7] suggest an interpretation where these mixed results could depend on different groups of children needing different forms of interventions, such as a higher intensity for children with particular risk factors. One potential cause of differing results is also the way SES is measured. While some studies use income and education, others use only income or educational level, yet others base their classification on living area (e.g., wealthy/poor neighborhood), and so on. To further clarify how different studies reach different conclusions when investigating the same or similar phenomena, transparency of how the different concepts – like SES – is measured, together with clear description of the implementations provided and, in particular, the fidelity of the implementation, need be addressed.

Turning to the other main explanatory factor of diverging results, we find that adding high quality Early Childhood Education and Care provisions (henceforth ECEC) as a variable makes long-term effects of preschool curricula more conclusive [36]. An example is a longitudinal study of 141 preschool provisions in the U.K. investigating the effects of preschool quality (measured with the environmental ECERS scale; [37]) on eleven-year-olds. Sylva et al. [38] showed that preschool quality significantly predicted most measured outcomes when considering key child and family variables. Children who had attended low quality preschools, however, did not significantly differ on cognitive and behavioral scores from children with no preschool experiences at all. At the same time, findings from a Norwegian study indicate that simply attending preschool for long enough period of time could be essential. Havnes and Mogstad [39] analyzed data from a 'natural experiment' in Norway based on a preschool reform of subsidized child care, comparing the long-term effects on children in municipalities who extensively expanded their preschool provisions with those who did not decide to do so. The results showed that preschool attendance had strong positive effects on educational attainment, labor market participation and reduced dependence on welfare. As there is no information as to the quality of the Norwegian preschools, the different conclusions are hard to conjoin.

As a part of the Norwegian Agder project, Rege et al. [40] investigated preschool quality, focusing on the structural quality of the services; i.e., child-teacher ratio, center size and the tenure of the director, when evaluating school readiness in 627 five-year-olds enrolled at 67 ECEC centers across Norway. Although the differences in quality cannot be ruled out as effects of unobservable background variables, the study demonstrates significant differences in school readiness skills in five-year-olds. Since this study only measures structural quality, the authors conclude that the results must be interpreted with caution. In a Danish study [41] aiming to investigate the effects of preschool quality (measured through class size, child-staff ratios, and teacher education), 30,444 children who had attended a formal preschool institution had their grades from ninth grade correlated to their earlier preschools' qualities. Findings suggest that an increase in structural conditions only have modest effects on children's development in general. However, on specific scales, significant findings emerged, such as boys benefitting more than girls from formal teacher training.

Albeit from similar settings and cultures, the Scandinavian studies end up with some inconsistent results. Bauchmüller and colleagues' [41] results of modest but persistent associations between quality of preschool services and outcomes by the end of ninth grade of schooling, contrasts Chetty et al. [42], who found that effects of preschool quality on cognitive skills will fade before the children reach their teens. A Danish study by Gupta and Simonsen [43] on non-cognitive outcomes of preschool vis-à-vis home care, had results showing that boys whose mothers had a low educational level benefited more than girls from an intervention (see also [41]). However, Havnes and Mogstad [39] also found that girls benefitted more in the long run than boys in terms of education attainment and labor market participation and had a lower level of social welfare. It is currently not clear why there are such immense differences in results from different intervention studies. Even in studies targeting the same ages and in the same or a similar cultural setting, specific skills appear to be enhanced in some studies but not in others. The array of explanatory factors suggested in earlier research and cited above are: children's socioeconomic background, children's sex and age, fidelity of intervention and implementation of intervention, number of hours in preschool, quality of preschool (as measured by e.g. ECERS), scripted vs non-scripted instructions, and assessment of targeted skills.

The present study set out to investigate the effectiveness of two pedagogical methodologies, which to some degree were already in use within the Swedish preschool context, though they had not yet been scientifically evaluated. One is based on socioemotional learning [44, 45], mainly group-based and with a focus on interaction, whereas the other is more individual as children work with digital tablets to enhance particular skills and/or learn to control and understand their bodies [4, 10, 46]. Both methodologies are believed to enhance children's language and communication, EF, socioemotional comprehension and math, albeit to different degrees and in different ways, and they are both advocated by the National Agency for Education by way of the preschool curriculum [47]. Nevertheless, they are often described as in conflict within the Swedish preschool setting. By performing an RCT intervention, comparing these methodologies in a boosted version to a control group where presumably a mixture of methodologies is in use, the present study aimed to deepen our understanding of how particular skills are enhanced in preschoolers. Following Neville et al. [4] whose research highlight two themes central to us: SES and executive functions, we included an ERP test of auditory selective attention as a complement to the behavioral test battery. By including SES, age, sex, number of hours at preschool and quality of preschool among the variables, and by carefully monitoring fidelity of implementation and assessment, we further hoped to be able to add to prior research by clarifying the relation between background factors and preschool outcome.

The aims, interventions, questions and hypotheses of the study

Aims

The present study aimed to investigate which – if either – of two intervention pedagogical methods would prove most suitable to enhance children's language and communication, executive functions, socioemotional comprehension, and early math skills in preschool settings. The full details of the study set-up and implementation are described in a Study Protocol [48]; however, for the convenience of the reader the main parts of the study will also be covered in the following paragraphs. The sample was unselected within the enrolled preschools, including all children who opted in for participation regardless of potential difficulties or developmental disorders. The study was performed in 29 preschool units involving all in all 431 children and 98 educators, in a municipality outside Stockholm, Sweden. The objective was to compare a group-based socioemotional learning strategy, henceforth referred to as SEMLA (socioemotional and material learning, [45]) with an individual digital learning paradigm called Digital Individual Learning for body-and-mind (DIL).

Interventions

The SEMLA intervention was designed to enhance children's language and communication, EF, socioemotional comprehension, and early math skills as part of an investigative learning strategy with emphasis on the STEAM subjects (Science, Technology, Engineering, Art and Mathematics, [49]), specifically focusing on early mathematics. This was done as part of a group-based collaboration designed to explore the overarching problem of how humans might live and get around 100 years from now, using a manifold of construction materials, digital tools, documentation and meta-reflecting practices [50]. In practice, SEMLA addresses socioemotional comprehension through face-to-face interaction [44], as well as in the creative handling of various forms of materials and artefacts used as multimodal tools for exploration and construction [51–53]. The emotional engagement in learning [54] was emphasized and used as an important driving force as the children engaged in hands-on investigations involving diverse materials and artefacts. This driving force would, in itself, create a positive learning ground, engaging children and help motivate them for learning [54]. As a group-based strategy, SEMLA is believed to enhance language and socioemotional comprehension by having the children listening to each other, expanding and reflecting on other's utterances of verbal as well as nonverbal matters [55, 56]. New words and/or concepts were introduced by the teachers and elaborated on in relation to both the overarching problem and the more specific problems emerging in the process of constructing and investigating [50]. Executive functions, including auditory selective attention were believed to be enhanced through these processes of verbally mediated reflection and focused attention – on materials, exploration themes, difficulties encountered, translations between words, meanings and materials – in combination with the close scaffolding from the educators [57–59].[1] The overarching problem of investigating how we might live and get around 100 years from now was introduced to smaller groups of six to eight children at a time, and targeted early math, as it contained instances of measuring, estimations, distances, and engineering and constructions of vehicles and buildings, thought to be part of a future life [49].

The second intervention, DIL, focused on individual training intended to enhance children's executive functions, including auditory selective attention and self-regulation, and early math skills [60, 61]. More specifically, the intervention was developed based on the theoretical understanding of self-regulation and early math as developing interdependently [10, 62]. DIL had two components: an adaptive, interactive math game and a set of attention-enhancing body-and-mind activities.

The interactive math game, *The Magical Garden* (MG, [46])[2] was played on digital tablets with headphones. It focuses on early math and number sense and is administered online by the Education Technology Group at Lund University [46]. The main theme of the game is for the child to solve math problems in order to collect water to create a flourishing garden. The game includes a teachable agent (TA) based on a learning-by-teaching methodology. The child is encouraged to teach the TA early math. The game design and narrative are adaptive, and the game progressively advances in difficulty, with feedback provided to motivate the child [57]. The game has been investigated scientifically, focusing on functionality, such as the TA, scaffolding, gaming strategies, eye movement and inhibition [62, 64]. The two tasks in combination were believed to improve self-regulation as well as early math skills [10, 65].

The body-and-mind exercises (Brain Development Lab,[3] cf. [4]) were introduced by the educators and included a package of 12 activities focused on self-regulation. Specifically, they targeted attention, executive functions and meta-reflection by means of strategically designed metaphors [67] that corresponded to the design of the MG. The exercises were inspired by the child component of the evidence-based program Parents and Children Making Connections - Highlighting Attention [4]. The activities aimed at teaching children strategies for handling and controlling their bodies and minds and focused on training attention, breath control, avoiding distractions and improving body control, as well as on metacognition. For example, "The Bird Breath" poster features a metaphor designed with the same characters as in the MG and teaches children to take a deep breath to regain focused attention.[4] The activities were introduced so as to gradually enhance the level of difficulty. The teacher scaffolds each child at his/her level throughout the activity.

The two interventions were compared to a control group in preschools where the daily pedagogical work was carried out as usual. The staff in the control group filled out a self-evaluative tool-kit, BRUK [68], administered by the Swedish National Agency for Education [69], which was aimed at enhancing motivation in the staff randomized to the control group.

Research questions

The study set out to answer the following questions: 1) What are the effects of the two different pedagogical methods (SEMLA and DIL) on language and communication, executive functions, socioemotional comprehension, and early math skills? 2) How do any observed effects in these areas differ between the two interventions? 3) To what extent are any observed effects mediated by language and/or EF? 4) To what extent are any observed effects moderated by background variables like sex, age, preschool start etc.? 5) To what extent are the background variables related to the outcome variables? 6) To what extent are the outcome variables related to each other? 7) Do any observed effects of the interventions differ in terms of strength and variation?

Hypotheses[5]

Our general hypothesis for the project was that both SEMLA and DIL would have a greater impact on the children's development of language, communication, EF, math and socioemotional comprehension than would the practice as usual in the control groups. However, the difference between the interventions made us hypothesize that DIL would have a stronger effect on math (due to the specific training of math through the digital app), whereas SEMLA would have a stronger effect on language, communication and socioemotional comprehension due to these abilities being at the forefront of the SEMLA approach. As all of the preschools were evaluated with the ECERS-3, our assumption was that preschools scoring high for quality would also get a better result with the implementations in all areas tested.

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[1] The intended activities can be found in the documentation formulary (see Additional file 1).

[2] The Magical Garden is developed in cooperation between Lund University and Stanford University, see [63]

[3] Brain Development Lab at Oregon University, see [66]

[4] The activities are described in detail in the manual Body and Mind Exercises (see Additional file 2).

[5] See Gerholm et al. [48] for a table overview of hypotheses, analyses, etc.

Background factors come together in particular patterns e.g. [70, 71]. Following prior research, our hypotheses in regard to this was that age would be correlated to language level (as measured by SCDI; [72]). High SES would, in a similar manner be correlated to SCDI scores, since earlier research has found a connection between middle-class parents and children's higher language proficiency. High SES was further expected to yield higher scores on EF and language at pre-testing. Other language-related findings made us expect that children with Swedish as their strongest language would have a higher SES than children with other L1 than Swedish. This is based on the assumption that these children might have arrived more recently in Sweden and be less established in terms of education and employment (see e.g. [73]). High-SES children (where both parents in the majority of cases have full-time employment) were also expected to have longer days at preschool, hopefully making them more affected by good pedagogical practices. Related to this, multilingual children were expected to enter preschool at a later age than Swedish monolingual children (in turn leading to multilingual children having less time to be influenced by pedagogical training in preschool). A trivial hypothesis was further that children with Swedish as their strongest language would have an easier time both partaking in and understanding the tasks where language was essential for performance. This was particularly the case for the math task. A high score on language tasks pre-intervention was also expected to correlate with a higher outcome score on socioemotional comprehension, as socioemotional comprehension is expressed most centrally through language [74–76].

Low SES was expected to have a moderating effect on language, EF, and socioemotional comprehension, since this is what earlier research has found [13, 35]. Guided by prior research, we also expected girls to perform better on EF, language, communication, and socioemotional comprehension than boys [44, 77–80]. As some research has found multilingualism to be positively correlated with EF [81, 82], we hypothesized that we would find the same relation.

Some variables were further expected to have a mediating effect, and based on prior research [83, 84], we expected EF to facilitate improvement in language, communication, math, and socioemotional comprehension regardless of intervention. Conversely, language and math were also expected to have a mediating effect on EF [10]. EF scores at pretesting were also hypothesized to have a moderating effect on any observed intervention effects with regard to EF in both SEMLA and DIL, so that a child with an initially low EF score would benefit more from the interventions in regard to EF than would a child who had already scored high in this domain at the start [4, 30].

Methods

Study design

The project was a three-armed, cluster-randomized, controlled study, implemented in three waves during a period of 10 months (September 2016 to June 2017), and was analyzed using mixed models regressions [85]. The protocol for this study was published in advance of its completion [48] and both the protocol and study are reported according to CONSORT guidelines [86]. The main research questions were initially tested as planned, using these univariate regressions (see Results). Because of problems with multicollinearity we also reformulated the analysis to a multivariate version where the composite measures of the planned analysis were entered as separate variables (see Results). However, the study also produced data suitable for qualitative analyses. The video recordings of the testing situations form the bases for transcriptional work through which we measured verbal and nonverbal language and communication skills among the children.

Recruiting

A municipality that already had an ongoing cooperation with Stockholm University was asked to participate in the study. All 30 preschools run by the municipality were invited and 18 preschools opted in. In order for a preschool to be accepted, all involved preschool staff needed to sign a written consent form in which they stated their interest in participation and their understanding of the conditions of the randomization that would determine to which intervention or control they would be assigned.

Following information meetings at the different preschools, the guardians of 431 children (223 girls) signed up to let their children participate in the testing procedures of the project. Parents were not asked to evaluate or take a stand concerning the interventions as such, as these were regarded as part of a regular preschool curriculum. All participating parents had to fill in a background document for their child, including information such as family situation, family income and education, languages spoken in the family, time spent at preschool, number and age of siblings, medical history of the child, hereditary language-related conditions in the family, etc. The questionnaire was delivered in sealed envelopes to the parents and returned anonymized in prepaid envelopes directly to the university.

The 18 preschools consisted of 29 units in all, where a unit could include between seven and 30 children. This was a consequence of the project only targeting children from 4 years of age, as some units had mixed groups of three- and four-year-olds, meaning that the number of four-year-olds in some units could be very low. In order to participate in the study, a unit had to consist of at least seven children. In one case, there were only two four-year-olds in a unit, so that the preschool merged two units, resulting in a total of 28 participating units. Some preschools had many units while others had only one. The randomization was conducted at the unit level and took into account the number and size of units the preschool had. For example, a single preschool was not allowed to have both interventions, since the risk of contamination between interventions was deemed to be high if units were adjoined physically or if siblings/friends participated in different interventions. Thus, in a preschool with many units, these could be randomized to one of the interventions or to the control. Yet another condition for the randomization was to have as equal a distribution of ages as possible. For SEMLA, the age range was 49–74 months, for DIL 46–74 months and for the control, the age range was 44–74 months at pretesting.

One consequence of making the intervention in three waves was that randomization could not allow for all variables related to the children, since we did not have all information at the same time. One example is socioeconomic status, as we did not know during the first intervention period exactly which preschools or which children would be involved in wave two. During wave two we did know which preschools had signed up for the third wave, but we did not know which children would be involved, as parents were informed and accepted/declined participation in close proximity to the start of each intervention.[6]

Sample

The units, interventions and background information on the children are presented in Table 1. The original sample consisted of 431 children (223 girls and 208 boys) with a mean age of 62 months. A majority of the children came from higher SES backgrounds. The sample was linguistically diverse, with 33% of the children having additional language(s) in the home environment and a total of 49 different languages being represented. English, Spanish, Arabic, Kurdish and Polish were the most frequent languages occurring in the children's home environment apart from Swedish. A vast majority of children lived in two-parent households. Children had started preschool at 1;6 years on average and spent an average of 38 h/week at preschool. There were cases were caregivers did not answer all of the questions in the background questionnaires, thus there are missing data points for children's age and SES (see also Table 1).

Table 1 The total number of participants were 431. Mean age was 62 months. The SEMLA group had a larger proportion of multilingual children than the other intervention groups. SES was generally high in the sample but differed significantly between intervention groups. A majority of children lived in two-parent households. Weekly preschool attendance was generally high and significantly higher in control than in SEMLA

		SEMLA	DIL	Control
Children, *n* = 431		137[a]	155[a]	139[a]
Child characteristics				
% boy, *n* = 431		54	47	46
Mean age in months (SD), *n* = 417		62 (6)	61 (7)	63 (7)
% multilingual, *n* = 431		53	27	22
Family characteristics				
SES, median, *n* = 393		7	8	9
% two-parent household, *n* = 431		89	88	91
Preschool attendance				
Mean age at preschool start (SD),	*n* = 411	18 (9)	18 (6)	17 (5)
Mean preschool hours/week (SD),	*n* = 370	37 (7)	37 (6)	39 (6)

a. Note: The uneven group sizes arose because preschool units have different sizes

The distribution of girls and boys did not differ significantly between groups (Kruskal-Wallis test, $\chi^2 = 4.273$, $p = 0.12$, df = 2), and there were no significant differences with regard to age at preschool start. However, despite random assignment, there were some significant differences between intervention groups. With regard to age, children in DIL were significantly younger than controls. Children from multilingual home environments were not evenly distributed: the SEMLA group consisted of 53% multilingual children, compared to 27% in DIL and 22% in the control group. For SES, there were significant differences between all groups and for preschool time, children in the control group spent significantly more time at preschool than the children in SEMLA.

One-way ANOVAs were conducted to compare SEMLA, DIL and the control group with regard to age, SES, and hours per week at preschool. Age differed significantly between groups, $F(2) = 3.291$, $p = 0.039$ ($n = 417$). A Tukey post hoc test revealed that children in DIL were significantly younger ($M = 61$, $SD = 7$ months, $p = 0.034$) than children in the control group ($M = 63$, $SD = 7$ months). There was no statistically significant age difference between DIL and SEMLA or between SEMLA and the control group. For SES, there was a significant difference between groups, $F(2) = 13.45$, $p < 0.001$. A Tukey post hoc test showed that SEMLA and DIL differed significantly with regard to SES at $p = 0.043$, SEMLA and control differed significantly at $p < 0.001$ and DIL and control differed significantly at $p = 0.01$. For current time at preschool, there was a significant difference between groups, $F(2) = 3.379$, $p = 0.035$. Children in the control group spent significantly

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[6] This short notice was needed for practical reasons as many children move or begin preschool even in the middle of semesters and we wanted to only approach families actually at the preschools during the intervention period. Some preschools further gave short notice of participation due to staff situation or other factors beyond our control.

more time at preschool ($M = 38.71$, $SD = 5.52$) than the children in SEMLA ($M = 36.82$, $SD = 6.64$, $p = 0.039$). For current time at preschool, there was a significant difference between groups, $F(2) = 3.379$, $p = 0.035$. Children in the control group spent significantly more time at preschool ($M = 38.71$, $SD = 5.52$) than the children in SEMLA (= 36.82. $SD = 6.64$, $p = 0.039$).

