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CENTRAL AUDITORY PROCESSING AND THE ACQUISITION OF PHONOLOGY IN 2-YEAR-OLD CHILDREN WITH RECURRENT ACUTE OTITIS MEDIA

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ABSTRACT

Middle ear infections (acute otitis media, AOM) are among the most common infectious diseases in childhood, their incidence being greatest at the age of 6–12 months. Approximately 10–30% of children undergo repetitive periods of AOM, referred to as recurrent acute otitis media (RAOM). Middle ear fluid during an AOM episode causes, on average, 20–30 dB of hearing loss lasting from a few days to as much as a couple of months. It is well known that even a mild permanent hearing loss has an effect on language development but so far there is no consensus regarding the consequences of RAOM on childhood language acquisition. The results of studies on middle ear infections and language development have been partly discrepant and the exact effects of RAOM on the developing central auditory nervous system are as yet unknown.

This thesis aims to examine central auditory processing and speech production among 2-year-old children with RAOM. Event-related potentials (ERPs) extracted from electroencephalography can be used to objectively investigate the functioning of the central auditory nervous system. For the first time this thesis has utilized auditory ERPs to study sound encoding and preattentive auditory discrimination of speech stimuli, and neural mechanisms of involuntary auditory attention in children with RAOM. Furthermore, the level of phonological development was studied by investigating the number and the quality of consonants produced by these children. Acquisition of consonant phonemes, which are harder to hear than vowels, is a good indicator of the ability to form accurate memory representations of ambient language and has not been studied previously in Finnish-speaking children with RAOM.

The results showed that the cortical sound encoding was intact but the preattentive auditory discrimination of multiple speech sound features was atypical in those children with RAOM. Furthermore, their neural mechanisms of auditory attention differed from those of their peers, thus indicating that children with RAOM are atypically sensitive to novel but meaningless sounds. The children with RAOM also produced fewer consonants than their controls. Noticeably, they had a delay in the acquisition of word-medial consonants and the Finnish phoneme /s/, which is acoustically challenging to perceive compared to the other Finnish phonemes.

The findings indicate the immaturity of central auditory processing in the children with RAOM, and this might also emerge in speech production. This thesis also showed that the effects of RAOM on central auditory processing are long-lasting because the children had healthy ears at the time of the study. An effective neural network for speech sound processing is a basic requisite of language acquisition, and RAOM in early childhood should be considered as a risk factor for language development.

TIIVISTELMÄ

Välikorvatulehdukset ovat lapsuuden yleisimpiä infektiosairauksia, ja niiden esiintyvyys on suurimmillaan 6–12 kuukauden iässä. Noin 10–30 % lapsista sairastaa toistuvia välikorvatulehduksia. Akuutissa välikorvatulehduksessa välikorvaontelon tulehduserite alentaa kuulokynnystä keskimäärin 20–30 dB, ja eritteen poistuminen tulehduksen parantuessa kestää muutamasta päivästä jopa pariin kuukauteen. Pysyvän, lievänkin kuulovian tiedetään vaikuttavan lapsen kielenkehitykseen. Sen sijaan välikorvatulehdusten aiheuttamien vaihtelevien kuulohavaintojen vaikutuksia keskushermostolliseen kuulojärjestelmään ja kielenkehitykseen ei täysin tunneta.

Tässä väitöskirjassa tutkittiin 2-vuotiaiden, toistuvia välikorvatulehduksia sairastaneiden lasten kuulotiedon käsittelyä sekä puheen tuottoa. Kuuloherätevasteita (englanniksi event-related potential, ERP) aivosähkökäyrästä rekisteröimällä saadaan luotettavasti tarkkaa tietoa keskushermostollisen kuulojärjestelmän toiminnasta. Tutkimuksessa hyödynnettiin ensimmäistä kertaa puheäänille ja yllättäville ääniärsykkeille syntyviä kuuloherätevasteita, kun pyrittiin selvittämään välikorvatulehduksia sairastaneiden lasten aivokuorella tapahtuvaa äänitiedon peruskäsittelyä, esitietoista kuuloerottelua ja automaattisen tarkkaavuuden kääntymisen mekanismeja. Lisäksi tarkasteltiin lasten tuottamien konsonanttien määrää ja laatua, koska akustisesti vokaaliäänteitä vaikeammin kuultavien konsonanttien omaksuminen heijastaa kykyä muodostaa tarkkoja muistiedustumia äidinkielen äänteistä. Myöskään konsonanttien tuottoa ei ole aiemmin suomen kieltä omaksuvilla, välikorvatulehduksia sairastaneilla lapsilla tutkittu.

Tulokset osoittivat, että toistuvia välikorvatulehduksia sairastaneiden lasten äänitiedon peruskäsittely oli vastaavaa kuin vertailuryhmän lapsilla, mutta heidän esitietoinen kuuloerottelunsa oli poikkeavaa useiden puheäänenpiirteiden osalta. Lisäksi automaattisen tarkkaavuuden suuntautuminen yllättäviin ääniärsykkeisiin oli välikorvatulehduksia sairastaneilla lapsilla poikkeavaa ja viittasi siihen, että nämä lapset häiriintyivät verrokkejaan enemmän yllättävistä mutta merkityksettömistä äänistä. Välikorvatulehduksia sairastaneet lapset myös tuottivat vähemmän konsonantteja kuin vertailuryhmän 2-vuotiaat. Erityisesti viive ilmeni sanan keskellä tuotettujen konsonanttien määrässä sekä akustisilta ominaisuuksiltaan vaikeasti havaittavissa olevan /s/-äänteen omaksumisessa.