Preschool quality, ECERS-3

To estimate preschool quality, the Early Childhood Environmental Rating Scale (ECERS-3) [37] was used. ECERS is an internationally established tool for measuring preschool quality and has been more predictive of children's learning than factors such as group size and staff-to-child ratio [87].[7] ECERS third edition measures 35 items organized into six different subscales: Space and furnishing, Personal care routines, Language and literacy, Learning activities, Interaction, and Program structure. Although not adapted for the cultural context of Sweden, the rating-scale is considered to hold for international comparison [92]. The assessment was conducted by trained researchers, not involved in the project in any other sense and blind to the interventions and the aims of the study.

Procedure

The preschools assigned to SEMLA (socioemotional and material learning) or DIL (digital individual learning for body and mind) had introduction courses prior to the pretesting. For SEMLA the introduction consisted of four 3 ½-hour evening sessions where the teachers were guided through the SEMLA intervention, their own part in the implementation and how to work with the children during the SEMLA sessions. SEMLA should be applied four days a week for approximately 1 ½ hours each day during the 6 weeks of intervention. For DIL the introduction consisted of four evening sessions of two hours where the educators were introduced to the Magical Garden digital game and learnt how to implement the game and support the children when needed. They were also taught the body-and-mind exercises and how these should be used. DIL was implemented one hour/day during the six-week intervention. The control preschools did not have specific training but met on one occasion for information about the self-evaluative toolkit, BRUK [68], administered by the Swedish National Agency for Education [69]. The control preschools agreed to work on the strand that concerned the learning environment and were then instructed to work with this instrument on their own and compare experiences afterwards, as a way to heighten their motivation during the intervention period (see [70]).

To support implementation, both SEMLA and DIL preschools had researchers or supervisors instructed to supervise the interventions. The teachers were also equipped with forms on which they were encouraged to follow children's activities related to the intervention, and which further aided the staff in implementing the practices (see Additional files 1 and 2).

Following the evening instruction classes for the enrolled preschool staff, 2 weeks of pretesting of the children commenced at the preschools. The test situations were video recorded using Canon XA 10 video camera and for audio recording Sennheiser MKE 2 lapel microphones were used. All language and communication data from interaction and narrative come from these recordings. The videos were transcribed using the ELAN Video Annotation Software [93] by the first and third author and trained research assistants.

Implementation fidelity

Fidelity of the implementation was tracked somewhat differently depending on the intervention. Preschool staff tracked how many days a child had been offered 1 ½ hours of SEMLA work. In the DIL implementation, each child's frequency data and play time on the Magical Garden was registered in the device whereas the amount of body-and-mind exercises was registered in a log book describing which children participated, which activities had been undertaken and whether anything out of the ordinary had occurred. The mean number of sessions and standard deviation are reported in the results section. As described in Gerholm et al. [48], a standardized fidelity score was also calculated for both SEMLA and DIL. For SEMLA this score was based on the number of SEMLA sessions each child participated in. The calculation for the DIL intervention consisted of the standardized sum of the number of body-and-mind sessions and the number of Magical Garden sessions, weighted according to the mean play time for each child. For the children in the control group, zero was used as a fidelity score. This resulted in a standardized fidelity score with a mean of zero and a standard deviation of 1, where zero were treated as a baseline value.

For SEMLA, which did not depend on a strict script in the same manner as DIL's game logs, a further fidelity

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[7] See however [88–91] for a critical discussion on the validity of ECERS and Garvis et al. [92] for a discussion on the need of cultural adaptation of the instrument.

measurement regarding the pedagogical quality was developed based on ratings using the extensive video data. All in all, 20 h of video recordings were retrieved from the SEMLA sessions, over the six-week intervention period at the nine units. The recordings were rated by one of the researchers using criteria based on the SEMLA documentation form describing and exemplifying how the seven components[8] were to be implemented (see Additional file 1). Each of these components was operationalized to comprise four to eight different criteria, making an evaluation of 41 criteria per film. The conditions for reaching good/excellent fidelity can be summarized as the teacher's ability to be responsive, not only to the learning group as a whole, but also to the individual children as a part of a collaborating team. To reach a good or excellent quality, the teacher was expected to often or routinely supply creative materials and to scaffold individual children with questions and comments, as well as with information and facts that enhance emotional desire, curiosity, reflection and learning, while exploring a problem as part of a learning group. The SEMLA ratings mirror the structure of the preschool quality environmental ECERS scale [37], where insufficient is rated from 1 to 2, minimal 2–4, good 4–6 and excellent 6–7.

In addition, all the project's preschool units were visited at random intervals by three research assistants blind to the interventions, with instructions to video record five minutes of preschool activities (so-called "fidelity filming"). The purpose of the recordings was to give a glimpse of the daily practices at the different preschools and their potential tendency to practice a particular pedagogical agenda regardless of intervention or control assignment. This was conducted as a precaution in order to control for a SEMLA or control intervention preschool regularly using digital tablets training math or vice versa. These recordings were rated by a blind research assistant using a protocol developed for this purpose.

Measures

The outcome measures included in the study were language, communication, math, executive functions, and socioemotional comprehension (see [48] for detailed descriptions). These were assessed in the following way: see (Table 2)

Most of the tests were behavioral standardized tests or adaptions based on standardized tests. For a subset of the children we also included Swedish AUDAT, an adaption of the experimental paradigm used by Neville et al. [4] to assess auditory selective attention with ERPs. The paradigm has proven sensitive to intervention effects in young children [4].

Testing procedure

The pretesting of the children commenced two weeks prior to the intervention start and the post testing followed directly after the intervention. Trained research assistants (speech-language pathologists, psychologist, and social scientists hired for the project) came to the different preschools and conducted the testing in a secluded room, chosen by the preschool. The testing sessions were divided into two for both pretesting and post testing, each session being approximately 30 min. This was done to avoid fatigue and boredom on the part of the children. The order of the tests was: DCCS, TEC, Bus Story (pretest)/Frog Story (posttest), math, HSKT for the first sessions, and: Flanker, What's Wrong Cards, PPVT, Digit span for the second session. The order was chosen based on a pilot study (Tonér & Gerholm, Language and executive function in Swedish preschoolers: a pilot study, under review, Applied Psycholinguistics). The sessions were video recorded in order to provide data on language and communicative behavior but also in order to check fidelity in test assessment.

Auditory selective attention was assessed through the Swedish AUDAT ERP-paradigm and could not be carried out on the complete sample. Thus, a subgroup of children was sampled to participate in the EEG-testing using a randomized priority list. Children and their guardians were previously informed about the general purpose and outline of the experiment and guardians had given informed consent about participation. Children were asked if they were ready and willing to record based on the order of the randomized priority list. If they declined, the next child on the list was asked. In the recording room they were seated on a small chair in front of a laptop (≈100 cm from the head) with speakers on each side (≈70 cm from the head). They were instructed on what participation would entail, and electrodes and a cap were applied. In Swedish AUDAT probe sounds are embedded in two simultaneously presented stories. The stories were differentiated by content, by gender of the voice of the reader, and by presentation to the left or right. The child was instructed to attend to one story while ignoring the other. Illustrations from the attended story were presented on the laptop. Probe sounds where either the syllable 'Ba' or a noise 'Bzz'. The 'Bzz' was constructed by splicing 20 ms segments of the 'Ba' sound and scrambling all segments except the first and last. Both probes were 200 ms and presented randomly with respect to probe type, left or

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[8] The seven components consist of: a relational ethics; content and problem-focussed learning derived from an overarching problem of concern; socioemotional and material learning; inclusion, participation and self-management; collaborative and individualized scaffolded learning; aesthetic and multimodal investigations; pedagogical documentation practices as tools for learning [50].

Table 2 Tests overview. All tests used pre- and post-intervention, and the targeted skills measures

Test	Skills measured
Language:	
The Peabody Picture Vocabulary Test [94]	receptive vocabulary
The Bus Story Test [95, 96] – used at pretesting	lexical diversity (number of word types used); information score (how many events a child included in the narratives), syntactic complexity (number of subordinate clauses), morphological complexity (amount of well-formed utterances), and text length (total number of clauses)
Frog, Where Are You? [97–99] – used at post-testing	lexical diversity (number of word types used); information score (how many events a child included in the narratives), syntactic complexity (number of subordinate clauses), morphological complexity (amount of well-formed utterances), and text length (total number of clauses)
What's Wrong Cards [100][a]	productive vocabulary, observation skills and created in order to develop emotional literacy
Communication[b]:	
An adapted version of ADOS [101]	meeting of gaze, adequate use of gestures, at ease body behavior, fluency/prosodic traits, following instructions, turn-taking behavior, and taking initiative/showing curiosity
Executive functions:	
The Dimensional Change Card Sort task (DCCS [59, 102])	cognitive flexibility/attention shifting (possibly working memory as well)
The Flanker Fish Task [103–105]	inhibition
The Head-Shoulder-Knees-Toes (HSKT, [106])	inhibition, focused attention, and working memory
Forward and Backward Digit Span [107]	short term memory, storage capacity, working memory
Auditory selective attention was measured using event related potentials (ERPs) to attended and unattended probe sounds embedded in stories, i.e. the Swedish AUDAT paradigm	ability to attend to one story while ignoring another simultaneously presented story
Emotional Comprehension:	
Test of Emotion Comprehension [108, 109]	socioemotional comprehension, ability to recognize facial expressions (drawn faces) of emotions related to different stories read to the child by the test leader
Math:	
An adapted version of the Number Sense Screener [110–112]	one-to-one correspondence, number sense cardinality, ordinality and subitizing

a. Note: What's Wrong Cards were used as an additional method to assess verbal skills in the child. Each child watched three different cards depicting odd situations, such as someone trying to put a sweater on as trousers or ironing a hat, and were encouraged to describe the picture and elaborate on the peculiarities of the activities seen. However, as this did not yield enough data and we already had speech samples from the narrative task, we did not proceed to analyse the results

b. Note: In the planning of the study [48], communication was regarded as a composite measure including the novel communication-rating of video-filmed interactions and the emotional comprehension test, TEC. However, as we did not know what to expect from the novel measure used, in the analysis phase we decided to keep the two measure separate and abandon the composite

right presentation and inter stimulus intervals of 200 ms, 550 ms or 1000 ms. Each recording session involved two pairs of stories, one longer (7 min) story pair and one shorter (5 min) story, with comprehension questions after each story. A child participating in both pre and post session would hear 8 stories, and attend half of them, balanced over presentation to the left or right and with regard to female or male voice, and presentation order. EEG was recorded using a BioSemi (BioSemi, Inc.) activeTwo amplifier with 16 head channels and a CMS/DRL loop in a cap, two external mastoid channels and four external eye channels (for activeTwo and CMS/DRL details see http://www.biosemi.com/). All processing was done in EEGLAB [113]. Sampling rate during recording was 2 kHz, downsampled to 256 Hz offline, re-referenced to average mastoids and filtered using the "pop_eegfiltnew" function in EEGLAB with a pass band of 0.1 Hz and 40 Hz. Bad channels among the head electrodes were identified visually and interpolated (on average 0.06 electrodes in each pre or post recording). The data was epoched from a 100 ms pre-stimulus baseline before any probe sound to 500 ms post stimulus response. Artifacts, including ocular artifacts, were rejected automatically (epochs with head channel amplitudes larger than + 200/− 200 μV or eye channel amplitudes larger than + 100/− 100 μV in a moving time window of 200 ms were rejected) and based on visual inspection. An estimated 50% of the epochs were rejected, leaving on average 158 epochs per participant in each condition (attended/unattended) and session. This is 82% of the number of trials in Coch et al. [114] when testing older children (6–8 years), and 42% of the number of trials for 3–8 year olds in Stevens [115], both using the original AUDAT paradigm. The high rejection rate is unfortunate but in some respects compensated by our very high number of child participants, and two recording sessions. Thirty pre-intervention recordings and twelve post-intervention recordings were excluded due to noisy or flat average response or less than 100 epochs remaining for attended or unattended events after artifact rejection. Sixteen more pre-intervention sessions and four post-intervention sessions were excluded due to failed comprehension tests. For statistical analysis, 89 pre-intervention and 89 post-intervention participant sessions, were used, with 76 participants having both pre and post recordings.

Reliability

With regard to the ratings of communication based on video recordings of the test session, a subset was scored for inter-rater agreement. Nonparametric tests were used and the overall correlation between raters was .82 ($p < .001$). With regard to inter-rater agreement for transcriptions, a subset of stories was transcribed by two annotators and the scoring based on the two versions was compared. For word types, syntactic complexity, number of clauses and well-formed utterances, scoring was identical for the transcriptions from different transcribers. For information score, the difference was at maximum two points.

Background variables

The information gathered through questionnaires delivered to the parents consisted of the following information: socioeconomic status (SES), estimated (if possible) on the bases of both caretakers' income and educational level[9]; the Swedish Communicative Development Inventory [72, 116]; age measured in months, as well as age at preschool start and number of hours per week spent at preschool at the time of the intervention; sex, which was included as a variable based on prior research in various areas [44, 76, 79, 117, 118]; second languages spoken and information on the child's strongest language; information on developmental disorders and family history of language disorders; and the Strengths and Difficulties Questionnaire (SDQ), [119–121].

Analytic strategy

The nested type of data in our study and the large number of measures, some continuous and some categorical, present challenges to statistical analysis. A type of analysis that is recommended for data with a nested structure and that can handle many variables of different types is mixed models [122]. Our planned analysis was a series of univariate mixed regression models described in [48], and below. The nested structure of individuals, preschool units and preschools was modeled using so-called random variables [85]. Because of an underestimated problem with collinearity, we also present an explorative analysis that combines the series of univariate models into one multivariate model. Aside from the planned univariate analyses and the exploratory multivariate analysis, we present correlations and group mean comparisons where some are planned, and some are exploratory, as stated in the text. The ERP measure *selective attention difference* was computed and analyzed as planned, except that only six frontal electrodes were used. We also added an ANOVA that was not described in Gerholm et al. [48] to test for differences between unattended and attended responses directly, and a similar ANOVA to test an unexpected late effect.

Results

The main purpose of the current study was to investigate potential intervention effects of the interventions SEMLA and DIL compared to a business-as-usual control group. The results section starts with a planned univariate regression analysis [48] that did not indicate any such intervention effects. Then follows an analysis of collinearity and a multivariate analysis that is motivated by collinearity. After this, the selective attention results are presented, and then results regarding implementation fidelity and an explorative analysis of intervention group differences. Ending the results section is an overview which sums up the results thematically.

Planned regression analysis

The planned regression models have been used to investigate the association (linear relationship) between one of the post-intervention outcome variables language post, communication post, EF post, TEC post or math post and a set of predictors comprising pre-intervention scores of the variables, intervention, individual background variables (sex, SES, SCDI, SDQ, age, preschool start time, L2, best language, and family language problems (FLP)), the control variables ECERS and fidelity, as well as interactions between pre score of the predicted variable and intervention, SES and intervention, and ECERS and intervention (PRE_SCORE×INTERVENTION, SES × INTERVENTION, ECERS×INTERVENTION). In the regression equation below the outcome

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[9] A 10-graded scale based on the basis of both parents' annual income (3 levels were used, 1: 0–200,000 SEK; 2: 200,001-500,000; and, 3: 500,001>) and their educational level (4 levels were used, 1: elementary school only; 2: upper secondary school; 3: vocational education; and, 4: college/university). See Gerholm et al. [48] for further details and explication of calculations used.

variable (one of language, communication, EF, TEC, or, math) is denoted as POST_SCORE. The variable PRE_SCORE represents the same variable pre-intervention. X_g, l = 9,…,17, represent background control variables (sex, SCDI, SDQ, age, preschool, start time, L2, best language and FLP). POST_SCORE_{ijk} refers to the response for the *i*th child, nested within *j*th preschool unit, in *k*th preschool.

$$\text{POST\_SCORE}_{ijk} = \alpha_{jk} + \alpha_k + \beta_1\text{INTERVENTION}_{jk} + \beta_2\text{SES}_{ijk} + \beta_3\text{PRE\_SCORE}_{ijk} + \beta_4\text{FIDELITY}_{ijk} + \beta_5\text{ECERS}_{jk} + \beta_6(\text{PRE\_SCORE}_{ijk} \times \text{INTERVENTION}_{jk}) + \beta_7(\text{SES}_{ijk} \times \text{INTERVENTION}_{jk}) + \beta_8(\text{ECERS}_{jk} \times \text{INTERVENTION}_{jk}) + \beta_g X_g + \varepsilon_{ijk},\ \varepsilon_{ijk} \sim N(0, \sigma^2_{\varepsilon}),\ \alpha_j \sim N(0, \sigma^2_{\alpha j}),\ \alpha_k \sim N(0, \sigma^2_{\alpha k}).$$

The equation above is a general model used for testing the hypotheses based on research question 1 and 4 (see also [48]). However, the intervention interactions in the model were non-significant in all planned regressions and were therefore omitted. This reduced the model's degrees of freedom from 20 to 14. A minor correction of the Gerholm et al. [48] equations is that ECERS is modelled on the *j*th level instead of the *k*th level.

The models and their significant predictors are presented in Table 3 and in Fig. 1. The full models are presented in Additional file 3.

Multivariate regression model

Correlations among the post scores were investigated (see Table 4) and since there was a strong association between responses, we decided to conduct a multivariate analysis. In the multivariate analysis the effect of covariates is investigated on several response variables (language post, communication post, EF post, TEC post, math post) simultaneously and tested as a MANOVA.

$$\mathbf{Y}_{ijk} = \alpha_{jk} + \alpha_k + \beta_1\text{INTERVENTION}_{jk} + \beta_2\text{SES}_{ijk} + \beta_3\text{PRE\_SCORE}_{ijk} + \beta_4\text{FIDELITY}_{ijk} + \beta_5\text{ECERS}_{jk} + \beta_6(\text{PRE\_SCORE}_{ijk} \times \text{INTERVENTION}_{jk}) + \beta_7(\text{SES}_{ijk} \times \text{INTERVENTION}_{jk}) + \beta_8(\text{ECERS}_{jk} \times \text{INTERVENTION}_{jk}) + \beta_g X_g + \varepsilon_{ijk},\ \varepsilon_{ijk} \sim N(0, \Sigma),\ \alpha_j \sim N(0, \sigma^2_{\alpha j}I),\ \alpha_k \sim N(0, \sigma^2_{\alpha k}I).$$

$\mathbf{Y}_{ijk}$ denotes the response vector with five components: language post and communication post, EF post, TEC post and math post. PRE_SCORE represent the same variables pre-intervention (language pre and communication pre, EF pre, TEC pre and math pre). X_g, l = 9,…,17, represent background control variables (sex, SCDI, SDQ, age, preschool, start time, L2, best language and FLP). As in the univariate analysis, all interactions with intervention were non-significant and omitted from the model. Significant effects and non-significant intervention effects are tested using MANOVA, and significant predictors are presented in Table 5. All results are presented in Additional file 3.

Auditory selective attention

The auditory selective attention effect is a hypothesized difference between unattended and attended event-related responses in average amplitude 100–200 ms after probe onset. These latencies capture the broad positive peak that is typical in children's responses to sounds, they are consistent with previous literature using AUDAT [4, 114, 115] and with our unpublished pilot data. The average amplitude for each participant was analyzed with an ANOVA with variables attention, electrode position, intervention and time (pre or post intervention). The results are presented in Table 6. There was a main effect of attention, and also an interaction between attention and electrode position, reflecting a stronger attention effect in fronto-central electrodes. There was no interaction between attention, time and treatment, and thus no intervention effects on selective attention. There were effects of electrode position, which is commonplace in ERPs but of little interest, and an interaction between electrode position and intervention that might have limited relevance as an indication of general group differences but is not analyzed further here. ERP responses are presented visually in Fig. 2a and b. Further ERP plots, grand averages of pre and post, for all participants, and all intervention groups can be found in Additional file 4.

A selective attention variable was then created using mean difference between attended and unattended responses over the six most frontal electrodes (where the effect was maximal in the ANOVA). This selective attention measure was created to fit regressions of the same form as for other outcome measures, and like them was analyzed in planned univariate regressions and in an exploratory multivariate regression, however with much lower number of participants ($N = 81$). These ERP-specific selective attention regressions did not reveal any significant effects of intervention, background variables or other variables, and the auditory selective attention difference was not a significant predictor of other outcomes. A few non-significant results are presented in Table 6 for comparison with other univariate regressions.

There were some unexpected ERP results: selective attention correlated with language in pre-sessions (see Table 6). In the group averages we also found a negative attention difference in a later time window (maximal at 300–400 ms) with a less frontal topography compared to the expected positive, early (100-200 ms) and frontal attention effect. This effect was potentially interesting since attention effects among older children

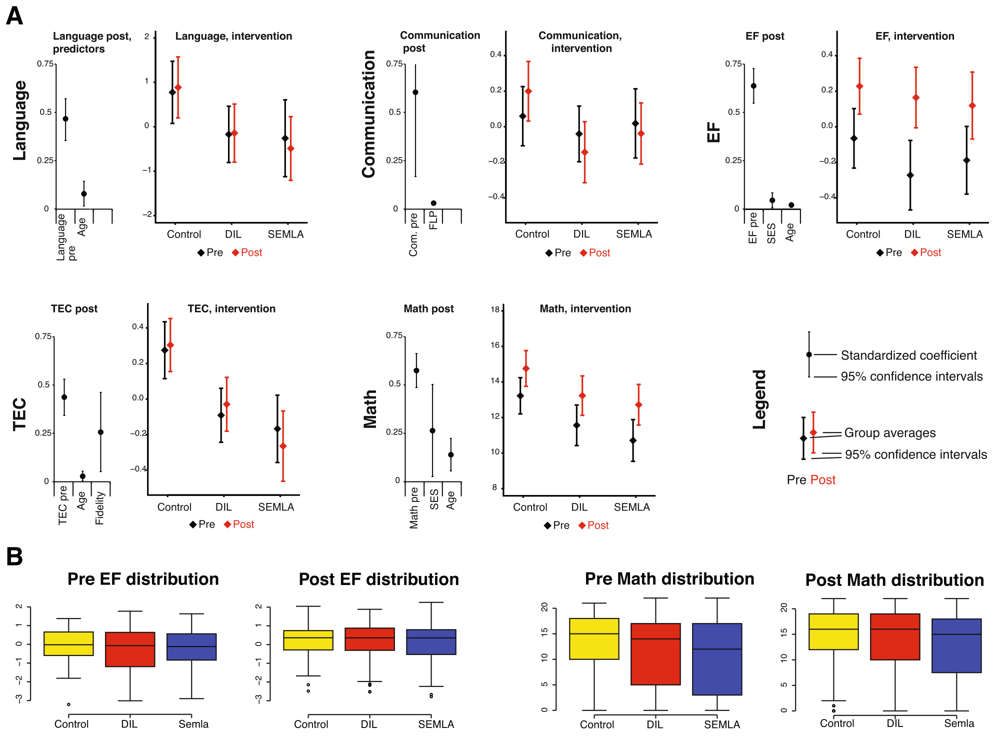

Fig. 1 **a** Significant predictors of all outcome variables, with standardized coefficients and 95% confidence intervals. Also group averages pre and post for all outcome variables with 95% confidence intervals. **b** Distributions of EF and math, pre and post as quartiles

and adults are often negative at longer latencies [123]). While the effect was nominally stronger in the post intervention recordings (see Fig. 2b) the analysis showed only a main effect of attention (see Table 6) with no interactions with time of test or electrode position. As in the ANOVA of the early attention effect there were also two less interesting effects, presented in Table 6: a main effect of electrode position and an interaction between electrode position and intervention. Since this late attention effect was unexpected and did not have any intervention effects (see Table 6) it is not explored further here.

Implementation fidelity

In the regressions, fidelity was a normalized value based on number of sessions each child attended and also, in DIL, time spent with the game Magical Garden. While thought of as a control variable, fidelity predicted TEC (see Table 3). To make further results more accessible we will discuss implementation fidelity in terms of number of sessions.

In SEMLA, children attended on average 13 sessions (*SD* = 4.6), while instructions prescribed 24 sessions in total. The range of sessions per child was 10–25, indicating that the low average was not a result of a few outliers. Each session was about 1.5 h. In the DIL intervention average number of sessions was 20.4 (*SD* = 4.6, range 10–28) for Magical Garden and 19.7 for body-and-mind (*SD* = 4.5, range 9–28). DIL sessions included both types of sessions, but participation could vary as seen in the slightly different averages. The instructions prescribed 20–30 sessions. Body-and-mind sessions were about 15–20 min, and average Magical Garden sessions were 27 min.

Implementation fidelity of SEMLA was also assessed by structured quality ratings of video material. The quality ratings of SEMLA show that only one unit reached the level of excellent with a score of 6.7. Three units varied from 4.1 to 5.1 and reached “good”, two varied between 2.6 and 3.9 were rated as “minimal”, and one unit

Table 3 Univariate regressions. Univariate regression results for each outcome variable. All significant effects are presented with regression estimates. Non-significant intervention effects are also presented. Auditory selective attention is presented separately (see Table 6: Selective attention regression). *P* values for estimates are omitted since they are exactly the same as for the main effects.

Selected results, main effects				Significant predictor estimates		
Outcome variable	*Predictor*	*DF*	*p*	*Estimate*	*SE*	*t*
Language post						
Model DF = 14, error DF = 290, $R^2 = 0.319$	Language pre	1	<.0001	0.459	0.054	8.43
	Age	1	0.014	0.079	0.032	2.48
	Intervention	2	0.318			
Communication post						
Model DF = 14, error DF = 302, $R^2 = 0.371$	Communication pre	1	<.0001	0.597	0.052	11.59
	FLP	1	0.020	0.030	0.013	− 2.34
				(FLP = 1, vs FLP = 0)		
	Intervention	2	0.131			
EF post						
Model DF = 14, error DF = 259, $R^2 = 0.636$	EF pre	1	<.0001	0.629	0.045	13.95
	Age	1	0.001	0.020	0.006	3.32
	SES	1	0.024	0.044	0.020	2.27
	Intervention	2	0.179			
TEC post						
Model DF = 14, error DF = 326, $R^2 = 0.368$	TEC pre	1	<.0001	0.431	0.047	9.16
	Age	1	0.034	0.027	0.013	2.13
	Fidelity	1	0.014	0.253	0.103	2.46
	Intervention	2	0.073			
Math post						
Model DF = 14, error DF = 326, $R^2 = 0.565$	Math pre	1	<.0001	0.571	0.044	12.91
	Age	1	0.001	0.140	0.042	3.31
	SES	1	0.028	0.264	0.120	2.2
	Intervention	2	0.892			

Table 4 Pearson Correlation Coefficients, (Number of Observations). Correlations among outcome variables

	Language post	Communication post	EF post	TEC post	Math post
Language post	1	0.37***	0.40***	0.41***	0.36***
	(382)	(382)	(354)	(382)	(382)
Communication post	0.37***	1	0.06	0.20***	0.17**
	(382)	(396)	(357)	(394)	(394)
EF post	0.40***	0.06	1	0.38***	0.63***
	(354)	(357)	(365)	(365)	(365)
TEC post	0.41***	0.20***	0.38***	1	0.44***
	(382)	(394)	(365)	(404)	(404)
Math post	0.36***	0.17**	0.63***	0.44***	1
	(382)	(394)	(365)	(404)	(404)

Note: *$p < 0.05$ **$p < 0.001$ ***$p < 0.0001$

was rated to reach an “insufficient” quality at 1.2. Similar video ratings of DIL implementation fidelity was not considered relevant since this intervention was more scripted.

Intervention group differences

In order to find any nuances or trends of interest that could help us understand the general results, we explored intervention group differences with a series of one-way ANOVAs and Tukey post hoc tests. The control group scored better on several measures compared to the intervention groups. In math, control scored better than SEMLA both pre and post intervention (See Fig. 1): Pre intervention differences were significant ($F(2) = 4.853$, $p = 0.008$), as were post intervention differences ($F(2) = 3.499$, $p = 0.03$). Post intervention scores for language were lower in SEMLA than in the control group (ANOVA: $F(2) = 4.114$, $p = 0.02$; Tukey post hoc test: $p = 0.014$), and post scores for communication were lower in DIL compared to controls ($F(2) = 4.114$, $p = 0.02$). Post intervention scores for

Table 5 Multivariate Analysis of Variance, and estimates. MANOVA analysis of multivariate effects, and univariate regression estimates for significant predictors in the multivariate model. Significant MANOVA results and a non-significant effect of intervention are presented. Estimates are shown for all significant predictors for each outcome variable

Multivariate effects (selected results)					
Predictor	*Wilks' Lambda*	*Num DF*	*Den DF*	*p*	
Language pre	0.853	5	229	<.0001	
Communication pre	0.689	5	229	<.0001	
EF pre	0.671	5	229	<.0001	
TEC pre	0.774	5	229	<.0001	
Math pre	0.787	5	229	<.0001	
Intervention	0.942	10	458	0.186	
Estimated effects for the multivariate model					
Outcome variables	*Predictor*	*Estimate*	*SE*	*t*	*p*
Language post					
	Language pre	0.397	0.066	6.050	<.0001
	EF pre	0.683	0.326	2.100	0.037
Communication post					
	Communication pre	0.592	0.059	10.040	<.0001
	Language pre	0.004	0.002	2.560	0.011
	TEC pre	0.009	0.003	2.540	0.012
EF post					
	EF pre	0.532	0.056	9.540	<.0001
	Communication pre	−0.877	0.409	−2.150	0.033
	Math pre	0.027	0.009	2.990	0.003
TEC post					
	TEC pre	0.440	0.056	7.890	<.0001
	EF pre	0.389	0.130	3.000	0.003
Math post					
	Math pre	0.464	0.061	7.540	<.0001
	EF pre	1.586	0.386	4.100	<.0001

language were lower in SEMLA than in the control group (ANOVA: $F(2) = 4.114$, $p = 0.02$; Tukey post hoc test: $p = 0.014$), and post scores for communication were lower in DIL ($F(2) = 4.114$, $p = 0.02$).

Ratings of preschool quality using ECERS-3 also differed significantly between groups ($F(2) = 68.36$, $p < 0.001$). A Tukey post hoc test revealed that preschool quality was higher in control than in SEMLA ($p < 0.001$) and higher in the control group than in DIL ($p < 0.001$). There was no significant difference between the two intervention groups ($p = 0.997$). Units within the same preschool differed substantially in their ratings.

Results overview

Regression results overview

In both univariate and multivariate regressions, all post-intervention measures were significantly predicted by pre-intervention measures of the same variable. Age predicts post intervention performance in language, EF, TEC, and math in the univariate analysis. SES predicts post EF and post math in the univariate analysis, likewise fidelity is a significant predictor of post TEC. Presence of family language problems (FLP) negatively predicts post communication.

In the multivariate regression there were no significant effects of background variables such as age, SES or FLP; however, pre-intervention scores for language, communication, EF, TEC, and math all have significant effects on post intervention scores: EF is predicted by pre-scores for math and communication, the latter negatively related. Math, language and TEC are all predicted by EF. Communication is predicted by language, and TEC; (see Table 5). We take the differences between univariate and multivariate analysis to reflect the relatively strong collinearity between many outcome variables (see Table 4, and Table 5),

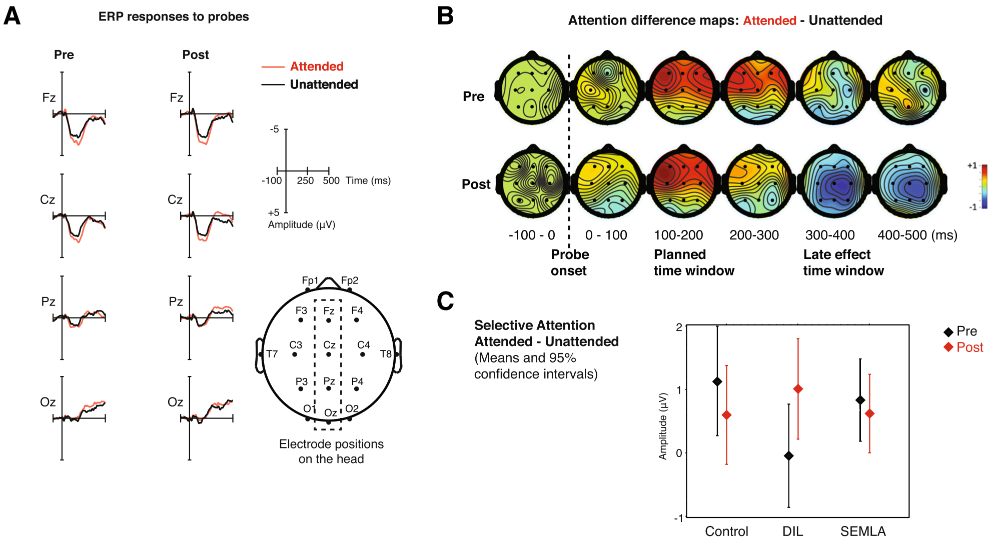

Fig. 2 **a** ERP grand average responses on midline electrodes (Fz, Pz, Cz and Oz) for attended and unattended responses, pre and post intervention. **b** Topographic grand average plots of the difference between attended and unattended responses averaged over 100 ms intervals. **c** Mean difference attended - unattended, per intervention group, pre and post with 95% confidence intervals in the 100-200 ms time window

compared to the significant but weaker effects of the background variables age and SES (see Table 3).

Intervention effects

In both planned univariate regressions and the follow up multivariate regression, there were no effects of interventions, neither as direct predictors nor as interactions. In the univariate regression model for communication, the interaction ECERS×Intervention was significant when other non-significant interaction factors were present in the model. However, when non-significant interaction predictors were removed, ECERS×Intervention was no longer significant and was removed as well. See Additional file 3 for details of non-significant results. The raw differences between intervention groups were small. The largest positive difference compared to controls was EF in the DIL group. EF difference pre – post in DIL was 0.15 standard deviations larger than the same difference for controls. The present study is not designed for such small effects: the sample size needed to detect such small effects is > 350. In Fig. 2c, mean post selective attention for DIL, is outside the 95% confidence interval for selective attention post. This effect is 0.24 standard deviations in the frontal electrodes, a small effect according to Cohen's rule of a thumb [126]. A sample size of 151 would be needed to detect such small effects. Our sample size was designed to handle medium to large effects, such as Neville et al. [4], were the effect size for one group, using the same paradigm, is 0.83 standard deviations among the best channels. Sample sizes in this section were calculated using G*Power [124]. The trend for an effect in ERP selective attention in DIL is discussed below but is not considered a genuine intervention effect.

The lack of intervention effects implies that there are no differences between effects, no mediating effects explaining the intervention effects, no moderating effects, and no differences in the distributions of intervention effects. The hypothesis about intervention effects (RQ1) found no support, rendering the hypotheses based on such an effect (RQ2, RQ3, RQ4 and RQ7) irrelevant.

EF

Only one hypothesized predictor of outcome variables was significant in the regression analyses. SES predicted EF in the planned univariate analysis. EF was also hypothesized to mediate intervention effects on language, communication, TEC and math. Math and language differences pre and post were also hypothesized as mediators of intervention effects in EF. While none of these mediating effects were present our results show that these variables are related both as correlations and as predictors in the multivariate regression (with the exception of language as a predictor of EF). Thus, EF pre-intervention predicted post-intervention language, TEC, math and (in a

Table 6 Auditory Selective attention results. A summary of ERP results regarding auditory selective attention. First, significant results from an ANOVA analyzing the attention effect at 100-200 ms is presented, and also the critical but non-significant Attention×Time×Intervention interaction. Second, two non-significant predictors of the selective attention difference are presented for comparison with similar regressions in Table 3. Third, selected exploratory correlations are presented. The last part presents exploratory ANOVA results for the late 300-400 ms attention effect, significant effects, and relevant non-significant effects

Attention effect ANOVA (selected results)			*Num DF*	*Den DF*	*F*	*p*
Attention			1	1606	6.3	0.0122
Attention×Time×Intervention			2	1606	1.33	0.2653
Electrode position			3	19000	1201.85	<.0001
Attention×Electrode position			3	19000	33.23	<.0001
Intervention×Electrode position			6	19000	16.62	<.0001
Selective attention regression (selected results, compare Table 3)						
Outcome variable		*Predictor*	*DF*	*p*		
ERP post		ERP pre	1	0.068		
Model DF = 14		Intervention	2	0.305		
error DF = 66,						
R^2 = 0.14						
Selective attention, Pearson Correlation Coefficients (selected results)						
	Selective attention pre	*N*		Selective attention post		*N*
Language pre	0.23*	84		0.07		89
Language post	0.03	82		0.00		86
Late time window attention effect ANOVA (selected results)		*Num DF*	*Den DF*	*F*		*p*
Attention		1	1613	5.52		0.0189
Attention×Time×Intervention		2	1613	0.1		0.905
Electrode position		3	19000	321.42		<.0001
Attention×Electrode position		3	19000	0.75		0.523
Intervention×Electrode position		6	19000	16.62		<.0001

Note: *$p < 0.05$

negative direction) communication. Math pre-intervention also predicted EF post intervention. EF is thus a predictor for most of the variables where it was hypothesized as a mediator for change. EF post also correlates with language post, TEC post and math post (see Table 4).