Väitöstutkimus osoitti, että varhaislapsuudessa toistuvia välikorvatulehduksia sairastaneiden lasten kuulotiedon käsittelyssä on kypsymättömyyttä, mikä saattoi ilmetä myös puheen tuotossa. Välikorvatulehdusten vaikutukset kuulotiedon käsittelyyn säilyvät myös tulehduseritteen poistuttua, sillä lasten korvat olivat tutkimushetkellä terveet. Koska varhaislapsuuden aikainen tehokkaan hermosoluverkoston kehittyminen puheäänten käsittelylle luo pohjan myös myöhemmälle kielen oppimiselle, toistuvat välikorvatulehdukset on syytä huomioida yhtenä riskitekijänä lapsen kielenkehitykselle.

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ABBREVIATIONS

ABR	auditory brainstem response
ANOVA	analysis of variance
AWP	any word position
AOM	acute otitis media
CV	consonant-vowel
EEG	electroencephalography
ERP	event-related potential
fMRI	functional magnetic resonance imaging
F0	fundamental frequency
LN	late negativity
MEE	middle ear effusion
MMN	mismatch negativity
OM	otitis media
OME	otitis media with effusion
p	probability
RAOM	recurrent acute otitis media
SD	standard deviation
SOA	stimulus onset asynchrony
WF	word-final
WI	word-initial
WM	word-medial

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following articles, which are referred throughout the text by their Roman numerals:

I Haapala Sini, Niemitalo-Haapola Elina, Raappana Antti, Kujala Tiia, Suominen Kalervo, Kujala Teija, & Jansson-Verkasalo Eira (2014). Effects of recurrent acute otitis media on cortical speech-sound processing in 2-year-old children. *Ear and Hearing, 35*, e75–83. doi: 10.1097/AUD.0000000000000002.

II Haapala Sini, Niemitalo-Haapola Elina, Raappana Antti, Kujala Tiia, Suominen Kalervo, Jansson-Verkasalo Eira, & Kujala Teija (2016). Long-term influence of recurrent acute otitis media on neural involuntary attention switch in 2-year-old children. *Behavioral and Brain Functions, 12*, 1. doi: 10.1186/s12993-015-0086-4.

III Haapala Sini, Niemitalo-Haapola Elina, Raappana Antti, Kujala Tiia, Kujala Teija, & Jansson-Verkasalo Eira (2015). Restricted consonant inventories of 2-year-old Finnish children with a history of recurrent acute otitis media. *First Language, 35*, 219–236. doi: 10.1177/0142723715589695.

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ORIGINAL PUBLICATIONS

1 INTRODUCTION

In early childhood, which in this thesis refers to the first two years of life, auditory skills are essential for language development. Auditory perceptual development is influenced not only by heredity but also by early environmental experiences (Werner, 2007). At the time of birth, and even before it (Huotilainen et al., 2005; Partanen et al., 2013), a child is exposed to sound environment facilitating the maturation of central auditory system and acquisition of language. The early years of life are a critical period for the development of efficient neural networks for speech sound processing (Kuhl, 2010). Therefore, factors that prevent optimal development should be specified. This is important because early interventions lead to the best results and are cost-efficient by preventing the accumulation of problems. One of the conditions possibly deteriorating optimal listening experiences in early childhood is recurrent acute otitis media (RAOM).

Otitis media (OM) is a common term for various forms of middle ear infections. Acute otitis media (AOM), a sudden middle ear infection with acute symptoms of upper airway inflammation (Lieberthal et al., 2013), is one of the most common infectious diseases in childhood. Its incidence is greatest during the first years of life. Fluid in the middle ear during AOM leads to a mild to moderate temporary hearing loss (Ravicz et al., 2004) lasting from a few days to over two months (Tapiainen et al., 2014). Approximately 10–30% of children undergo repetitive periods of AOM (Niemelä et al., 1999; Teele et al., 1989), referred to as RAOM. While the effects of OM on language acquisition have been partly discrepant across studies, there has been a debate over decades about the possible consequences of it on the developing linguistic system. Several studies have found delayed or atypical linguistic skills in children with OM but there are studies that have not found this relationship (for a review, see Whitton & Polley, 2011).

Because the exact effects of OM on the underlying neural mechanisms beyond language development are mostly unsolved, this thesis utilized event-related potentials (ERPs) to evaluate possible adverse effects of OM on the developing auditory nervous system. ERPs, which are small changes in electrical brain activation, have made it possible to noninvasively study neural mechanisms and the maturation of central auditory processing in young children. In the field of speech and language pathology, brain research has been helpful in illuminating the early stages of language development and the neural bases of speech and language disorders. It has been shown, for example, that the formation of accurate representations of phonemes of the first language during the first year of life predicts later language development (Jansson-Verkasalo et al., 2010), and that auditory processing deficits are connected to different kind of linguistic problems (see e.g. Jansson-Verkasalo, 2003; Korpilahti, 1996).