Age, SES, sex differences, multilingualism and time at preschools

Age predicts post-intervention performance in language, EF, TEC, and math in the univariate analysis. Age also correlated significantly with SCDI-words (Spearman's $\rho = 0.29$, $n = 383$, $p = < 0.001$) and to SCDI-morphology ($\rho = 0.23$, $n = 378$, $p < .001$), showing that older children had higher language skills, as reported by parents. There were no effects of age in the multivariate analysis.

SES predicted EF in the univariate analysis. While average SES of the multilingual group was lower than monolinguals, the hypothesized relation between SES and language was not significant in the regressions. Hypothesized positive effects on EF due to multilingual background, negative effects on math from having another L1 than Swedish, and positive relationship TEC and language were all non-significant.

The hypothesized sex differences in communication, EF or TEC were not significant (see Additional file 3).

A Kruskal-Wallis test was used to examine potential differences between monolingual Swedish-speaking children and multilingual children with regard to age at preschool enrollment and SES. Mean age at preschool start was slightly higher ($M = 19$ months) in the multilingual group than in the monolingual group ($M = 17$ months), but the difference was not significant. There was a significant SES difference between groups ($\chi^2 = 27.81$, $p < .001$, df = 1) with higher SES for the monolingual group (median = 8, $n_1 = 264$) than the multilingual group (median = 6, $n_2 = 129$).

Based on results from our pilot study, it was hypothesized that age at preschool start would have a negative relationship to current time spent in preschool (measured in hours per week). Spearman rank-order correlation coefficients were computed and there was a significant negative correlation between age at preschool start and weekly amount of time at preschool ($\rho = -0.16$, $n = 390$, $p = 0.0015$), thus indicating that children who were younger at preschool enrollment currently spend more time per week in preschool.

Higher SES was expected to correlate with children spending more time at preschool. There was a significant but small positive correlation between SES and weekly time in preschool ($\rho = 0.1$, $n = 391$, $p = 0.046$), thus indicating that children from relatively higher-SES backgrounds spend more time per week at preschool than children from lower-SES backgrounds. However, there was no significant correlation between SES and age at preschool start. There was no significant correlation between SES and SCDI-words ($\rho = 0.05$, $n = 378$, $p = 0.32$). There was however a significant correlation between SES and SCDI-morphology ($\rho = 0.24$, $n = 378$, $p < 0.001$).

Study limitations

There are some limitations to this study to be discussed. To begin with the available resources meant that the study was set to 6 weeks based on Neville et al.'s study [4], which showed results from a short-term intervention. However, Neville et al.'s study was two-generational and as such more comprehensive, involving both preschool and home. This suggests that future studies should be more comprehensive and implemented for a longer period of time in order to enhance the likelihood for significant effects. The 29 units were divided into three time-spans, which effected the randomization, as has been discussed already above. A limitation is also that this municipality is inhabited by a more than average amount of higher SES-families, and RCT:s are known to show effects mostly on lower-SES children, as explained by Wilson & Farran [32] among others. We therefore suggest that future studies in the Swedish context be situated in low-SES areas where learning potentials are expected to be greater. Another limitation in the context of intervention RCT studies, is that the involved preschools' pedagogical quality was shown to be higher than average, something that the ECERS-3 evaluations confirmed. A limitation, also lifted by [125] can be that the interventions were "*simply not ready for trial*" (p. 258). Both interventions might be limited according to how well they were designed and performed as well as according to their strength and intensity. We suggest that future studies make use of more pilot testing and quasi-experimental designs, before undertaking a more largescale RCT in the search for generalizable evidence. Such preparatory studies should include investigations to make sure that the intervention components are functional in the particular context in which the intervention is implemented, that intervention preparations in terms of training of teachers are efficient and that the tests used to evaluate the study are valid and reliable in relation to the specific learning goals targeted in the interventions.

Discussion

No statistically significant results were found in relation to effects of the two interventions on children's language and communication, EF, socioemotional comprehension and early math (RQ 1–4, 7). The sizes of the behavioral intervention group differences are very small, below what is referred to as 'small effects' in Cohen's rule of thumb [126] and below the effect sizes the study is designed to detect [48]. The discussion will first turn to possible explanations for this null result, followed by a closer discussion of the results and tendencies found in sub-parts of the data, e.g., the relation between background variables and outcomes on the one hand, and between different outcome measures on the other (RQ5 and RQ6).

Interventions

The SEMLA intervention is based on principles which to some extent are part and parcel of the general approach in Swedish preschools, such as group-based collaboration with playful exploration of a common overarching problem or theme. The rationale behind SEMLA is that it was expected to impact children's outcomes indirectly, for instance in that EF is enhanced by processes of verbal reflection and focused attention or that math is improved by children spending time with activities involving measuring, engineering and construction. DIL on the other hand, consists of individual, specific training of attention and early math skills and can thus be regarded as a contrasting working method compared to SEMLA. However, neither SEMLA nor DIL showed any effects on outcome measures compared to the control group, in which teachers and children carried on with business as usual in accordance with the preschool curriculum.

Intervention implementation

Both interventions were implemented by the regular preschool staff, with support from researchers and assistants. In the present study, the learning objectives were made clear during the instruction classes prior to interventions for both DIL and SEMLA staff. However, due to the contrasting nature of the interventions, there were differences with regard to intervention complexity and the specificity of intervention guidelines/manuals. For DIL, there were detailed instructions for how to teach the body-and-mind exercises (Additional file 2), and for the digital tablet game Magical Garden, the instructions to the child were delivered consistently through the tablet. SEMLA, on the other hand, did not have to be identically implemented across preschool units, since teachers were free to implement the particular means of helping children progress towards the learning goals, guided by examples from the SEMLA documentation form (Additional file 1). With regard to level of teacher instruction, Bleses et al. [21] recently conducted a large-scale Danish preschool intervention study, targeting language and pre-literacy skills and comparing the effect of script-based versus open intervention strategies. When teachers were provided with clear goals to strive towards but were left to their own devices to reach these objectives, the success of the intervention was far greater than among the teachers who had to follow strict scripts for teaching. In light of the study by Bleses et al. [21], it could thus be noted that the success of an intervention may depend on the level of action space given to the teachers, but that it may also rely on the specificity of the goals to strive for. Whereas the current study investigated potential intervention effects on a vast array of skills, it may be advisable to have a narrower scope in future preschool intervention studies. Future studies are needed to clarify the role of script-faithfulness of the SEMLA and DIL methods, and more research is needed with regard to implementation fidelity and effectiveness of pedagogical methods that are open-ended and/or highly complex.

Previous studies have indicated that in order to achieve effects of interventions, the level of difficulty needs be continuously adjusted to each child. For Magical Garden in DIL, this was the case, since the game is adaptive and provides tasks according to the child's ability and progression through the game. The body-and-mind exercises are harder to adapt individually, and it is unclear how this could have affected the intervention outcomes. The SEMLA intervention is individually adjusted in the sense that the teachers are expected to adjust to and to scaffold each child on his/her level. SEMLA was supervised and checked for implementation quality, but it is difficult to control for individual teachers fulfilling their part of the implementation. However, we have no reason to believe that the level of SEMLA was too high for the involved children.

Intervention duration and fidelity

The duration of the intervention was set to 6 weeks. Initially, a longer intervention program was planned. However, previous research with a similar focus of interest and similar target groups has led to intervention effects after intervention periods of a similar duration as in the current study (e.g. [4, 104, 19]). It was furthermore deemed too intrusive to keep the preschools committed to the project for a full semester, with consequences such as not being able to follow other interests, go on excursions etc. Additional factors for the decision to have a six-week intervention period were time and funding available. It is possible that the kind of pedagogical methods included in the current project could have been more successful if the staff had had more time at their disposal. In particular, SEMLA could have benefitted from this, since some of the teachers expressed difficulties with getting into the prescribed activities (see Lenz Taguchi et al., forthcoming). SEMLA was more time-consuming and more demanding to implement than DIL, and the results regarding intervention fidelity reveal that SEMLA units did not fulfill the requirements regarding number of sessions. The mean exposure to SEMLA was 13 out of the prescribed 25 sessions, compared to the mean exposure in DIL, which was 20. Fidelity is crucial in intervention studies, but has been found to be rather low, even in studies with a high level of support and coaching from researchers e.g. [127–129]. However, DIL did not have an effect on the targeted skills although intervention fidelity was in line with recommendations. The body-and-mind exercises were based on a successful intervention program in Head Start classrooms [4]. It should, however, be noted that the efficacy of Magical Garden as a way of improving early math skills has not previously been evaluated beyond measuring children's progress within the game itself.

How do we measure progress?

The choice of test battery is crucial when it comes to intervention studies. The tests must target and assess the same skills that the interventions target, but at the same time, the test should not be too close to the intervention targets, as this would constitute training for the test. In this study, the results from pre- and post-testing in the total group of children show that the test results improve slightly with time and that the different measures correlate significantly at pre- and post-testing, indicating that the measures used were reliable. However, as the intervention groups did not improve more than controls, we must also conclude that the interventions were not better than business as usual. The connections between tests, what they measure, and the skills actually trained within a particular intervention or pedagogical practice are not always clear-cut. This was the case for socioemotional comprehension and communication, which were both hypothesized to improve more in SEMLA, which was thought to focus children's abilities to be empathetic, listen to one another and pay attention to each other's utterances and thoughts to a higher degree than DIL. However, this was not the case. There are several test tasks and measures that need further investigation with regard to validity and reliability, not least since they have not previously been used in the Swedish context. There is one result that stands out as particularly unexpected: DIL had improvement of early math skills as its primary target, through the application Magical Garden, and yet there was no improvement in early math skills in the DIL group. The math test was not based on this game, but the same type of mathematical calculations appeared in both the game and the math test. Why did the DIL intervention not succeed in improving these children's math abilities above the level of the groups who did not train math in this specific and targeted way? Previous research has revealed a lack of far transfer with regard to computerized working memory training [29], but less is known with regard to math training. In a study by Goldin et al. [130], children showed transfer of EF skills after an intervention consisting of computerized games, but only when the assessment was also computerized, suggesting that changes in the contextual setting can hamper transfer of specifically trained skills. Another tentative explanation comes from a recent qualitative study in Swedish preschool by Nilsen [131], who suggested that children may not learn the intended content in a pedagogical application, but rather progress through a game by means of trial-and-error.

With regard to the measure of auditory selective attention, the ERP selective attention effect did not show any intervention effect in the regression analysis or ANOVA (see Table 6), but there was a small change in the DIL group (see Fig. 2c). Pre-intervention amplitudes were lower in the DIL group compared to both SEMLA and control but after intervention, amplitudes were similar. There is thus a problem with group differences before intervention, weakening any conclusions about an intervention effect. The effect size is also small, see discussion in the results section. Considering that DIL is in part based on training that has previously been shown to have effects on the same selective attention ERP measure [4], our results are not in sharp contrast to that research, but rather a weak tendency in the same direction. This trend is also in line with the notion that ERP effects are often sensitive to group level experimental manipulations but less stable over repeated tests of the same person, while many stable psychological tests are not very sensitive to experimental manipulations cf. [132].

Future direction

Some additional questions arise in the context of the current study. What did children learn in the control group where business as usual was implemented? This is of particular interest since the control units had significantly higher preschool quality, as rated with ECERS-3, than the intervention groups. To what extent are preschool teachers effective in employing pedagogical strategies, whether these are advocated by their education, part of a research project or stem from ideological beliefs of child rearing and teaching? Given the rather ambitious goals of the Swedish preschool curriculum [69], it would be expected that preschool teachers have a high level of control of pedagogical means and how these means support individual development and learning. However, in light of a recent preschool audit by The Swedish Schools Inspectorate [133], revealing uneven preschool quality, this is something that needs further exploration. The present study is but a first step in building a scientific base from which to provide this knowledge for the Swedish context.

Apart from evaluating which of two pedagogical methodologies that were best suited to enhance different abilities in children, the study aimed to add to prior research by investigating and hopefully disentangling the relation between background factors like SES, age, sex, languages spoken and outcome variables. In addition, the study aimed to clarify the potential relations between the different outcome variables language and communication, EF, socioemotional comprehension, and early math. Below, we discuss the results and tendencies found in the data in relation to first, background factors, and then the relation between tested skills.

Background factors

While prior studies have found a clear relation between intervention and enhanced executive functions in preschoolers from low-income backgrounds [12, 31], these results have been hard to replicate in more diverse SES samples [32]. The present study had a mainly higher-SES population, when SES is measured as a combination of parental education level (4 grades: elementary school, upper secondary school, vocational education, and college/university) and family income (3 grades: 0–200,000 SEK, 200,001–500,000 SEK, and 500,001 > based on both parents scores divided by two). However, going into details of the data, there was a bias as to the spread of SES between the groups, yielding a control group which had children with significantly higher SES than both the SEMLA and DIL groups. The DIL group, in turn, had a higher SES than the SEMLA group. Based on earlier findings, children with lower SES (in this case both intervention groups as compared to the control group) would be expected to improve more than the children with higher SES (e.g., the control group), at least in EF and auditory selective attention (e.g. [4]). As this was not the case, either our sample did not comprise enough low-SES[10] children, or the interventions simply were not better than business as usual in enhancing the targeted skills. SES was also correlated to

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[10] Comparing SES between countries is hard as the rating is relative. The general low SES within the Swedish or Scandinavian context can be expected to be above the general low SES of, for example, U.S. where poverty is quite wide-spread and have a much lower "lowest" degree, as 83% of the adult Swedes has high school education or more and relative minor income differences compared to most other OECD countries [134].

both EF and math, which was in line with previous research. Yet another complicating factor regarding SES in the present sample is that the children with lowest SES (most of whom were assigned to the SEMLA intervention) also formed the group with the highest proportion of multilingual children. As SEMLA is an intervention which in many respects relies on language use and interaction, this could have put this group at a disadvantage. Also, the testing procedure and, obviously, the results thereof, are challenging when the child is not fluent in the language of testing. A study with children from more diverse SES backgrounds, and from various parts of the country, would have given a better foundation for a study of this kind. Time and funding limits did affect the ambition, as did the preschools themselves: preschools with many lower-SES families, which in this setting also meant that they were less familiar with Swedish, would not have had the time needed to enroll in research of this kind, which demands quite a bit of devotion and time. So, biases are likely even in larger-scale studies, unless we find ways to make interventions less straining for the staff. A suggestion made by other research [135] is to try effects in small-scale, well-controlled, and highly supervised studies and only proceed to larger-scale contexts once teachers have proven that they fully understand the implementation part and the effect of the intervention is documented. This is worth pursuing but does not do away with the problem of potentially more complex pedagogical methodologies like SEMLA.

Lastly, in relation to SES, even high-SES children should benefit and enhance their abilities while in preschool, so the general finding that this group of children rarely shows effect in intervention studies is problematic (see however [33, 34] who found effects in high-SES children for pre-literacy intervention). Our understanding of why this group of children is difficult to further improve in regard to the targeted skills is low. Therefore, in order to fulfill the curriculum goal of offering a preschool for all children, this need to be addressed in future studies. Likewise, the findings of this study which also replicate earlier studies, is that SES is correlated to all outcome measures (language composite, communication, EF composite, TEC, math), again indicating the need for preschools to improve their pedagogical techniques in order to give all children an equal start in preparing for the school years to come.

Among the hypotheses was also one pertaining to bi- or multilingual children. While bilingual children have long been reported as having an advantage in terms of EF skills (in particular inhibition and flexibility), this belief was recently challenged. Duñabeitia et al. [136] conducted a large-scale study with school-aged children and adolescents and found no support for a bilingual advantage for inhibition. A recent meta-analysis did not reveal enhanced EF in bilingual adults [137]. In the current sample, there was a significantly higher proportion of bilingual children in the SEMLA intervention group compared to both the DIL and control groups. This is unfortunate but explicable, since children typically attend preschool in the area where they live, and low SES tends to come together with a multilingual background, leaving a particular preschool with a homogenous population [138]. This is also seen in that monolingual children in the sample had a significantly higher SES than the bi- or multilingual children. Thus, the low-SES and multilingual situation of at least one of the SEMLA intervention groups could have affected the outcome.

Time at preschool has been shown to influence children's life outcomes, at least when the quality at the preschool is high (e.g. [36]). This led us to expect that children who started early and/or stayed longer each day could potentially benefit more from good pedagogical input than children who entered preschool at an older age and/or spent only a limited amount of time at the preschool. We did not find any such indications in the present data. What we could see was that if a child starts preschool early (e.g. around 1 year old), s/he will also spend longer days at preschool when s/he is between four and six-years old. In order to address the question of whether and how preschool attendance relates to life prospects, we would have to return to the sample in years to come. There was no correlation between SES and preschool start, but there was a tendency for higher-SES children to also spend more hours/week at the preschool.

However, one complicating factor in terms of similarity between groups (in line with earlier complications such as SES and multilingualism) is that the children at control preschools had a significantly greater presence (hours/week) at the preschool than the SEMLA groups. The difference between the control and DIL groups was not significant. The children in the DIL group were also significantly younger than the children in the control group, but not the children in the SEMLA group (in the SEMLA group, the age range was 49–74 months, in the DIL group 46–74 months and in the control group the age range was 44–74 months at pretesting) making the skewness of groups go through almost all background variables (the exception is sex where there was an even distribution between groups).

As for age, we expected that a higher age would correspond to higher scores in all areas tested. This is trivial in the sense that children develop, regardless of interventions, and can be expected to improve with age. This was also found to be the case, as age was correlated to all measures (language, EF, socioemotional comprehension and math skills) except communication. The measure of communicative ability was a novel invention of this project (Tonér & Gerholm, Language and executive function in Swedish preschoolers: a pilot study, under review, Applied Psycholinguistics). It was based on the screening tool ADOS [101], and targeted behaviors connected to interaction quality such as meeting of gaze, gestural behavior, adequate response to questions, etc. The many nonverbal aspects of the measure can explain why it did not follow language generally in terms of predictive value. Social and pragmatic ability is a skill that is unevenly spread in populations and even if it is highly malleable and might change with age, a very young child can easily outperform a much older child given that their interest in interaction and other people, their self-esteem, and general outgoingness differ. At the same time, mood and other more fluctuating aspects of behavior can influence how a particular child is rated, making the scores potentially unstable if used only twice as in the present data.

The Strengths and Difficulties Questionnaire (SDQ), a questionnaire that both preschool staff and the children's parents filled in, was used to see whether specific aspects of personality traits would matter for the study outcomes. We found no such correlation, neither in regard to other background variables nor to the skills tested in the pre- and post-testing. There was further no difference between the groups as to SDQ.

As for EF, there were no differences between the groups at either pre- or post-testing.

Between the intervention groups, there were furthermore no differences in communication score at pretesting but at post-testing, the control group scored significantly higher than the DIL group. As there is no reason to assume that DIL would have had a negative influence on children's pragmatic skills, this is not easily explained. Children were tested by the same test leader in the clear majority of cases (some exceptions can have occurred due to illness among testing staff) both pre and post, and a similar test-retest difference could be expected.

Yet another result that needs some footwork to account for is that the control group at pre-testing had better math scores than the SEMLA group. However, at posttest the difference was non-significant. It is unclear how this came about, in particular as our expectation of the SEMLA intervention was not particularly high in regard to math, which was elaborated on and practiced in a more holistic manner in comparison to DIL's firmer math training. As SEMLA did not show intervention effects we cannot interpret this posttest finding as if SEMLA had effects on math. We furthermore have no reason to assume that children in the control group deteriorated in regard to math between pre- and post-testing. As already mentioned, the surprising finding in regard to math was that the DIL group did not enhance their skills.

Earlier research made us expect to see a language advantage in girls [39, 41, 139]. No such findings were evident from the data, nor did a pilot study on a similar group of children reveal any differences in language between girls and boys (Tonér & Gerholm, Language and executive function in Swedish preschoolers: a pilot study, under review, Applied Psycholinguistics). As recent evaluations of school performance and results in older children and adolescents [140, 141] show a clear advantage for girls, a comment from our study would be that either times are about to change and the generation of boys studied here will catch up with girls even later on; or, the gender-related difference seen in older children and adolescents does not appear until after the children have left preschool.

Preschool quality was a measure evaluated by ECERS-3 in the present study. Results from prior studies on preschool quality [e.g. 36, 38, 39] indicate that attending a high quality (as measured by ECERS mostly) preschool has long lasting effects in areas such as cognition, literacy and general school readiness. These studies were not short-term intervention projects, making comparisons flawed, yet the results of the present study show that preschool quality was significantly higher in the control preschools compared to both SEMLA and DIL preschools. Moreover, all but three preschool units (which were rated "minimal") within the present study were rated from "good" up to "excellent", making a distinction based on qualitative aspects less usable as a sorting variable. A curious finding is that the ECERS-3 team in some cases rated different preschool units within the same preschool very differently. In these cases, the units share the same physical space but occupy different rooms. In many cases the teachers also go between and cover for each other in the event of absences, etc. The quality would be expected to be the same. If the difference relates to specific teachers being in one unit rather than the other at specific times, the need to understand teacher impact on pedagogical practices in more detail is urgent. Another possibility is that different members of the ECERS team visited the different units and interpreted the findings differently. Future studies would have to proceed with a closer scrutiny of the relation between the ECERS-3 ratings scales and the pedagogical skills and working conditions of the teachers and rating teams.

Summarizing background factors, we can see that the skewness of the randomization led to the control group starting out with higher SES and longer days than the SEMLA group, which in turn had a large group of multilingual and lower-SES children. It cannot be ruled out that this influenced the study outcome and future studies will have to find ways to balance groups more evenly. Adding preschool quality to the mix, we see that the control group appears to have also been favored by the highest quality marks of the assessed preschools. As has already been mentioned, the current study was performed in three waves where each wave had to be randomized without information on how the following groups/preschools would be composed. This is a drawback that should be avoided in the future.

Fidelity of intervention was measured as the amount of time a child was involved in the intervention, the control group having the value 0. Our measure of socioemotional comprehension, TEC, was predicted by the fidelity of the intervention in the univariate analysis. Perhaps children with high socioemotional comprehension (as measured by TEC) are more in tune with teachers and other children and this resulted in higher participation? This remains highly speculative, and we have not found any further evidence in this direction. Most likely, it is a spurious effect, and we present it without further attempts at interpretation.

Although research supports the possibility of obtaining effects from interventions as short as five to eight weeks e.g. [104, 4] there is reason to discuss how realistic rapid change might be in the selected outcome measures. Complex skills like language, EF and socioemotional understanding share the problem of also being difficult to evaluate and assess, as these skills tend to blend and depend on one another and, potentially, on other skills that were not tested [142]. Adding to this, the standardized tests available for clinical use are often too time consuming and focused on children at risk to suit the research intervention context. In the present study, we further needed to test an array of complex skills within a limited time frame, which made the assessment even more delicate (Tonér & Gerholm, Language and executive function in Swedish preschoolers: a pilot study, under review, Applied Psycholinguistics). This stated the present study found pre-intervention measures to predict post-intervention measures in both the univariate and the multivariate regressions analyses, indicating that the measures per se were up to the task.

Relation between outcome variables

As skills come together in complex ways, the results in some domains are expected to correlate more than results in other domains. This is also why a composite measure was used, e.g., for language on the one hand and EF on the other. The results showed a correlation between measures as expected. Furthermore, EF was predicted by pre-intervention scores for math, i.e. having a high/low score on the math tasks was related to the child's scores on EF. EF was in general indicative of other measures; apart from math, it predicted language and TEC. This is likely a result of abilities being related to one another and to a background general cognitive ability measure (such as IQ, which was not tested in the present study). SCDI-III, our parental questionnaire measuring the child's productive vocabulary and morphology, would similarly be expected to correlate with the language measures actually tested on the child him/herself, (such as PPVT and the morphosyntactic and semantic measures extracted from the narratives). Results from the post-testing show that both SCDI-words and SCDI-morphology correlated significantly with each other, PPVT, number of subordinate clauses, and the information score. However, less expectedly, neither SCDI-words nor SCDI-morphology correlated with the following measures, all extracted from the narrative data: number of unified predicates, the number of morphosyntactically well-formed utterances, and the communication score. SCDI-words and SCDI-morphology further differed in their relation to SES, as SES did correlate with SCDI-morphology but not with SCDI-words from the same questionnaire. Age and SCDI were, more expectedly, correlated for both words and morphology. One thing to keep in mind while investigating SCDI and other parental questionnaires is that parents tend to interpret questions differently. As for the morphology measure of SCDI-III, it can be difficult for parents to understand what is being asked when they are instructed to check the kinds of sentences their child uses most, guided by examples of utterances with or without, for example, subordinate clauses. However, as the word count part of the SCDI-III is fairly straightforward, one would expect a correlation with the word measure rather than with the morphology one.

Language is a complex skill composed of a number of different abilities, apart from also having both a productive and a perceptive side and being part of tests which also target EF, socioemotional comprehension, math, etc. As many intervention studies use either a single measure, such as vocabulary size, or a composite measure for language, the results from the present study will have to be used as a starting point for more detailed examinations and analyses of the different parts of language use and understanding and, in particular, the reliability and validity of the tests used to assess these different parts where cultural adaptation is a much needed aspect (Tonér & Gerholm, Language and executive function in Swedish preschoolers: a pilot study, under review, Applied Psycholinguistics).

The ERP attention difference, measuring auditory selective attention, had a positive correlation with language (pre-intervention) see Table 6. This possibly reflects general task demands such as listening to the story and communicating with testers, i.e. language skills might help children understand and execute the attention task, perhaps more so the first session, but this is a highly speculative explanation.

Another unexpected ERP effect was a late (300–400 ms) negative attention effect (see Table 6 and Fig. 2) with central topography. The effect is similar to attention effects in adults and was unexpected for the present age group [114, 143]. This effect seems stronger in post testing but the analysis shows an attention as a main effect that does not interact with time (pre or post session). The effect might be of interest when comparing our population with populations in previous research, but this is beyond the scope of the present paper.

Novel rating system for communication

As stated above, the communication rating measure was novel and only tested in a pilot to the present study. In the present study it was not correlated to the other language measures, which was expected, as a child can be perfectly in tune interactionally despite not having a large vocabulary or complex syntactic abilities and vice versa. An indication that the measure is worth pursuing in further studies is that it was predicted by the background factor Family Language Problems. These problems could, of course, be of a strictly verbal nature (such as dyslexia) but they could also relate to more interaction-related difficulties such as autism spectrum disorders etc. Future studies will have to look into these relations more closely. Also, communication and EF were negatively related at pre-testing. This could be explained by the fact that children who have difficulties with attention and with focusing on the testing tasks might also find it difficult to interact with the test leader. At post-testing there was no significant relation between the two scores, potentially due to children being more at ease with the test situation and/or test leader the second time around. Communication was also predicted by the composite language measure and by TEC. The levels of socioemotional comprehension and communicative uses of language and interaction do not necessarily come together but the correlation in the present data appears intuitively plausible. As the communication measure is novel and the measure for socioemotional comprehension consisted of only one test, future studies will have to further investigate the relation between these two areas.

Conclusion and future directions

As the interventions did not yield results, we have to conclude either that the interventions were not implemented in the right manner, that they were too short, that the groups were too heterogeneous to compare, or that the pedagogical methods in use in preschools are less important for children's outcomes than what might be expected. Having a high overall quality might be good enough in order for children to embark on their developmental trajectories in the best way they can.

Summing up the discussion on background variables, we can see that SES is an important component even in the typically higher-SES Swedish preschool context. Children with similar backgrounds also tend to live in close proximity to one another and thus attend the same preschools. This entails an obvious risk/opportunity for these children also remaining in the same SES environment. For the lower-SES children this is a critical condition threatening to influence the rest of their lives in a negative way [26, 27]. Although a political issue on the whole, pedagogical practices in Swedish preschools, which reach almost all children from an early age, could well be the best way forward to even out the differences associated with SES. To succeed in this, the pedagogical practices as such need be closely scrutinized with regards to their efficiency and impact. This study was one of the first attempts within the Swedish preschool context to accomplish this, and the lack of conclusive results can be used as a foundation for future attempts.

Additional files

Additional file 1: SEMLA. Observation protocols. Observation protocols featuring the seven components and the processes of the group and individual children. (DOCX 72 kb)

Additional file 2: DIL. Intervention protocol. DIL. Instructions to teachers for how to implement the digital learning paradigm for Magical Garden and body-and-mind exercises. (DOCX 594 kb)

Additional file 3: All Univariate results and all Multivariate results. All tests for univariate and multivariate regressions. (PDF 53 kb)

Additional file 4: Supplementary ERP data. Supplementary ERP grand average plots for all head electrodes, HEOG and VEOG. 1. All pre intervention 2. All post intervention 3. Control pre 4. Control post 5. DIL pre 6. DIL post 7. SEMLA pre 8. SEMLA post. (XLSX 15 kb)

Abbreviations

ADOS: Autism Diagnostic Observation Schedule; ANOVA: Analysis of variance; BRUK: Bedömning, Reflektion, Utveckling, Kvalitet (Assessment, Reflection, Development, Quality); CMS/DRL: Common Mode Sense active electrode/ Driven Right Leg passive electrode; CONSORT: Consolidated Standards of Reporting Trials; DCCS: Dimensional Change Card Sort task; DIL: Individual digital implemented attention and math training paradigm; ECEC: Early Childhood Education and Care provisions; ECERS-3: Early Childhood Environmental Rating Scale, third edition; EEG: Electroencephalography; EF: Executive functions; ERP: Event-related potential brain response; FLP: Family Language Problems; HSKT: The Head-Shoulder-Knees-Toes task; L2: Language two (second language); MANOVA: Multivariate analysis of variance; MG: Magical Garden; OECD: Organisation for Economic Co-operation and Development; PPVT: The Peabody Picture Vocabulary Test; RCT: Randomised controlled trial; RQ: Research Question; SCDI: Swedish Communicative Development Inventory; SD: Standard Deviation; SDQ: Strength and Difficulty Questionnaire; SEMLA: Socioemotional and Material Learning group paradigm; SES: Socioeconomic status; STEAM: Science, Technology, Engineering, Art and Mathematics; TA: Teachable Agent; TEC: Test of Emotion Comprehension

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Authors' contributions

HLT and TG received the funding for the project through an application to the Swedish Research Council (April 2015). The design of the project was done by all authors. During the project, SF and SK were responsible for the DIL intervention. AP and HLT were responsible for the SEMLA intervention. ST and PK were responsible for the EEG experiment. TG was responsible for the background information, the pre- and post-testing of the children and the handling of data at the Department of Linguistics. HLT and SF were responsible for the handling of data at the Department of Child and Youth Studies. At bi-weekly meetings throughout the planning and the execution of the study, all project participants, except testers who were employed solely for carrying out the testing procedures, took part in and contributed to the creation and implementation of the project. In the article, TG was responsible for the main text and structure of the paper. PK and ST were responsible for text relating to the analyses. PK, together with a statistician, was responsible for the analyses of RQ 1–4 and 7, and ST was responsible for, and performed all descriptive statistics and statistical analyses related to, RQ 5 and RQ6. The other authors appear in alphabetical order. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated and analyzed during the current study are not publicly available due to personal integrity related to our ethics approval but parts of the data (on group level) could be made available from the corresponding author on reasonable request. We are happy to provide openly accessible materials as well as information on how we have proceeded in test management, mobile EEG laboratory set-up, and translation of various materials to Swedish.

Ethics approval and consent to participate

All participating adults and parents of participating children have signed an informed consent form allowing for project members to publish results on the group level. No analyses of individual children have been performed and individual scores cannot be released, not even to parents. All data is coded and depersonalized. All data is kept in accordance with the regulations of data handling from the Swedish Research Council [144]. The project was reviewed and ethically approved by The Regional Ethics Board [145] DNR nr: 2015/1664–31/5.

Consent for publication

No individual data is presented in this article.

Competing interests

The interventions employed subscription materials from the NIH Toolbox [146] as well as a math application developed by Stanford and Lund Universities [74]. None of these had control over the data or the design of the study but do retain the right to see the results of the data analysis. The authors have no other competing interests.

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Selective Auditory Attention Associated With Language Skills but Not With Executive Functions in Swedish Preschoolers

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Associations between language and executive functions (EFs) are well-established but previous work has often focused more on EFs than on language. To further clarify the language–EF relationship, we assessed several aspects of language and EFs in 431 Swedish children aged 4–6, including selective auditory attention which was measured in an event-related potential paradigm. We also investigated potential associations to age, socioeconomic status (SES), bi-/multilingualism, sex and aspects of preschool attendance and quality. Language and EFs correlated weakly to moderately, indicating that relying on measures of vocabulary alone may overestimate the strength of the language–EF relationship. Contrary to predictions, we found no correlations between selective attention and EFs. There were however correlations between morphosyntactic accuracy and selective auditory attention which is in line with previous work and suggests a specific link between morphosyntax and the ability to suppress irrelevant stimuli. In Sweden, socioeconomic differences are rather small and preschool is universally available, but nevertheless, aspects of parental SES predicted children's performance on all measures. Bi-/multilingual children performed lower on language also when controlling for SES, highlighting the need for interventions to reduce inequalities in educational outcomes already in preschool. A female advantage was found for both language and EFs, whereas preschool attendance and quality were not significantly related to outcome measures. Future work should include longitudinal studies of language and EF development, include children from diverse SES backgrounds and contribute toward a theoretical framework that further clarifies the language–EF relationship.

Keywords: language, executive functions, selective attention, early childhood, socioeconomic status, bilingualism, event-related potentials

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INTRODUCTION

The development of language skills and executive functions (EFs), including selective attention, seem to be overlapping processes, but the direction and nature of the relationship is still somewhat unclear. Aspects of language skills have been shown to strongly predict later outcomes on an array of domains: literacy, school readiness and psychosocial outcomes (e.g., Justice et al., 2009; Law et al., 2009; Feeney et al., 2012; Duff et al., 2015). Likewise, EFs have predictive value for aspects such as academic achievement, physical health and socioeconomic status (SES; e.g., Moffitt et al., 2011;

Stephens et al., 2018). Both language and EF are amenable to improvement (see e.g., Diamond and Lee, 2011; Diamond and Ling, 2016; Grøver et al., 2020; Tarvainen et al., 2020), and improved knowledge about the language-EFs association has possible applications in preschool practices and curricula. However, for typically developing Swedish preschoolers, little is known about the possible relationships between language and EFs and potential differences in these skills due to factors related to the individual and to the environment. Earlier studies from other contexts that have investigated language and EFs have often put EFs in the foreground, conducting an array of EFs tests and experiments but focusing the investigation of language to measures of vocabulary (e.g., Gathercole et al., 1999; Fuhs and Day, 2011; Petersen et al., 2013; Weiland et al., 2014; Miller and Marcovitch, 2015). In our view, empirical investigations of the language-EFs relationship would benefit from a more language-focused approach, and theoretical accounts of the language-EFs association need to more carefully define what is meant by "language," which in turn would aid in formulating more detailed hypotheses and predictions.

Language Development

Over the preschool period, children develop their language at an impressive pace, including expanding vocabulary and mastery of morphological and syntactical structures, both receptively and productively (e.g., Tomasello, 2000; Song et al., 2015). The use of language in discourse undergoes rapid development in particular from 3 to 5 years of age, and the ability to tell a story–to construct a narrative–is one aspect of language use that requires and reflects increased linguistic skills as well as cognitive and social skills (e.g., Berman et al., 1994).

Swedish language is an East-Scandinavian language of the North-Germanic branch, and is characterized as a verb-second language, with relatively limited morphology: verbs are not conjugated for person or number and nouns are inflected for number and definiteness only. There are two grammatical genders. For individuals learning Swedish as a second language, word order and noun phrase gender agreement present main challenges (see also Reuterskiöld et al., 2021).

Executive Functions

There are differing views about the nature of EFs and the debate is ongoing with regard to how to best operationalize these aspects of cognitive control. However, EFs are often described as consisting of three core, interrelated skills: working memory, cognitive flexibility/shifting and inhibition (Miyake and Friedman, 2012; Diamond, 2013), upon which more complex and later-developing skills, such as problem-solving, reasoning, and planning, are developed (Diamond and Lee, 2011). It has been suggested, that EFs are best conceptualized as a unitary construct before school age since EF tasks thought to measure different EF components load onto a common factor in young children (e.g., Wiebe et al., 2008; Fuhs and Day, 2011) but there is no complete agreement, see for instance Howard et al. (2015), for a differing viewpoint. It has furthermore been suggested that a two-factor model with inhibition and working memory as separate dimensions, best describes EFs from age 5 (e.g., Miller et al., 2012), and the authors conclude that the latent structure of EF may depend on the choice of particular tasks and performance indicators.

Selective Attention

Selective attention can be regarded as either a part of EFs, or as a prerequisite for EFs (see e.g., Diamond, 2013; Dajani and Uddin, 2015). In the former case, selective attention could be reframed as an aspect of inhibition in the form of interference control. Selective attention, or selective information processing, refers to the ability to prioritize relevant stimuli over irrelevant distractors, in other words, to the rather advanced ability to suppress interfering input from complex stimuli (see also Gandolfi et al., 2014). Attention in infancy has been demonstrated to predict EFs in toddlerhood: Frick et al. (2018) found that sustained attention predicted early EF in Swedish infants and toddlers, and authors concluded that early attention is a foundation for EF development. Veer et al. (2017) showed that visual selective attention predicted working memory and inhibition in 2–3-year-olds. Furthermore, selective attention has been proposed to link specifically to the working memory system (Vandierendonck, 2014).

Selective auditory attention is also involved in language processing, specifically so in speech segmentation (Toro et al., 2005) but also in a broader sense: Selective attention helps us communicate in everyday situations in which we need to pay attention to one speaker in the presence of distractors, and to dynamically redirect attention to different speakers or other sources of auditory information (e.g., Shinn-Cunningham and Best, 2015). Neural correlates of auditory sustained selective attention has been investigated with behavioral methods but also in experimental designs using event-related potentials (ERPs), starting with classic dichotic listening experiments on adults (e.g., Hillyard et al., 1973) as well as ERP paradigms adapted for young children (e.g., Coch et al., 2005; Sanders et al., 2006; Stevens et al., 2009).