To the best of my knowledge, this is the first study to investigate cognitive components of the ERPs in children with RAOM. This thesis included a typical population affected by middle ear infections – young children with RAOM and a need for tympanostomy tube insertion. In Study I, the basic neural encoding of acoustical sound features reflected by ERPs was inspected. Furthermore, mismatch negativity (MMN) of the cognitive ERPs elicited by several different acoustical deviances in Finnish syllables was studied to investigate children's preattentive discrimination of these sound features. Further steps in central auditory processing were examined in Study II, which inspected the neural mechanisms of involuntary auditory attention in children with RAOM by utilizing cognitive ERPs, P3a and late negativity (LN), elicited by distracting novel sounds. Finally, Study III investigated the behavioural manifestation of the accuracy of neural sound discrimination and phonological representation forming. Spontaneous speech samples were analysed to examine consonant acquisition in the same children who participated in the ERP studies. The number of words produced in speech samples and consonant inventory sizes were calculated. Additionally, the place and manner of articulation of consonants produced were established.

The subject of this thesis has a clinical basis. Speech and language pathologists meet lots of children with a history of RAOM. However, we need more scientific evidence on which to base our recommendations to carefully monitor the language development of these children. Knowledge of the consequences of early childhood RAOM should be available to the parents of these children and to health care clinicians. This work was motivated by a large number of children with RAOM whose language development we could support by various means we already have.

2 REVIEW OF THE LITERATURE

2.1 Childhood recurrent acute otitis media and language acquisition

OM is an umbrella term for several kinds of middle ear infections with different symptoms (Table 1). The present study investigated children with RAOM. However, the clinical diagnosis of different kinds of middle ear infections is challenging, especially in young children, due to varying definitions and clinical practices. For example, AOM is sometimes diagnosed based on the symptoms of inflammation but without the presence of the middle ear effusion (MEE). This kind of condition should be referred to as OM without effusion (Lieberthal et al., 2013). Other forms of OM include otitis media with effusion (OME; also known as secretory otitis media or glue ear) and chronic OME. Thus, comparison of studies concerning OM is obviously challenging because of this variety of conditions, definitions, and clinical practices.

In Finland, about 500 000 AOMs are diagnosed per year (Niemelä et al., 1999). The incidence of AOM is greatest between 6–12 months and about 80% of children undergo at least one episode of AOM before the age of three years (Alho et al., 1991; Sipilä et al., 1987; Teele et al., 1989). It is estimated that AOM episodes start to repeat leading to RAOM in 10–30% of children (Arason et al., 2005; Niemelä et al., 1999; Postma et al., 1997). In those cases, tympanostomy tubes are often inserted into the eardrum in order to keep the middle ear aerated and free of effusion.

Table 1. Definitions of diagnoses of different kinds of middle ear infections (Lieberthal et al., 2013)

	OM (otitis media)				
Condition	**OM without effusion**	**AOM**	**RAOM**	**OME**	**Chronic OME**
Symptoms	Acute symptoms of inflammation in the middle ear and/or respiratory system without MEE	MEE and acute symptoms of inflammation in the middle ear and/or respiratory system	An incidence of a new AOM at least three times per six months or four times per year	MEE without acute symptoms	OME lasting at least for three months

Note. MEE: middle ear effusion; AOM: acute otitis media; RAOM: recurrent acute otitis media; OME: otitis media with effusion

Some risk factors for RAOM have been found (see also Uhari et al., 1996), such as upper respiratory tract infections (e.g. Winther et al., 2007), passive tobacco smoke (e.g. Etzel et al., 1992), bottle feeding (e.g. Brown & Magnusson, 2000), and use of pacifier (e.g. Niemelä et al., 2000). Furthermore, a great number of young children attend day care in large centres, in which infectious diseases spread easily (e.g. Zutavern et al., 2007). Children at day care centres have 2–2.5 times higher risk for OM than children in home care (Uhari et al., 1996).

Effusion in the middle ear causes a mild to moderate (20–30 dB on average) hearing loss (Koivunen et al., 2000; Ravicz et al., 2006). The time to the disappearance of the middle ear effusion varies a lot among children, lasting from a few days to as much as two months or more (van Buchem et al., 1981; Tapiainen et al., 2014). For that reason, the amount of exposure to the fluctuating hearing loss caused by RAOM is largely individual, further complicating the area of research. Since the medical care of children with RAOM has improved, only a few of these children have permanent impairments in peripheral hearing later in life (Valtonen et al., 2005).

Children with RAOM, however, may suffer from a distorted auditory input in the early years crucial for language development. It is well established that children with a permanent mild to moderate hearing loss are at risk for problems in language development (e.g. Fitzpatrick et al., 2011). These deficits can be long-lasting until adolescence (Delage & Tuller, 2007). In contrast, the association between the fluctuating hearing loss caused by OM and language development have been shown to be contradictory. The first study on linguistic skills in children with OM was carried out already in 1969 by Holm and Kunze. They found that 5–9-year-old children with OM history were poorer than their age-matched controls in speech, language, and auditory processing tasks. After that, there were several studies supporting the finding that OM is a risk factor for developing language (e.g. Friel-Patti & Finitzo, 1990; Gravel & Wallace, 1992; Luotonen et al., 1998; Teele et al., 1990; Winskel, 2006; for a review, see Whitton & Polley, 2011). The effects of childhood OM on linguistic skills were also found to be long-lasting (Luotonen et al., 1998; Winskel, 2006). However, there have been several studies which found no relationship between OM and speech, language, or academic skills (e.g. Johnson et al., 2008; Paradise et al., 2000, 2003, 2005, 2007; Roberts et al., 1995, 2004; Serbetcioglu et al., 2008). These discrepant findings have led to an ongoing debate.