The Language–EF Relationship

Some studies have indicated that aspects of EFs seem to lay the foundation for aspects of language development, leading to the assumption that good EFs facilitate language learning (e.g., Weiland et al., 2014; Woodard et al., 2016; ten Braak et al., 2018). On the other hand, language has been claimed to play a crucial role in the development of EFs (e.g., Kuhn et al., 2014; Miller and Marcovitch, 2015; Botting et al., 2017). It has also been suggested that the relation between language and EFs is dynamic and may depend upon the specific skills investigated and when during development these skills are assessed (e.g., Friend and Bates, 2014; Bohlmann et al., 2015; Slot and von Suchodoletz, 2017). The lack of consensus regarding the language–EF relationship is in turn related to the lack of a universally accepted theory of EFs and, possibly, to vague and/or limited definitions and operationalizations of language. The investigation of relationships between aspects of language and specific EF components is also obstructed by the lack of clarity regarding the latent structure of EF in early childhood, as mentioned above.

Examples of existing EF theories, which to some extent include language include Barkley's (1997) suggestion that internal speech should be considered as an EF, and Zelazo's (2015) suggestion that EFs are verbally mediated and that EF development involves the improvement of formulating increasingly complex hierarchical rules. For Barkley's theory, it is unclear exactly what such an idea would entail in terms of predicting more specific aspects of the language-EF relationship, see also Jones (2009) for a critical appraisal of internal speech as a concept. If Zelazo's idea holds, one would predict stronger associations between EFs and syntactic skills compared to other aspects of language, since syntax is concerned with embedded, rule-governed structures, and one would expect language measures to predict EF better than vice versa. Results pointing to the crucial role of language for EF development include a study by Botting et al. (2017) who examined language and EFs in deaf children and found that language mediated (non-verbal) EFs but not vice versa, suggesting that language is key to EF.

However, an opposite direction of the relationship is also suggested, in other words that aspects of EF are involved in language processing. To the extent that inhibitory processes can be reliably isolated in early childhood, aspects of inhibition in particular have been shown to associate with language. Gandolfi and Viterbori (2020), hypothesized that inhibition would be important in language acquisition by enabling children to deal with interfering information during sentence processing, and results suggested that interference suppression could be involved in both lexical production and expressive grammar in preschool-aged children. Kaushanskaya et al. (2017) showed that non-verbal inhibition predicted school-aged children's syntactic abilities. For Swedish preschool-aged children, Tonér and Nilsson Gerholm (2021), found concurrent associations between measures of inhibition and morphosyntactic accuracy. Woodard et al. (2016) showed that inhibition plays a role in young children's interpretation of ambiguous sentences. Furthermore, findings by Friend and Bates (2014) indicate that the ability to maintain focus and inhibit prepotent responses at 4 years of age supports subsequent narrative ability, and Blain-Brière et al. (2014) showed that EFs contributed more than IQ to typically developed preschoolers' pragmatic skills during conversation.

With regard attention in a broad sense, D'Souza et al. (2017) proposed that infants' ability to allocate attention may be crucial for them to attend to important linguistic input, which in turn would affect language development – in other words, attentional capacities is one of several possible constraints on language development. If on the other hand some aspect of language aids selective auditory attention specifically, one might predict that language-focused intervention would improve attention, which has actually been shown to be the case: auditory selective attention was improved after vocabulary training (Stevens et al., 2008) and after intervention targeting early literacy (Stevens et al., 2011). However, it is still unclear what constitutes the mechanism behind the gains in attention, and it is theoretically possible that the language and literacy interventions also included aspects targeting attention specifically.

There is a risk that tests that purport to assess EFs, actually also place high demands on language. Even "non-verbal" EF tests often require at least some level of language comprehension, something that is seldom mentioned or problematized in the literature on EFs (see Deák, 2014; Kaushanskaya et al., 2017 for a discussion). Conversely, language tests often require some EFs. There is in other words a potentially large task impurity problem which needs consideration when selecting tasks and interpreting the results. It could also be argued that associations between pragmatic abilities and EFs could be regarded as trivial: Emerging pragmatic skills, including children's narrative ability, involve both linguistic, social, and cognitive abilities (e.g., Berman et al., 1994; Fernández, 2011), However, finding spurious relationships between narrative ability and EFs would probably be more likely when examining narratives with respect to overall coherence than when extracting information regarding content, syntax and vocabulary from the narratives.

Demographic Factors

Development is constrained both by our biological heritage and by factors in human environments. It is well established that SES is connected to children's acquisition of language and EFs skills, including auditory selective attention (e.g., Hoff, 2003; Stevens et al., 2009; Sarsour et al., 2010; Ursache and Noble, 2016). In Sweden, the socioeconomic differences are smaller than in most other OECD countries despite a rapid surge of income inequality since the early 1990s. Poverty rates are among the lowest, 28% of the population have higher education, women have a high employment rate compared to other OECD countries and unemployment is receding, although it remains high for foreign-born (OECD, 2017; SCB, 2017, 2018). The association between SES and language/EFs/attention could thus be expected to be weaker in Sweden than in contexts with larger socioeconomic differences and more unequal access to high quality child care.

In Swedish preschools, 25% of children are either born in another country or have two parents that are foreign-born and are thus likely to be dual language learners (Puskás and Björk-Willén, 2017). Increased variability in majority language skills may be a result of variations in exposure, which in turn could be related to age at preschool start (children to foreign-born parents start preschool later than children to Swedish-born parents), and the possibility to use the majority language in an array of communicative contexts. It has been shown in a large sample of German preschoolers that high preschool quality seems to be extra important for dual language learners with low exposure to the majority language (e.g., Kohl et al., 2019). Calvo and Bialystok (2014) showed in a sample of Canadian children that bilingual children performed lower than monolingual children on language tasks in the majority language also when taking SES into account. However, a small Swedish study indicated that there were no significant differences in language skills when comparing monolingual and bi-/multilingual children (Tonér and Nilsson Gerholm, 2021). Bi- or multilingual children have often been reported in the literature to perform better with regard to EFs than monolinguals (e.g., Adesope et al., 2010; Calvo and Bialystok, 2014; Barac et al., 2016). However, Duñabeitia et al. (2014) conducted a large-scale study with school-aged children and adolescents and found no support for a bilingual advantage. A small Swedish study did not find any differences in EFs between monolingual and multilingual children (Tonér and Nilsson Gerholm, 2021) and a meta-analysis has indicated that cognitive advantages related to bi-/multilingualism may be a result of publication bias (de Bruin et al., 2014). With regard to possible differences between girls and boys in language skills, previous results are diverging. Eriksson et al. (2012) found a female language advantage in a large sample of children aged 8–30 months across 10 language communities, including Sweden, indicating that sex-related language differences can be detected from an early age. For EFs, previous work regarding associations to sex is inconsistent. On one hand, girls have outperformed boys with regard to EFs in a number of studies (e.g., Fuhs and Day, 2011; Mulder et al., 2014). On the other hand, no EF or language differences were found in a sample of German children aged 3–4 (Slot and von Suchodoletz, 2017), a cross-cultural study including French, German and Icelandic children found no sex-related EFs differences (Gestsdottir et al., 2014) and a recent review concluded that there is little support for significant sex-related differences in EFs (Grissom and Reyes, 2019).

A vast majority of Swedish children attend preschool more or less full-time from an early age, and in the age range 4–6, over 95% of children attend preschool (The Swedish National Agency for Education, 2019). Fees are heavily subsidized, and there is a national curriculum for the preschool, intending to guarantee that quality is equally high in all preschools. However, audits and reports during recent years (e.g., The Swedish Schools Inspectorate, 2018) have shown that this is not the case, prompting the Swedish parliament to call for a thorough investigation of the conditions for an equivalent and sustainable preschool.

CURRENT STUDY

Aims and Research Questions

There is a need for a better understanding of the relationships between language skills, EFs and auditory selective attention and of the potential links between these measures and factors relating to the individual and the environment. In the current study, potential links between diverse measures of language, EFs and auditory selective attention are investigated, as well as possible links between these measures and age, SES and multilingualism. Additionally, we explore potential differences between girls and boys with regard to language EFs and selective attention as well as potential associations to preschool quality.

RQ1. What is the relationship between different language skills, EFs and auditory selective attention in a sample of Swedish preschoolers?

RQ2. Do age, SES, sex, bi/-multilingualism, and aspects of preschool attendance and quality make significant contributions in explaining language/EFs/selective attention variance?

The first research question is addressed by applying descriptive methods. We expect that language skills and EFs will be significantly correlated in Swedish preschoolers, similar to previous findings in other populations and that correlations will be at least moderate in magnitude. We predict an association between behaviorally assessed EF and auditory selective attention measured with ERPs, based on assumptions that selective attention is either a prerequisite for or an intrinsic part of EFs (e.g., The second research question is addressed by fitting multiple regression models. We hypothesize that child age and aspects of family SES will explain unique variance in language/EFs/selective attention. With regard to associations to sex. bi-/multilingualism and preschool quality, we refrain from formulating any hypotheses, since previous research is diverging and/or scarce.

MATERIALS AND METHODS

Participants

Ethics approval for this project was granted by the regional ethical review board[1]and data were treated in accordance with the EU General Data Protection Regulation. Data for the current study were collected within the framework of an intervention study aimed at all children in 18 preschools from a municipality in the Stockholm region (Gerholm et al., 2018, 2019). The proportion of trained preschool teachers was 27%, whereas the national average was 39% at the point of data collection (The Swedish National Agency for Education, 2016). All children whose caregivers gave written consent were considered eligible for participation. The children were informed about the study, including their right to withdraw at any time. Participants did not receive any compensation for participating in the study. The sample consisted of 431 children aged 44–74 months (M = 62, SD = 7; 52% girls),. Children came mainly from higher-SES backgrounds; 65% had at least one parent with university level education. They spent on average 38 h per week at preschool and had started preschool at on average 18 months of age; 90% of participants were enrolled in preschool at 2 years of age or younger. Bi-/multilingual children composed 33% of the final sample and 43 different languages were represented. English (n = 24), Arabic (n = 12), Spanish (n = 12), Polish (n = 10), and Kurdish (n = 8) were the most frequent languages spoken in the home apart from Swedish, and in 40 cases, parents reported that Swedish was not the child's strongest language. According to parental reports, 29 children (12 girls), corresponding to 7% of the sample, had a language disorder, largely in line with the prevalence of language disorders in the population (e.g., Tomblin et al., 1997). Children with language disorders did not differ from children with reported typical language development with regard to age or SES.

Materials

Language

In terms of language assessment, narratives provide rich information concerning form, content, and use of language with little risk of ceiling effects even when collecting data from children of various ages. The *Bus Story Test* (*BST*; Renfrew, 1995;

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[1] https://ki.se/en/orgid/303872, DNR nr: 2015/1664–31/5.

Svensson and Tuominen-Eriksson, 2002) was used to elicit narratives. The child first listens to a story told by the examiner, then retells the story, aided by picture prompts. The children also completed the *Peabody Picture Vocabulary Test (PPVT-IV)*, which assesses receptive vocabulary (Dunn and Dunn, 2007). The examiner says a word and the child's task is to indicate which out of four alternatives presented on a picture plate best resembles the meaning of that word. Since there is neither an authorized Swedish translation nor Swedish norms available for the PPVT, only raw scores were used. Parents completed a preliminary Swedish version of the *McArthur-Bates communicative development inventories* (SCDI-III) for children aged 30–48 months (Eriksson, 2017), rendering information about parents' perceptions of their child's expressive vocabulary and morphology. SCDI-III norms do not cover the age span in the current sample and results were treated with caution.

Executive Functions

The *Dimensional Change Card Sort* (*DCCS*) primarily assesses the ability to flexibly switch between rules (Doebel and Zelazo, 2015). The child sorts pictures according to the shape of the objects (pre-switch phase, 5 items) and then switch to a new rule and instead sort by color (post-switch phase, 5 items). In the final stage of the task, the child needs to alternate between these two sorting strategies (mixed trials, 30 items). Scoring is done automatically via the application and is based on a combination of accuracy and reaction time. For any given individual, accuracy is first considered, and if accuracy levels are $\leq$ 80%, the final score is equal to the accuracy score. Reaction times are log transformed to create a more normal distribution (for full details of scoring, see Slotkin et al., 2012). The *Fish Flanker task* mainly taps into the ability to disregard irrelevant visual stimuli and the test requires children to indicate the direction of a central stimulus flanked by congruent or incongruent flankers (Rueda et al., 2012). For children aged 3–7, 20 trials with fish stimuli are conducted. If performance is $\geq$ 90%, 20 additional trials with arrows are presented. The two tests mentioned above were delivered via a tablet application, but instructions were given by the examiner, since no Swedish-speaking version of the tablet application is available. Scoring is completed automatically in the application and is identical for DCCS and the flanker task. However, for children who do not proceed to the arrow trials in the flanker task, reaction time is not considered (Slotkin et al., 2012; Weintraub et al., 2013). *Forward and Backward digit span* (FDS and BDS), assesses short term memory and working memory in the auditory-verbal modality (Gathercole et al., 1999). The *Head-Shoulders-Knees-and-Toes task (HTKS)*, places demands both on inhibitory control and working memory (Cameron Ponitz et al., 2008). The child is first instructed to touch his/her toes when the examiner says "Touch your head!" and vice versa. In the second phase, the child is instructed to touch his/her knees when the examiner says "Touch your shoulders!" and vice versa, and in the third phase, all four instructions are included.

Selective Auditory Attention

A Swedish adaptation of a dichotic listening ERP paradigm (e.g., Coch et al., 2005; Stevens et al., 2009; Neville et al., 2013) was used, henceforth referred to as AudAt. The child was instructed to pay attention to one of two simultaneously played stories and the attention effect was measured as the difference between the average response to attended and unattended probe sounds. The task could thus be described as tapping into selective, sustained auditory attention.

Background Information

Parents provided information via a questionnaire about the child's age, family background, medical conditions, heredity for language or reading difficulties, languages spoken at home as well as income and educational level. There were three income categories, where low and high income corresponded to approximately the 10th and 90th percentiles in the Swedish population. There were four educational level categories: elementary school, upper secondary school, vocational education and college/university education. See also **Table 1**. Parents also gave information regarding their child's age at preschool enrollment and current amount of preschool time/week. Questionnaires including background

TABLE 1 | Raw scores for the language, EF, and selective attention measures.

	Mean	SD	Range	First quartile	Third quartile
Language					
Information* (*n* = 384)	17.74	9.64	0–44	10	24.25
Syntactic complexity* (*n* = 383)	2.40	2.19	0–13	1	4
Unified predicates* (*n* = 384)	16.73	6.88	0–35	12	21
Morphosyntactic accuracy* (*n* = 384)	0.64	0.24	0–1	0.50	0.81
Receptive vocabulary** (*n* = 395)	79.19	30.73	0–129	62	100
SCDI vocabulary*** (*n* = 404)	82.61	14.10	0–100	76.30	93.00
SCDI morphology*** (*n* = 398)	8.29	2.24	0–11	7.00	10.00
EF					
DCCS (*n* = 377)	4.20	1.40	0.13–7.83	3.38	5.0
Flanker (*n* = 371)	4.35	1.67	0.13–8.78	3.13	5.56
FDS (*n* = 380)	4.56	1.73	0–10	4	6
BDS (*n* = 367)	1.17	1.41	0–5	0	2
HTKS (*n* = 386)	15.5	7.93	0–24	10	22
Selective attention					
Early attention effect (*n* = 106)	0.69	2.28	−5.57 to 6.98	−0.78	2.37
Late attention effect (*n* = 108)	−0.28	2.08	−5.03 to 5.75	−1.61	1.09

*Number of respondents for each measure within parentheses. *The measure was extracted from transcripts of the Bus Story narratives. **Receptive vocabulary was based on results from the PPVT. ***SCDI measures were based on parental questionnaires.*

information, medical history, and SCDI-III were administered to parents in paper versions via the preschools and returned in prepaid envelopes. For every preschool unit/classroom, quality was rated with Early Childhood Environmental Rating Scale (ECERS-3, Harms et al., 2014) by researchers with extensive experience with the instrument. The full ECERS scale was used, encompassing information regarding preschool space and furnishings, care, language and literacy, play and learning, interaction, and organization. *Z*-scores were used in further analysis.

Procedure

Behavioral Measures

Language and EF testing was conducted in two sessions by trained research assistants on-site at the preschools during a 2-week period. Each session lasted 20–40 min. All behavioral testing was audio- and video recorded to enable multimodal annotation and to double-check examiners' adherence to protocol. The tasks were presented in a predetermined order to provide sufficient variation for the participants and to control session duration, based on a pilot study (Tonér and Nilsson Gerholm, 2021). The order of presentation for the first session was DCCS, Test of Emotion Comprehension (not further reported here), BST, a math task (not further reported here) and HTKS. The order for the second session was the Flanker task, PPVT, and finally the digit span tasks.

Event-Related Potential Recording

AudAt was conducted on-site on a randomized subsample representing all preschool units and consisting of 138 children (75 girls). Selection was based on a randomized priority list so that if a child declined to participate, the next child on the list would be asked instead. Recordings took place during the same 2-week period as the behavioral testing and were conducted by the first and second author. EEG was recorded using a BioSemi activeTwo amplifier with 16 head channels and a Common Mode Sense/Driven Right Leg (CMS/DRL) loop in a cap, two external mastoid channels and four external eye channels[2]. The child was seated on a small chair with speakers 0.7 m from each ear to the left and to the right. The child was informed about the experiment (information had also been given previously) and cap and electrodes were applied (for experimental setup, see **Figure 1**; for electrode placement, see **Figure 2**).

Probe sounds in the form of the syllable "Ba" and a "Bz"-like noise were embedded in two simultaneously played stories, that differed by content, by gender of the reader's voice and by presentation to the left or right. The "Bz" noise was constructed by splicing 20 ms segments of "Ba" and then scrambling all segments except the first and the last. The procedure resulted in a broad-spectrum "Bz" that preserved many of the acoustic properties of the linguistic "Ba" probe but at the same time sounding non-linguistic (see also e.g., Stevens et al., 2011). Both types of probes had a duration of 200 ms and were presented randomly in both channels at inter-stimulus intervals of 200, 550, or 1,000 ms. The child's task was to attend to one story while ignoring/suppressing the other, and images from the attended story were displayed on a laptop 1.0 m in front of the child to further aid selective attention. Each recording session involved two pairs of stories, with comprehension questions after each story pair, and lasted 20–40 min, including application and de-application, see also Gerholm et al. (2019).