One reason for the different findings on language development in children with OM may be the heterogeneity of OM populations, which is caused by the clinical challenges in the diagnosis of various forms of OM and individual exposure to possible hearing loss. It could also be that the effects of OM are not obvious in comprehensive language tests but emerge only in some sub-processes of language. Furthermore, individual biological and environmental factors have a great influence on children's language development (Clark, 2009). In order to understand OM's significance as a possible risk factor for language development there is still a need to define and comprehend the exact mechanisms of OM and temporary hearing loss on the developing central auditory system.

2.2 Auditory processing as a basis of language development

In this thesis, auditory processing connected to RAOM refers to processing of auditory information in the central nervous system from the brainstem level to the widespread cortical areas (Richard, 2007). The acoustic signal is converted in the cochlea into the neural signal, which travels along the auditory pathway up to the cortical areas involved in auditory processing. The early stage of auditory processing is termed *sound encoding,* referring to the sensory processing of physical sound features, such as the frequency of the sound (see Werner, 2007). It is a bottom-up process, which takes place from the ear to the cortex. On the way to the cortex, the ascending impulse is integrated with other signals from the brain. These top-down processes have an influence on the sensory information arriving from the cortex down along the descending auditory system. Even though still maturing during the first months of life, the auditory pathway is well developed already at the time of birth while the auditory top-down mechanisms continue to develop up until adulthood (for reviews, see Moore, 2012; Werner, 2007).

Decoding of the incoming speech stream requires accurate perception of minor and rapid variations in successive signals (Kraus et al., 1996; Tallal & Piercy, 1975). A child has an innate ability to categorize sounds (Kuhl et al., 2008) and even fetuses are able to perceive sounds and speech (Huotilainen et al., 2005; Partanen et al., 2013). This ability develops to accurate *auditory discrimination* capability. Auditory discrimination is a prerequisite for the formation of memory representations and identification of speech sounds. The language environment has an influence on the development of phonetic discrimination so that an infant's specialized ability to discriminate their native language phonemes already occurs during the second half of the first year (Kuhl et al., 2008). During the first year of life, sensations of the first language induce permanent physiological changes in the central auditory nervous system, as demonstrated by studies on the discrimination of native and non-native phoneme contrasts in infants (Cheour et al., 1998; Kuhl et al., 1992, 2006; Jansson-Verkasalo et al., 2010). During this period, children learn to discriminate the speech sounds of the first language despite their acoustical variations due to different speakers or sound environments.

Attention is a cognitive function guiding our perception and processing of environmental events and including abilities to orient toward, select, switch between events, and maintain focus on something (Posner & Petersen, 1990). Selective attention mechanisms are active, top-down processes regulating our management of tasks without unnecessary interruptions by distracting stimuli (Corbetta & Shulman, 2002).

Involuntary attentional mechanisms, in turn, are passive, bottom-up processes allowing the detection and evaluation of potentially biologically meaningful but task-irrelevant stimuli (Corbetta & Shulman, 2002). This kind of auditory stimulus causing an involuntary attention switch and distraction from the ongoing task could be, for example, a sudden bark of a dog while one is walking in the forest and talking with a partner. Orientation (orienting response; Pavlov, 1927; Sokolov et al., 2002) induces the physiological (e.g. changes in heart beating) and behavioural changes (e.g. head turn) associated with the detection of a novel stimulus and thus has a great effect on ongoing neural processing and behaviour. After the distracting stimulus has been evaluated, reorientation back to the ongoing activity takes place.

Orienting to biologically meaningful environmental events is the first manifestation of attention development in infancy (Gomes et al., 2000). The human auditory system is sensitive to large acoustic deviances already at birth (Kushnerenko et al., 2013a) and even young infants have been shown to attend more strongly to speech than to other sounds (Vouloumanos & Werker, 2007). However, in young children the ability to ignore and inhibit irrelevant stimuli is poorer than in adults or older children (Gomes et al., 2000; Wetzel et al., 2006). Due to the maturation of top-down mechanisms, children learn to ignore distractors which are not meaningful, in other words, to separate the relevant from the irrelevant (Gomes et al., 2000; Wetzel et al., 2006). This is connected to the development of frontal cortical areas (e.g. Casey et al., 2000). Distractibility, an excessive tendency to orient to the irrelevant stimuli requiring a lot of attentional resources, makes goal-directed behaviour harder (Escera et al., 2000). Abnormal distractibility in early childhood may lead to problems of language acquisition (Hari & Renvall, 2001; Kushnerenko et al., 2013b).

Several studies have supported the predictive value of early auditory processing skills for language development (e.g. Guttorm et al., 2005; Molfese, 2000; Maurer et al., 2009). During the first year of life, there is a strong evidence for the critical period of the optimal acquisition and sharpening of language-specific phonological representations on which language development is based (Benasich et al., 2006; Dehaene-Lambertz et al., 2010; Jansson-Verkasalo et al., 2010; Kuhl et al., 1992, 2008; Tallal & Gaab, 2006; for a review, see Kuhl, 2010). For example, a well-functioning ability to discriminate native phoneme contrasts at the ages of 6 and 12 months was shown to predict vocabulary size at two years of age (Jansson-Verkasalo et al., 2010) Likewise, atypical auditory processing in children (for a review, see Kujala, 2007) was found to be connected with several kinds of difficulties concerning language development, such as developmental language impairment (Korpilahti, 1996; McArthur & Bishop, 2005), dyslexia (Kujala et al., 2006; Leppänen et al., 2002; Lovio et al., 2010; Maurer et al., 2009), stuttering (Jansson-Verkasalo et al., 2014), or autism spectrum disorders (Jansson-Verkasalo et al., 2003; Lepistö et al., 2005).

2.3 Phonological development and consonant acquisition

2.3.1 Phonological development as an index of early language acquisition

As an initiation to the spoken language, phonological development emerges together with cries and other vocalizations prior to words. Early phonological development, including consonant acquisition, is a predictor of ambient language and correlates with the later development of other fields of language such as vocabulary and morphology (e.g. Stoel-Gammon, 2011; Vihman, 1996) and reading (e.g. Turunen, 2003). At the early stages of language acquisition, weak phonological representations due to the deteriorated auditory processing capability may be reflected in expressive speech in the form of small phonemic repertoires[1]. Early phonological impairments, even mild ones, in turn, were suggested to lead to later problems in speech and/or literacy skills (Bishop & Clarkson, 2003; Lewis et al., 2006). It has been found that the phonological development of children with a permanent hearing loss is delayed; for example, their consonant inventories are smaller and differ from those of their normal hearing peers (Moeller et al., 2007; Stoel-Gammon & Otomo, 1986). Fluctuating hearing loss due to RAOM may also lead to challenging circumstances for the developing central auditory system while stable phonological representations are probably hard to achieve from the alternating and inaccurate auditory input.

Phonological and lexical development overlap in a compact, reciprocal manner (for a review, see Stoel-Gammon, 2011). The discrimination of native language phoneme contrasts creates a basis for learning word meanings (see Jansson-Verkasalo et al., 2010), and later a child's lexicon has a further impact on phonological knowledge (Stoel-Gammon, 2011; Vihman, 1996). Recently, newborns were also shown to learn the frequencies of co-occurrence between different syllables (Teinonen et al., 2009). This statistical learning was suggested to enable them to detect word boundaries and isolate words from the continuous speech stream. On the other hand, it has been suggested that children adopt word patterns first in a holistic manner and the phonemic patterns of words are build up incrementally (Locke, 1997). In the period of early words, however, there is comprehensive support for the theory that phonological development has an influence on lexical development (McCune & Vihman, 2001; Stoel-Gammon, 1998b; Velleman & Vihman, 2006; Vihman, 1996). At later stages a child's intention to produce more words to make themself understood accelerates

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[1] It should be noted that, while focused on auditory processing and consonant acquisition, this review does not aim to introduce the entire area of phonological development. There are several theories emphasizing different factors modifying the developmental trajectory. Auditory processing capabilities are not the only factor even though they have an essential role, however. For a comprehensive description, an interested reader is warmly recommended to explore e.g. Vihman (2014) and Rvachew and Brosseau-Lapré (2012).

phonological development (Stoel-Gammon, 1998a). It may be that initial orientation to the contrasting sounds of native language provides a foundation for building the stronger phonemic representations that result from lexical acquisition.

Early phonological development can be assessed by investigating phonemic inventories, such as which consonants are produced by young children. Acquisition of consonants is an excellent indicator of the functioning of the central auditory system, because consonants are harder to discriminate than vowels, which are stronger in intensity, longer in duration, and more stable over time than consonants. It has been shown that representations of native language vowels develop earlier than those of consonants (Kuhl et al., 2008). However, representations of at least some native language consonants are also already well-developed by the end of the first year (Kuhl et al., 2008).

By studying consonant production we can get information on the underlying skills for the formation of phonemic representations. In addition to the sizes of these inventories, the phonemes produced are often inspected in terms of the quality, referring to the place and manner of articulation. Because phonological and lexical development overlap, it is important to examine the size of the lexicon in addition to phonological analysis (Kunnari et al., 2006; Stoel-Gammon, 2011).

2.3.2 Models of consonant acquisition

In addition to the well-functioning auditory system, appropriate linguistic-cognitive abilities and speech-motor skills are needed for consonant production. Practicing of consonant production starts early in infancy. Early productions of consonants have been shown to correlate with later language development. For example, consonants of early vocalizations predominate in the first words of the expressive lexicon (Stoel-Gammon, 1998b) and the use of consonants in babbling predicts the onset and the later development of speech (McCune & Vihman, 2001; Stoel-Gammon, 1998a). Children start to produce repeated consonant-vowel (CV) syllables, referred to as canonical babbling, at the age of 6–10 months (Oller, 1980), and the first words are often constructed from these syllables (Stoel-Gammon, 2011).