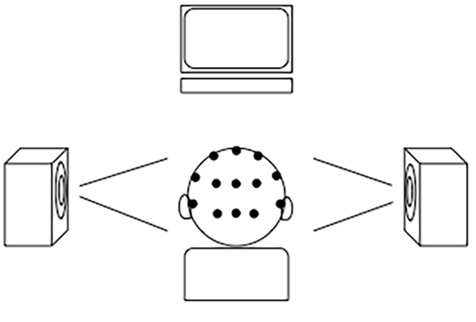

FIGURE 1 | Experimental setup of Swedish AudAt.

Data Processing

Care was taken to ensure the anonymity of participants. All test protocols, test data achieved by the tablet application, teacher and parental questionnaires and ECERS data were coded by a researcher not directly involved in data collection or statistical analysis. The code key was not known to any of the authors (see also Gerholm et al., 2018).

Behavioral Measures

Language

The bus stories were orthographically transcribed and annotated in ELAN (Max Planck Institute for Psycholinguistics, The Language Archive, Nijmegen, The Netherlands; Wittenburg et al., 2006[3]) and a number of language measures were extracted. Two of those were based on the BST manual (Renfrew, 1995; Svensson and Tuominen-Eriksson, 2002), namely information score and, as a proxy for syntactic complexity, the number of subordinate clauses. Information score concerns the information density in the retell and that children include relevant content, correct sequencing of those events and provide appropriate amount of context; a scoring guide for Swedish is provided in the test manual. In addition, we extracted a measure of text length, counted as number of unified predicates (e.g., Berman, 1988), and a measure of morphosyntactic accuracy, an often-used measure in first as well as second language acquisition (e.g., Zwitserlood et al., 2015; Meir, 2018), here operationalized as the proportion of morphosyntactically well-formed utterances (see also Tonér and Nilsson Gerholm, 2021, for results regarding Swedish children).

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[2] For activeTwo and CMS/DRL details, see http://www.biosemi.com/

[3] https://tla.mpi.nl/tools/tla-tools/elan/

Raw scores from the PPVT were used to represent a crude measure of receptive vocabulary.

Executive functions

In addition to examining correlations to language and attention for the separate EF tasks, raw scores from DCCS, the Fish Flanker task, digit span and the HTKS tasks were z-transformed and summed to a composite EF score with a mean of 0 and a standard deviation of 1. The composite EF measure was used in regression models since the suggested EF components are hard to measure in isolation and since it has been argued that the components cannot be clearly separated for the current age span.

Event-Related Potential Data

Data processing was done in EEGLAB (Delorme and Makeig, 2004). Sampling rate during recording was 2 KHz, downsampled to 256 Hz offline, re-referenced to average mastoids and filtered with a band pass filter of 0.1 and 40.0 Hz. Bad channels were identified visually, removed and interpolated. The continuous data was epoched with respect to probe sound onsets (100 ms before stimulus onset to 500 ms after stimulus onset). Artifacts were first automatically rejected by using the ERPLAB moving window peak-to-peak artifact detection algorithm (Lopez-Calderon and Luck, 2014), removing epochs with head channel amplitudes larger than $+200/-200$ μV or eye channel amplitudes larger than $+100/-100\mu$V across a 200 ms time window, moving at 50 ms increments. Thereafter, EEG data was visually inspected by the first and second author and residual artifacts were removed manually (see also Stevens et al., 2009). The rejection rate was on average 45%. Complete exclusion of 29 recordings was necessary due to noisy or flat average response and/or less than 100 epochs remaining after artifact rejection. Following the original AudAt studies as well as the analytic procedure in an unpublished pilot study on Swedish AudAt, mean amplitudes relative to baseline were measured between 100 and 200 ms post-stimulus onset. Any difference in amplitudes in this time window, between responses to attended and unattended probes, constitute the early attention effect. Additionally, a separate analysis was conducted of the attention effect in a later time window, at 300–400 ms post-stimulus onset. There were 19 children who failed to answer any of the comprehension questions correctly. Previous studies using the original AudAt paradigm have used a cutoff of at least 50% correctly answered comprehension questions to include children's ERP data in further analysis (Stevens et al., 2009; Neville et al., 2013; Karns et al., 2015; Hampton Wray et al., 2017). In an early study, Coch et al. (2005) used a cutoff of 8/10 correctly answered comprehension questions but commented that this procedure may have biased their sample. For the current study, we decided not to exclude children based on results on comprehension questions. The expected difference in response to attended versus unattended stimuli is considered pre-linguistic, and electrophysiological signs of selective auditory attention should thus not be dependent upon language comprehension. Furthermore, there was no significant difference in attention, neither in the early nor in the late time window, between children who passed comprehension questions and those who failed to answer any question correctly.

Questionnaires

Background information and SCDI questionnaires were already anonymized when arriving by post to the handling researcher. Data thereof were connected to behavioral and ERP data via individual codes (see also Gerholm et al., 2019). Raw scores from SCDI subscales for vocabulary and morphology were used in analysis.

RESULTS

Data were analyzed with R software (Version 3.7.0; R Core Team, 2019). There are missing values for separate test measures due to children declining to participate and due to technical problems, see also **Table 1** for number of respondents for each measure.

RQ1: Associations Between Language and EFs

An overview of children's performance on separate language and EF measures is provided in **Table 1**. Children who gave some verbal output, for instance in form of one-word and/or elliptical utterances in the narrative task were included in analysis, which entails that a score of 0 is possible for several of the language measures. Non-parametric correlations were calculated since some tests/tasks did not fulfill the requirements for parametric testing. See **Table 2** for all significant correlations. There were strong correlations between all language measures extracted from the narratives. Correlations between receptive vocabulary (PPVT score) and the other language measures were moderate in strength (ρ ranging from 0.38 to 0.57, $p < 0.001$). Additionally, parents' ratings of children's vocabulary skills and morphology with SCDI-III were weakly to moderately correlated with behaviorally assessed language. All EF measures correlated significantly with one another ($p < 0.001$), but the correlations were moderate at best, the strongest correlations were found between the Flanker task and BDS ($\rho = 0.47$), between DCCS and HTKS ($\rho = 0.45$) and between HTKS and BDS ($\rho = 0.43$).

As for associations between language and behaviorally assessed EFs, all measures correlated weakly to moderately, the strongest correlations were found between EF measures and PPVT (see **Table 2**). The SCDI measures also showed significant but overall weak correlations with EFs. With regard to auditory selective attention, the magnitude of the attention effect in the early time window (100–200 ms) correlated with the number of unified predicates ($\rho = 0.24$, $p < 0.05$), and with morphosyntactic accuracy ($\rho = 0.27$, $p < 0.01$). In other words, children who told longer stories and who had a higher ratio of correct utterances had a larger early attention effect. Selective auditory attention in the early time window did not correlate with any other language or EF measure. The late time window attention effect did not correlate with any language or EF measures. See **Figure 2** for ERP responses to attended and unattended probes.

TABLE 2 | Significant Spearman correlations for language, EF, and selective attention measures.

Measure			1	2	3	4	5	6	7	8	9	10	11	12	13	14
Bus Story Test	1	Information	–													
	2	Syntactic complexity	0.67	–												
	3	Unified predicates	0.80	0.73	–											
	4	Morphosyntactic accuracy	0.77	0.67	0.94	–										
PPVT	5	Receptive vocabulary	0.57	0.41	0.40	0.38	–									
SCDI	6	Expressive vocabulary	0.28	0.25	0.20	0.19	0.34	–								
	7	Expressive morphology^{C}	0.32	0.26	0.23	0.21	0.38	0.45	–							
DCCS	8	EFs; cognitive flexibility	0.33	0.24	0.23	0.22	0.42	0.22	0.26	–						
Flanker Fish Task	9	EFs; inhibition	0.33	0.25	0.18	0.15	0.44	0.17	0.31	0.42	–					
FDS	10	EFs; short-term/working memory	0.31	0.17	0.23	0.25	0.31	0.16	0.19	0.30	0.29	–				
BDS	11	EFs; working memory	0.43	0.22	0.29	0.26	0.56	0.27	0.36	0.36	0.47	0.41	–			
HTKS	12	EFs; inhibition, working memory	0.42	0.30	0.25	0.19	0.49	0.26	0.26	0.45	0.36	0.39	0.43	–		
AudAt	13	Early attention effect			0.24	0.27									–	
	14	Late attention effect													0.43	–

All correlations were significant at $p < 0.001$ except associations between morphosyntactic accuracy and the flanker task, morphosyntactic accuracy and early attention effect, SCDI vocabulary and FDS, SCDI vocabulary and the Flanker task ($p < 0.01$), and between early attention effect and unified predicates ($p < 0.05$).

RQ2: Associations to Background Factors

Multiple linear regression models were fitted with the lm function (R Core Team, 2019) to investigate whether background factors significantly predicted language, EF and auditory selective attention measures. Morphosyntactic accuracy represents children's productive grammar abilities, whereas the PPVT score represents receptive vocabulary and the EF composite score represents EFs. Included predictors were based on the hypotheses of the current study. The role of SES was investigated by including educational level and income separately for each parent[4]. Effects of being a dual language learner were explored by including multilingualism as a predictor but also including information on whether or not Swedish was the child's stronger language, as judged by parents. Possible effects of preschool-related factors were explored by including age at preschool enrollment, current time/week at preschool and preschool quality assessed with ECERS-3 as predictors. All models controlled for age. A backward elimination procedure was employed, in each step removing the least contributing predictor, and models which could explain as high proportion of variance as possible with as few predictors and as low residual standard error as possible, were preferred.

Receptive Vocabulary (PPVT)

Two models explained very similar levels of PPVT score variance (**Table 3**). The preferred model included only significant predictors and explained 40% of PPVT variance. Age, having Swedish as a stronger language, and higher parental SES (both education and income) positively predicted PPVT score, whereas being a boy and being multilingual were significant negative predictors of children's receptive vocabulary. See also **Figure 3** for residuals versus fitted plots of receptive vocabulary regression models.

Morphosyntactic Accuracy

No model provided a good fit to the morphosyntactic data, see **Table 4** for model comparison. A reduced model including

TABLE 3 | Model comparison for PPVT score.

Predictor	Full PPVT model Adjusted $R^2 = 0.41$ RSE = 0.72 (300 DF) $p < 0.0001$			Preferred PPVT model Adjusted $R^2 = 0.40$ RSE = 0.73 (354 DF) $p < 0.0001$			
	β	SE	$p <$	β	SE	$p <$	95% CI
Intercept	−6.77	0.67	0.0001	−5.89	0.49	0.0001	−6.84 to −4.93
Age	0.07	0.006	0.0001	0.07	0.006	0.0001	0.05–0.08
Boy	−0.18	0.08	0.05	−0.16	0.08	0.05	−0.31 to −0.005
Multilingual	−0.24	0.10	0.05	−0.32	0.09	0.001	−0.50 to −0.14
Swedish stronger language	0.58	0.17	0.001	0.70	0.15	0.0001	0.40–1.0
Education parent 1	0.09	0.03	0.01				
Education parent 2	0.02	0.03		0.07	0.02	0.01	0.02–0.35
Income parent 1	0.17	0.08	0.05	0.21	0.07	0.01	0.08–0.35
Income parent 2	0.10	0.09					
Preschool time/week	0.0003	0.007					
Age at preschool start	0.001	0.008					
Preschool quality	−0.05	0.04					

Standardized estimates, standard errors, and significance levels for predictors are included, as well as 95% confidence intervals for predictors in the preferred model. Adjusted R^2 and residual standard error (RSE) displayed for the full model and the preferred model. Significant predictors in bold script.

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[4] The parental questionnaire was gender-neutral in order not to discriminate against non-binary parents or families with same-sex parents.

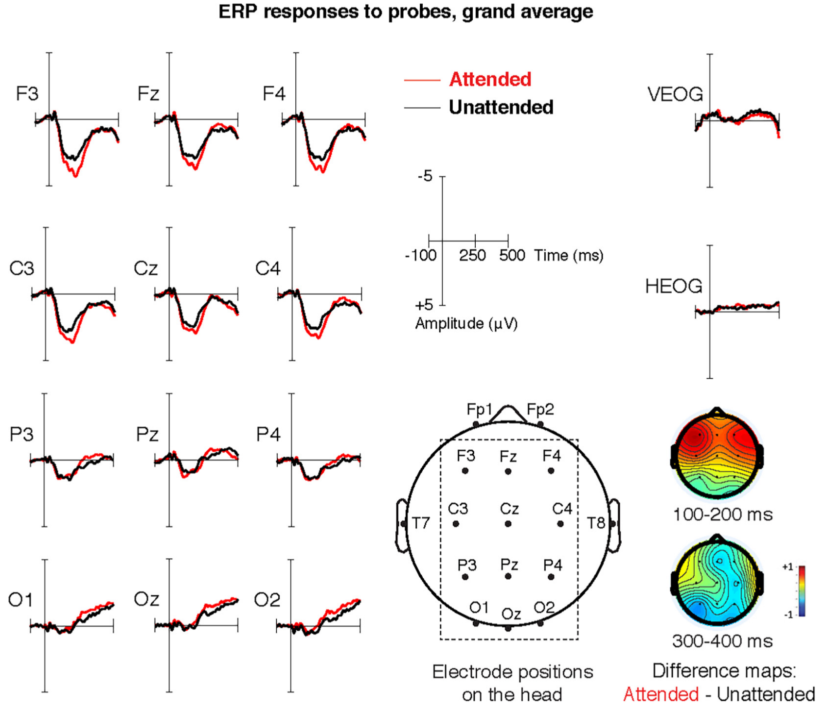


FIGURE 2 | Grand average ERP responses to probes in the attended and unattended channel and electrode placement in Swedish AudAt. Topographic maps show differences in amplitude between attended and unattended in the early and the late time window respectively.

age, sex, education in one parent, income in both parents, age at preschool enrollment, time/week at preschool and preschool quality explained 13% of variance and had a slightly lower residual standard error than the full model and any intermediate models. Age and parental education were significant positive predictors of morphosyntactic accuracy whereas male sex was a negative predictor. Further reduction of the model rendered lower levels of explained variance.

Executive Functions

Two models explained similar levels of variance, see **Figure 4** and **Table 5** for model comparison. The preferred model included age, sex, educational level in parent 1 and age at preschool enrollment and explained 29% of EF score variance. Age and parental education were highly significant positive predictors, male sex was a highly significant negative predictor and age at preschool enrollment was a negative, albeit not significant predictor of EF score ($p = 0.05$). Since EF scores were z-transformed, the results can thus be interpreted as follows: when keeping all other variables constant at their mean, male sex corresponded to a decrease in EF score of −0.33 SD.

Selective Auditory Attention

The full model for the early attention effect (in other words, the mean difference in brain responses for the attended story versus the unattended story in the time window between 100 and 200 ms post stimulus onset) with all background variables as predictors was not significant. Significance was first reached with a model including age, Swedish as the stronger language, education and income levels for both parents, however explaining only 9% of variance in the early attention effect, see **Table 6**. Having Swedish as a stronger language was a negative predictor of early attention effect. Eliminating the least contributing factor (income in parent 1) did not improve the model (adjusted R^2 = 9%) but education level in parent 1 turned out a significant positive predictor of early attention effect. Removing additional predictors did not improve the model.

For the late attention effect (mean difference in brain responses for attended versus unattended story in the time window 300–400 ms post stimulus onset), a full model was not significant and significance was first reached with a model including age, having Swedish as a stronger language, educational level, time/week at preschool, age at preschool enrollment and preschool quality, together explaining 11% of the variance in late attention effect. Reduction of the least contributing predictors led to additionally two models with very similar levels of explained variance and residual standard errors. Education in parent 2 positively predicted late attention. Further elimination of predictors made models slightly worse. See **Table 7** for model comparison.

DISCUSSION

In the current study we examined associations between aspects of language and EFs in a sample of 431 Swedish 4–6-year-olds as well as potential relations to age, sex, presence of other/additional languages than Swedish at home, parental SES and aspects of preschool attendance and quality. A subsample of 138 children participated in Swedish AudAt, an ERP experiment assessing selective auditory attention, hypothesized to be a neural correlate of EFs. In line with expectations, language and EF correlated significantly but we did not find any correlations between behaviorally assessed EF and selective auditory attention

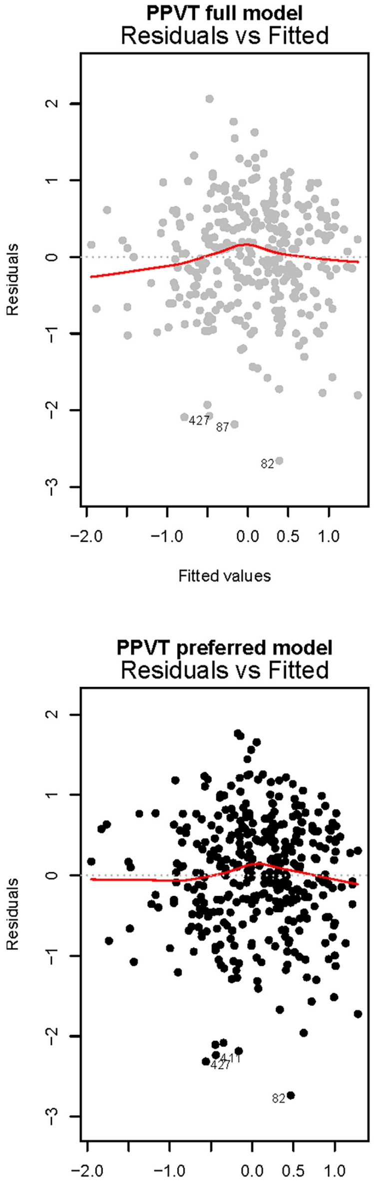
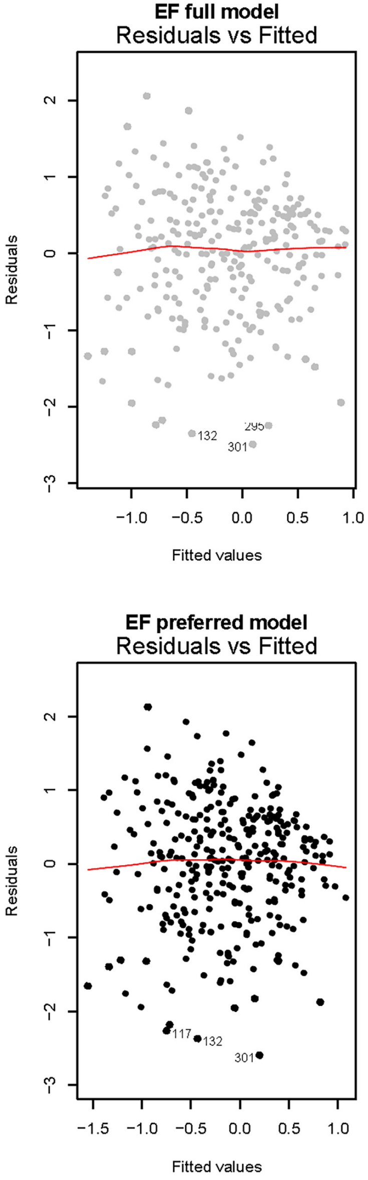


FIGURE 3 | Residuals versus fitted plots of receptive vocabulary regression models. The full model for receptive vocabulary included all predictors and explained 41% of PPVT score variance, whereas the preferred model included only significant predictors, explaining 40% of PPVT variance.