Word production begins very close to the time children have been shown to begin recognizing word-forms at 11 months (Hallé & Boysson-Bardies, 1994, 1996: Vihman et al., 2004; Swingley, 2005, Vihman & Majorano, 2016; for electrophysiological findings, see Thierry et al., 2003; Vihman et al., 2007). It is likely that word production further strengthens the representations of phonemes. It has been established that the experience of the phonetic structure of the native language appears in children's vocalisations before the end of the first year (Boysson-Bardies et al., 1992; Velleman & Vihman, 2006) and in early words (Kunnari, 2003; Stoel-Gammon, 1985). Regardless of the language, however, children may favor some individual templates of babbling, which also predominate in early words (Velleman & Vihmann, 2006).

Jakobson (1968) proposed a universal developmental trajectory for consonant acquisition, from stops to nasals, and further to fricatives and liquids (laterals and trills). Even though current knowledge emphasizes early experiences and the hypotheses of straightforward universality of early productions have been rejected, there may be some universal characters in the consonant acquisition. Regardless of the language that the child is learning, the first consonants are often highly visible, such as bilabial stops (Vihman et al., 1985). Phonemes with an anterior place of articulation are often acquired earlier than phonemes with posterior articulation (Locke, 2002). The acoustic features of phonemes seem to have an effect on consonant acquisition. Stop consonants contain short, rapid spectral variations and are therefore more likely to be perceived categorically than, for example, fricative noises lacking dynamic spectral variations (Liebenthal et al., 2005). It was proposed that those consonants that occur most commonly in languages are learned earlier than consonants with a low frequency (Locke, 2002; see also Velleman & Vihman, 2006). However, the so-called functional load of phoneme, which refers to the rate of using a phoneme in an ambient language to differentiate one word from another, also has an effect on the acquisition order of consonants (van Severen et al., 2013). Despite some universals, the acquisition of phonology adheres strongly to language specific patterns and phonological processes described as atypical in one language may belong to typical development in another language. Therefore, it is important to analyse consonant acquisition in relation to the language specific phonemic system.

2.3.3 Special characteristics of Finnish consonant acquisition

The Finnish consonant system (Table 2) constitutes of 13 consonants and is complemented by an additional four consonants, which occur in loanwords (Sulkala & Karjalainen, 1992). Hence, Finnish has relatively few consonants, for example compared with the 24 consonants of English. In some dialects /d/ is rare or even missing. Consonant /ŋ/ occurs only medially in words. Consonants are infrequent in the final positions of words, where only dentals/alveolars /t, n, l, r, s/ occur in endogenous Finnish words. Due to the simple fricative system and the almost complete lack of voiced/voiceless opposition Finnish phonemes are acoustically relatively easy to distinguish (Karlsson, 1983; Suomi et al., 2006).

Both vowel and consonant phoneme length influence the meaning of Finnish words, as in the words [tuli] ‘fire’ vs. [tulli] ‘customs’ vs. [tuuli] ‘wind’. Thus, Finnish is a quantity language (Sulkala & Karjalainen, 1992). All consonants except /d, h, v, and j/ can appear as double consonants, known as geminates, in the medial position of words. Even though the bisyllabic word structure is the most frequent construction in the

Finnish language, long words of three or more syllables are common (Karlsson, 1983, p. 217). The length of words is further increased by a rich morphology including word formation with several suffixes (Helasvuo, 2008). In contrast to English (Stoel-Gammon, 2011), Finnish children typically attempt to produce two-syllabic words as their first words (Kunnari, 2003), since monosyllabic words are rare in Finnish (Karlsson, 1983). Basically, Finnish syllable structure includes one to three moras (consisting of the first vowel of the syllable and the following segments), with CV syllables being the most common (Helasvuo, 2008).

Table 2. Finnish consonant system according the place and manner of articulation (see e.g. Karlsson, 1983)

Manner of articulation	**Place of articulation**			
	Labials	**Dentals/ Alveolars**	**Palato-velars**	**Glottal**
Stops				
Voiceless	p	t	k	
Voiced	(b)	d	(g)	
Fricatives	(f)	s, (ʃ)		h
Lateral		l		
Trill		r		
Nasals	m	n	ŋ	
Semivowels	ʋ		j	

We now have up-to-date, comparative data on consonant acquisition in typically developing Finnish speaking children (Kunnari, 2003; Kunnari et al., 2006). On average, typically developing 2-year-old Finnish children produce six word-initial, seven word-medial, and only one word-final consonant (Kunnari et al., 2006), while English-speaking children produce about ten word-initial and six word-final consonants at that age (Stoel-Gammon, 2011). The saliency of the medial positions of words in Finnish, especially for consonant geminates, was suggested to be one reason that Finnish children acquire consonants faster in word-medial position than in word-initial position (Kunnari, 2003; Kunnari et al., 2006; Savinainen-Makkonen, 2007). The omission of word-initial consonants is also a typical developmental feature in Finnish children which may have an effect on the finding of a medial position advantage (Kunnari, 2003; Savinainen-Makkonen, 2000). Stops and nasals are often acquired first, and word-final consonants emerge slowly and are rare during the early phases of development (Kunnari, 2003; Kunnari et al., 2006; Saaristo-Helin et al., 2011), as is the case in English also (Stoel-Gammon, 2011). The majority (60%) of Finnish 2-year-olds were shown to use [m], [p], [t], and [k] in word-initial position, [p], [t], [s], [n], [k], and [h] in word-medial position, but none in word-final position (Kunnari et al., 2006). However, the variation in typical development is large, as it is in other languages (Vihman, 1996).

2.4 Auditory ERPs as indices of central auditory processing

2.4.1 Definition of ERPs

The underlying neural mechanisms of speech and language can be objectively studied by ERPs (for a review, see Kujala & Näätänen, 2010). Auditory long-latency ERPs are small changes in electrical brain activation elicited by sound stimuli (for a review, see Näätänen, 1992). When large populations of neurons are synchronously activated, the summation of their activity can be measured at the surface of the scalp with electroencephalography (EEG). ERP recordings are non-invasive, easily achievable, and do not necessarily require the attention or co-operation of the participant.

The ERP waveform elicited by auditory stimuli is typically a sequence of positive and negative peaks named according to their polarity, timing, serial order, or cognitive meaning (for a review, see Luck, 2005). The latencies and amplitudes of the responses reflect the speed and magnitude of processing, respectively. The time resolution of ERPs is excellent but the spatial resolution is much poorer than, for example, that of functional magnetic resonance imaging (fMRI). The amplitude scalp distribution (topography) of ERPs provides a coarse estimation of the brain areas contributing to the response. The obligatory (exogenous) ERPs are elicited by any auditory stimulus and reflect sensory processing of the physical features of the sound, such as frequency and intensity (Näätänen, 1992). In contrast, cognitive (endogenous) ERPs reflect internally generated mental events and, thus, more complicated cognitive processes (Näätänen, 1992). In the studies of this thesis, both obligatory (P1 and N2) and cognitive (MMN, P3a, and LN) components of ERPs were measured.

Different ERPs show distinct maturational trajectories, some even being unidentifiable in early childhood. During childhood, brains' functional specialization, synaptic organization, and changes in tissues and skull thickness lead to major changes in ERPs influencing their morphology, timing, magnitude, and scalp distribution (He et al., 2009; Wunderlich & Cone-Wesson, 2006). Thus, the following sections reviewing the literature considering obligatory and cognitive ERPs inspected in this study focus on children.

2.4.2 Obligatory responses

Obligatory ERPs represent cortical sensory processing of physical stimulus features received by the senses. From early childhood to the school-age, children's long latency auditory ERP waveform is characterized by a large positive and a smaller negative obligatory component called P1 and N2, respectively. The second negative deflection, called N4, is also often observed in children but its functional significance is not well known (e.g. Čeponienė et al., 2005; Kushnerenko et al., 2002). For that reason, it was not analysed in this study and will not be discussed here. In contrast, P1 and N2 and their developmental changes in the morphology, amplitudes, and latencies are well documented (for a review, see Wunderlich & Cone-Wesson, 2006).

P1

The children's auditory P1 (P100) is typically elicited about 100 ms after any auditory stimulus onset (Korpilahti & Lang, 1994). It is generated by thalamic and cortical sources, mainly by the lateral part of Heshl's gyrus known as secondary auditory cortex (Liégeois-Chauvel et al., 1994), being maximal at fronto-central scalp locations (Čeponienė et al., 2005). It has been suggested to primarily reflect the integrity of the central auditory pathway and basic encoding of acoustic stimulus features (Čeponiené et al., 2002; Sharma et al., 1997; Ponton et al., 2000). The precursor of P1 is detectable already at birth and it is well-matured by the age of 12 months (Kushnerenko et al., 2002). P1 latency decreases with increasing age (Čeponiené et al., 2005; Choudhury & Benasich, 2011; Korpilahti, 1996; Kushnerenko et al., 2002; Sharma et al., 1997). During maturation, P1 amplitude first increases (Choudhury & Benasich, 2011; Kushnerenko et al., 2002) and then decreases (Čeponiené et al., 2002; Korpilahti, 1996; Sharma et al., 1997).

Wagner et al. (2013) found that the obligatory ERPs elicited by non-native or native language syllables did not differ from each other and suggested that the neural mechanisms generating P1 are not specialized by language experience. However, there is evidence that P1 correlates with language development (Mikkola et al., 2007; Sharma et al., 2004). Children at risk for dyslexia (Lovio et al., 2010) and children with developmental language disorders (Gilley et al., 2006) have been shown to have atypical P1 responses, but typical P1 responses have also been found in these children (Kabel et al., 2009; Korpilahti & Lang, 1994). Thus, it can be concluded that the association between P1 and language development is not yet well defined.

N2

Children's auditory N2 (N250) is elicited at about 250 ms after the stimulus onset (Čeponiené et al., 2002; Cunningham et al., 2000; Korpilahti & Lang, 1994). It has been suggested to originate in the superior temporal plane (Halgren et al., 1995). Like P1, the N2 response is fronto-centrally maximal (Čeponiené et al., 2005). The N2 is associated with the representation formation of a repeating stimulus (Karhu et al., 1997). The N2 precursors can also be detected already at birth (Kushnerenko et al., 2002). With age N2 maturation follows a similar path as that of P1 while its latency decreases (Choudhury & Benasich, 2011; Ponton et al., 2000; Sharma et al., 1997) and amplitude first increases (Choudhury & Benasich, 2011; Kushnerenko et al., 2002; Ponton et al., 2000) and then decreases (Ponton et al., 2000). However, this probably happens in a slower and a more stable manner than the changes in P1 (Čeponienė et al., 2005; Cunningham et al., 2000; Korpilahti, 1996; Kushnerenko et al., 2002; Sharma et al., 1997).