TABLE 4 | Model comparison for morphosyntactic accuracy.

Predictor	**Full morphosyntax model** **Adjusted R^2 = 0.12** **RSE = 0.89 (293 DF)** **$p < 0.0001$**			**Preferred morphosyntax model** **Adjusted R^2 = 0.13** **RSE = 0.89 (298 DF)** **$p < 0.0001$**			
	β	**SE**	**$p <$**	**β**	**SE**	**$p <$**	**95% CI**
Intercept	−3.43	0.83	0.0001	−3.54	0.79	0.0001	−5.09 to −1.99
Age	0.04	0.008	0.0001	0.04	0.008	0.0001	0.03–0.06
Boy	−0.28	0.10	0.01	−0.27	0.11	0.01	−0.48 to −0.07
Multilingual	0.05	0.12					
Swedish stronger language	0.05	0.22					
Education parent 1	0.09	0.04	0.05	0.09	0.04	0.05	0.02–0.17
Education parent 2	−0008	0.04					
Income parent 1	0.17	0.10		0.17	0.10		
Income parent 2	−0.05	0.11		−0.06	0.10		
Preschool time/week	−0.008	0.009		−0.008	0.009		
Age at preschool start	−0.009	0.01		−0.01	0.009		
Preschool quality	0.06	0.05		0.05	0.05		

Standardized estimates, standard errors, and significance levels for predictors are included, as well as 95% confidence intervals for predictors in the preferred model. Adjusted R^2 and residual standard error displayed for the full model and the preferred model. Significant predictors in bold script.


EF full model
Residuals vs Fitted

EF preferred model
Residuals vs Fitted

FIGURE 4 | Residuals versus fitted plots of EF regression models. The full model for EF included all predictors and accounted for 26% of EF score variance, whereas the preferred model included age, sex, parental education, and age at preschool enrollment, and explained 29% of EF score variance.

as assessed with ERPs. Age, sex and aspects of parental SES significantly predicted receptive vocabulary, morphosyntactic accuracy and EF. Selective attention was associated to parental education but not to age nor sex.

RQ1. the Relationship Between Language Skills, EFs, and Auditory Selective Attention

Language and EF measures correlated significantly, but the correlations were to a large extent rather weak. Receptive vocabulary score showed the highest correlation with EFs, whereas measures of language extracted from children's narratives correlated weakly to moderately with EF. Previous studies have often used vocabulary measures to represent "language" and the current results indicate that focusing solely on vocabulary may lead to overestimating the strength of the relationship between language and EF. BDS, considered an assessment of verbal working memory, was the EF measure that showed the strongest correlation to most language measures. It has been suggested that there is no functional separation between language processing and the capacity commonly referred to as verbal working memory (e.g., MacDonald and Christiansen, 2002). Such a statement may be seen as overly radical, but can nevertheless suggest that the associations in the current data between language measures and working memory may not be the most informative to shed further light on the language-EF relationship. The correlations among the different EF tasks were weak to moderate, indicating that the different tasks tap into different aspects of EFs.

Contrary to our hypothesis, the auditory selective attention measures did not show any significant relationships with any performance-based measure of EFs. Previous studies using the original AudAt paradigm have not used behavioral measures of EF (Coch et al., 2005; Sanders et al., 2006; Stevens et al., 2009; Neville et al., 2013; Hampton Wray et al., 2017). Nevertheless, it seems surprising that auditory selective attention was not associated with any EF test results in the current data, given the idea that selective attention may either be a foundation of EF or part and parcel of EF abilities, and empirical work indicating an association (e.g., Veer et al., 2017; Frick et al., 2018). In particular the lack of association between the attention affect and the Flanker task, which assesses interference control in the visual modality, is intriguing. However, it has been shown that auditory distractors are more difficult for young children to deal with than visual distractors (e.g., Robinson et al., 2018). Recent work has also shown modality differences for interference control in adults with dyslexia, suggested to reflect the importance of auditory selective attention for aspects of language such as speech processing and phonological awareness (Gabay et al., 2020, see also ten Braak et al., 2018). Further work is needed to investigate potential modality differences in selective attention and interference suppression during early childhood and the relation between AutAt and behaviorally assessed EF.

We found weak correlations between early attention effect and unified predicates and with morphosyntactic accuracy. Earlier work has suggested links between inhibition, which

TABLE 5 | Model comparison for EF score.

Predictor	**Full EF model** **Adjusted R^2 = 0.26** **RSE = 0.84 (258 DF)** **$p < 0.0001$**			**Intermediate EF model** **Adjusted R^2 = 0.28** **RSE = 0.82 (294 DF)** **$p < 0.0001$**			**Preferred EF model** **Adjusted R^2 = 0.29** **RSE = 0.83 (315 DF)** **$p < 0.0001$**			
	β	**SE**	***p* <**	**β**	**SE**	***p* <**	**β**	**SE**	***p* <**	**95% CI**
Intercept	−6.03	0.84	0.0001	−6.03	0.69	**0.0001**	−5.91	0.62	0.0001	
Age	0.07	0.008	0.0001	0.07	0.007	**0.0001**	0.07	0.007	0.0001	0.06–0.08
Boy	−0.33	0.10	0.01	−0.34	0.1	**0.001**	−0.33	0.09	0.001	−0.5 to −0.14
Multilingual	0.003	0.13								
Swedish stronger language	−0.13	0.22		−0.13	0.19					
Education parent 1	0.10	0.04	0.05	0.10	0.04	0.01	0.13	0.03	0.0001	0.07–0.19
Education parent 2	0.03	0.04		0.03	0.04					
Income parent 1	−0.005	0.1								
Income parent 2	0.07	0.11		0.06	0.09					
Preschool time/week	0.002	0.009	–							
Age at preschool start	−0.007	0.01	–	−0.01	0.008		−0.02	0.008		
Preschool quality	0.01	0.06	–	−0.02	0.05					

Standardized estimates, standard errors, and significance levels for predictors are included, as well as 95% confidence intervals for predictors in the preferred model. Adjusted R^2 and residual standard error displayed for the full model and the preferred model. Significant predictors in bold script.

TABLE 6 | Model comparison early selective attention.

Predictor	**First significant early attention model** **Adjusted R^2 = 0.87** **RSE = 2.19 (87 DF)** **$p < 0.05$**			**Preferred early attention model** **Adjusted R^2 = 0.89** **RSE = 2.19 (88 DF)** **$p < 0.05$**				**Reduced early attention model** **Adjusted R^2 = 0.77** **RSE = 2.21 (89 DF)** **$p < 0.05$**		
	β	**SE**	***p* <**	**β**	**SE**	***p* <**	**95% CI**	**β**	**SE**	***p* <**
Intercept	−5.29	3.46		−4.31	3.26			−5.08	3.24	
Age	0.03	0.04		0.04	0.04			0.04	0.04	
Swedish stronger language	−2.95	1.16	0.05	−2.86	1.16	0.05	−5.16 to −0.56	2.53	1.14	0.05
Education parent 1	0.35	0.23		0.43	0.20	0.05	0.02–0.84	0.51	0.20	0.05
Education parent 2	0.16	0.18		0.65	0.43					
Income parent 1	0.72	0.44								
Income parent 2	−0.95	0.49		−0.84	0.47			−0.61	0.45	

Standardized estimates, standard errors, and significance levels for predictors are included, as well as 95% confidence intervals for predictors in the preferred model. Adjusted R^2 and residual standard error displayed for the full model and the preferred model. Significant predictors in bold script.

could include the ability to suppress irrelevant information, and aspects of morphosyntax (Ibbotson and Kearvell-White, 2015; Kaushanskaya et al., 2017; Gandolfi and Viterbori, 2020). Another possibility is that language somehow acts as a confounding factor in attention tasks, which has been shown to be the case in performance-based tasks (Victorino and Schwartz, 2015). It seems reasonable to believe that a listener facing the complex task to listen to two stories simultaneously, depends on both language skills and attentional skills to focus on one story and suppressing the other. Strong language skills may aid the child to attend one story over another, perhaps by making probabilistic predictions about linguistic events in the near future, and strong attentional skills may serve specifically to suppress unwanted information. Experiments with adults (e.g., Oberfeld and Klöckner-Nowotny, 2016) have indicated that variance in adult participants' comprehension of speech in noisy environments could in part be explained by selective attention. In any case, potential links between children's grammar skills, language comprehension and auditory selective attention need further consideration.

RQ2. Associations Between Age, SES, Sex, and Bi/-Multilingualism and Language/EFs/Selective Attention

Age Associated With All Measures Except Selective Attention

Contrary to predictions, neither the early nor the late attention effect was significantly predicted by age. In contrast, all the behavioral and parent-rated measures were associated with age. An early study using the AudAt ERP paradigm also failed to find significant associations between attention effect and age (Coch et al., 2005). Receptive vocabulary score had the strongest correlation to age, suggesting that, although the PPVT is a

TABLE 7 | Model comparison for late selective attention.

Predictor	**First significant Late Attention Model** **Adjusted R^2 = 0.11** **RSE = 2.0 (78 DF)** **$p > 0.05$**			**Preferred Late Attention Model** **Adjusted R^2 = 0.11** **RSE = 1.99 (79 DF)** **$p < 0.05$**				**Reduced Late Attention Model** **Adjusted R^2 = 0.11** **RSE = 2.0 (80 DF)** **$p < 0.05$**		
	β	**SE**	**$p <$**	**β**	**SE**	**$p <$**	**95% CI**	**β**	**SE**	**$p <$**
Intercept	−2.04	4.04		−1.30	3.95			−0.77	3.92	
Age	0.06	0.04		0.05	0.033			0.04	0.03	
Swedish stronger language	−1.66	1.25		−1.31	1.18					0.05
Education parent 1	−0.34	0.19		−0.30	0.19			−0.37	0.18	
Education parent 2	0.37	0.17	0.05	0.34	0.17	0.05	0.008–0.68	0.31	0.17	
Preschool time/week	−0.06	0.04		−0.06	0.04			−0.06	0.04	
Age at preschool start	0.06	0.04		0.06	0.04			0.06	0.04	
Preschool quality	−0.23	0.26								

Standardized estimates, standard errors, and significance levels for predictors are included, as well as 95% confidence intervals for predictors in the preferred model. Adjusted R^2 and residual standard error displayed for the full model and the preferred model. Significant predictors in bold script.

somewhat problematic test due to the lack of Swedish official translation and norms, it reflects an expected increase in receptive vocabular as children grow older.

Socioeconomic Status Associated With Language, EFs, and Selective Attention

In accordance with our predictions, aspects of SES were significantly associated with receptive vocabulary, morphosyntax, EF composite and attention, although the current sample was skewed toward higher SES which may reduce the differential sensitivity to SES effect. For selective attention, levels of explained variance were low for both early and late attention effect. However, partly in line with previous studies and our hypothesis, aspects of SES (parental education) significantly predicted the early attention effect.

Associations to Bi-/multilingualism

The multilingual children did not perform on par with monolingual peers with regard to Swedish receptive vocabulary when controlling for SES. Bi- or multilingual children do not necessarily exhibit a gap in receptive vocabulary compared with monolingual children (Thordardottir, 2011), but our result is in line with outcomes in a large-scale Danish study on preschool-aged children, in which language skills of native Danish and immigrant children were compared (Højen et al., 2019). Immigrant children scored significantly lower than non-immigrant children on standardized language tests when controlling for SES, leading to the conclusion that measures should be taken to reduce inequalities in educational outcomes already in preschool, focusing on L2 language skills (ibid.). In our data, aspects of the child's language situation with regard to stronger language and/or bilingualism did not explain EF variance, which could suggest that the EF tasks did not disfavor children who did not have Swedish as a first language. A curious finding was that having Swedish as a stronger language was a negative predictor of early attention effect. The challenging task of selectively listening to a narrative may require a child who is less proficient in the majority language to allocate more attentional resources to the task compared to a peer with stronger language skills, but further investigation, including gathering more data regarding the language situation for bi-/and multilingual children, is needed to see if this result replicates.

Possible Female Advantage

No specific predictions were made with regard to possible differences between girls and boys, given that previous results are diverging. Male sex was a negative predictor of receptive vocabulary score, morphosyntactic accuracy and EF composite score. Current results are thus in line with studies that suggest a female advantage for both language and EF. Language and EF differences between girls and boys are often explained by theories that stress the influence of social environment on language as well as other cognitive domains (see e.g., Eriksson et al., 2012, for a summary), for instance that parents expect different behaviors from girls and boys and interact differently depending on the child's sex (e.g., Wanless et al., 2013). When it comes to gender equality, Sweden regularly ranks among the top countries (see e.g., United Nations Development Programme, n.d.). Nevertheless, child-rearing and pedagogical practices in relation to children's gender and cognitive development could be further explored in the Swedish context.

Aspects of Preschool Attendance

Aspects of preschool attendance and quality were included in regression models primarily to control for variation. We found no significant effects of preschool quality but age at preschool start was a negative, albeit not significant predictor of EF score. Loeb et al. (2007) conducted a large study in the United States, attempting to find out what would be the ideal age for children to start daycare/preschool/nursery school. They found greater gains in prereading and math skills in children who started center care between ages 2 and 3, whereas starting earlier than age 2 was related to negative social effects (ibid.). Potential effects of age at preschool enrollment on children's individual cognitive development needs further attention, not least since there may be complex interactions between age at preschool start, family SES and home situation.

Low Levels of Explained Variance for Morphosyntactic Accuracy and Selective Attention

For morphosyntactic accuracy, the proportion of explained variance was low, highlighting the need to investigate language in a broader sense than focusing solely on aspects of vocabulary, which has often been the case in previous studies showing associations between, for instance, language and SES (e.g., Hart and Risley, 1995; Geoffroy et al., 2007). Previous work has indeed indicated that individual differences in language ability to a large extent is due to genetic factors (see e.g., Stromswold, 2001, for a review) and has also revealed an increase in heritability of language skills from early to middle childhood (e.g., Hayiou-Thomas et al., 2012). For selective attention, levels of explained variance were also low. Earlier work using the original AudAt paradigm has primarily investigated selective attention in lower-SES samples (e.g., Stevens et al., 2009; Neville et al., 2013; Hampton Wray et al., 2017). In a rather homogeneous sample with regard to SES such as the current, genetics may play a bigger role than environmental factors in explaining variance in attention.

Methodological Issues

Contextual factors can have a large impact on children's performance in highly controlled experiments – for instance it has been shown that children's performance on tasks assessing so called "hot" EFs, such as delay of gratification, is highly sensitive to factors such as group norms (e.g., Doebel and Munakata, 2018), and to which extent children find the test leader trustworthy (e.g., Ma et al., 2018). Such factors are difficult to entirely control and may have potential impact on the results' general implications. The speakers who recorded the stories in Swedish AudAt were asked to read the stories with the same level of engagement and character speech as they would in a real-life situation, reading aloud to a preschooler. This may have driven bottom-up, stimulus-driven attentional processes to a larger extent than in the original AudAt. However, the original AudAt could hardly be interpreted as a pure measure of endogenous attention, as the probe sounds "ba" and "bz" are likely to attract stimulus-driven attention. Additionally, the images displayed on a screen during the experiment may drive bottom-up visual attentional processes. Several researchers have put forward the idea that endogenous and exogenous attention systems interact during real-time prioritization of attentional focus, especially in tasks requiring some kind of vigilance (e.g., Corbetta and Shulman, 2002; Maclean et al., 2009), and if an experiment should be considered ecologically valid, such interactions may be difficult to control/avoid completely. With respect to the subsample for AudAt, it should also be noted that there was an element of self-selection in the sampling procedure, since children themselves had the opportunity to decline participation. While such a procedure fulfills ethical requirements and gives agency to the child, it may have led to an ERP subsample that was not entirely representative of the full sample. Another methodological aspect is that the reliability of ERP components has relatively seldom been reported in previous work, which is remarkable considering how widely ERP measures are used in research (see also Huffmeijer et al., 2014).

Another potential methodological shortcoming concerns the parental questionnaire. Our desire to formulate the background questions in a way that would not discriminate non-traditional families had the downside that we cannot make any conclusions regarding the relative importance of maternal and paternal educational level and/or income.

Future Work

There is a need for future empirical studies as well as theoretical work to further clarify the associations between language and EF, including the role of selective auditory attention, in children. Such an endeavor should attempt at recruiting children from diverse SES backgrounds and to follow participants longitudinally. It seems vital to administer an array of both language and EF tasks to reveal any specific links between language and EF skills, however there is a clear need for further development and validation of suitable assessment materials. In the Swedish context, in which a majority of children attend preschool more or less full-time from 1 to 2 years of age, effects on cognitive development of preschool attendance in general and of specific pedagogical practices need further investigation. Future work should preferably be based on and/or contribute toward a theoretical framework that is more informative than merely stating that strong skills within one cognitive domain is associated with, and/or leads to strong skills within another. Existing theories of EF are not always explicit with regard to potential connections to language. Exceptions include Barkley's (1997) model of inhibition, sustained attention and EFs, which includes internal speech as an EF, and models put forward by Zelazo and colleagues (e.g., Cunningham and Zelazo, 2007; Zelazo, 2015), suggesting that EF is verbally mediated. Recent work by Gandolfi and Viterbori (2020) suggests that high levels of interference suppression may aid a child to develop their lexicon, both receptively and productively, but the authors also show that it is the ability to suppress irrelevant stimuli, rather than other forms of inhibition which is linked to, and may even predict, grammar skills. However, existing theories seem underspecified with regard to causal links between or common mechanisms in language and EF.

CONCLUSION

In the current study, we confirmed links between language and EFs in Swedish children aged 4–6, although the strength of the relationship seems to be less pronounced if including measures of morphosyntax instead of focusing solely on vocabulary. Results confirmed a female advantage and associations to age and SES for both language and EF, whereas for auditory selective attention, only links to parental education were confirmed. Contrary to expectations we did not find associations between behaviorally assessed EF and selective auditory attention measured with ERPs. The current findings provide some evidence of links between selective attention and aspects of morphosyntax, and between working memory and language measures in general, but further work is needed to clarify the nature of the language–EF relationship.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Regionala etikprövningsnämden [Regional ethics board], Karolinska Institute, Stockholm. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

ST and PK contributed to the conception and design of the study. ST performed the statistical analysis. PK organized and pre-processed the ERP data. ST wrote the first draft of the manuscript. PK and FL wrote the sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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PETTER KALLIOINEN works with EEG/brainwaves at the Department of Linguistics at Stockholm University. He is part of most projects that involves brainwaves there, often studies of children or infants. The present thesis investigates how children with cochlear implants use semantic predictions to compensate for difficulties in bottom-up language processing, cognitive abilities of children in Swedish preschools, and how language skills, attention and executive functions relate to each other.

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