Sound representation formation is a crucial function for language development. There is evidence that the N2 response might in some conditions be a predictor of language development. Infants with higher amplitude of N2 at 6 and 9 months achieved better language scores at 3 and 4 years of age (Choudhury & Benasich, 2011) and children with language disorder were shown to have diminished N2 amplitudes (Korpilahti & Lang, 1994). Furthermore, Čeponienė et al. (2005) found that phonetic stimuli elicited a greater negativity at the latency range of N2 than non-phonetic stimuli. However, not all studies have found the relationship between N2 and language measures (Cunningham et al., 2000), which might be due to differences in the paradigms and the stimuli used in the studies.

2.4.3 MMN

The auditory MMN is a negative cognitive component of ERPs reflecting preattentive auditory discrimination. It is elicited when a discriminable change (deviant) occurs in some repetitive aspect of stimulation (standard) (Näätänen et al., 1978; for recent reviews, see Garrido et al., 2009; Kujala & Näätänen, 2010; Näätänen et al., 2011). Thus, it reflects the process in which an incoming sound is compared with and differentiated from the memory trace for the regularities of the auditory input (Näätänen, 1992). The MMN is elicited even when a person is not attending to the stimuli (Näätänen et al., 2011). The auditory MMN is elicited by changes in sound features (e.g. frequency and intensity), but also by more complex changes, such as phonemes (Jansson-Verkasalo et al., 2010), order reversals of tones in pairs (Kujala et al., 2001), and rule violations (Näätänen et al., 2001). It reflects speech memory traces (Näätänen et al., 1997; Dehaene-Lambertz, 2000; Huotilainen et al., 2001; Näätänen et al., 2007; Pulvermüller & Shtyrov, 2006) and their early development (Cheour et al., 1998). Neural discrimination accuracy can be studied with the MMN, and it correlates with behavioural discrimination tasks (for a review, see Kujala & Näätänen, 2010). Because no attention or tasks requiring co-operation are necessarily needed in the MMN recording, it is an attractive tool for studying cognitive functions in children.

The MMN is identifiable from the difference wave, which is calculated by subtracting the ERP to a standard stimulus from that of a deviant stimulus, peaking at around 150–250 ms after the onset of the deviant stimulus (Näätänen, 1992). The MMNs for distinct stimulus features have at least partly different neural sources (Näätänen, 1992; Näätänen & Rinne, 2002). The MMN elicited by phonemic stimuli gets a contribution from the left supratemporal auditory cortex (Näätänen et al., 1997; Shtyrov et al., 2000), whereas the MMN to non-phonemic stimuli primarily originates from the corresponding right hemispheric area (Paavilainen et al., 1991; Sorokin et al., 2010). One MMN sub-component is generated in the frontal cortical areas and it was suggested to have a role in involuntary attention switch (Escera et al., 1998, 2000).

The developmental trajectory of the MMN during childhood is fairly well known. The MMN was found even in fetuses (Draganova et al., 2005; Huotilainen et al., 2005) and newborns (Alho et al., 1990, Leppänen et al., 2004; Sambeth et al., 2006, 2008). In infancy, some studies have found a corresponding positive mismatch response (MMR) instead of a negativity to changes in auditory stimuli (e.g. Benasich et al., 2006; Friedrich et al, 2004). As a function of age, the MMN latency decreases and its amplitude first enhances and then decreases (Cheour et al., 1998; Csépe, 1995; Shafer et al., 2010; for a review, see Cheour et al., 2000).

Several studies have been shown that the MMN (or MMR) in children is connected to language development. For example, MMRs elicited by changes in linguistic stimuli were delayed or atypically lateralized in children with familial risk for language disorder during their first year of life (Choudhury & Benasich, 2011; Friedrich et al., 2004). The MMN (or MMR) in early childhood has also been shown to predict later language outcomes (e.g. Jansson-Verkasalo et al., 2010, Leppänen et al., 2002; for a review, see Kujala, 2007).

2.4.4 P3a

The other main domain of preattentive cognitive processing, attention switching, is reflected by the family of P3 responses (Escera et al., 2000). Acoustically large deviant stimuli elicit the P3a component of ERPs, which is said to be an electrophysiological index of the orienting response (Squires et al., 1975). By measuring P3a, neural mechanisms of involuntary auditory attention can be studied without tasks requiring the skills to co-operate (for recent reviews, see Escera et al., 2000; Kujala & Näätänen, 2010; Polich, 2007). The auditory P3a is a large positive deflection elicited by unexpected novel sounds, which differ substantially from other sounds (e.g. slamming of the door or human coughing). It reflects higher-level event detection mechanisms (Horváth et al., 2008), attentional capture (Escera et al., 2000; Friedmann et al., 2001), and the evaluation of the relevance of a rare sound in a context (Horváth et al., 2008). The P3a peaks fronto-centrally at 200–300 ms after the onset of a distracting stimulus

(Courchesne et al., 1975; Escera et al., 2000; Squires et al., 1975). Sources of P3a are located in prefrontal, temporal, and parietal cortices, and in the posterior hippocampus, parahippocampal gyrus, and cingulate gyrus (Escera et al., 2000).

In addition to adults, the P3a is found in school-age children (Čeponienė et al., 2004; Gumenyuk et al., 2004), toddlers (Niemitalo-Haapola et al., 2013; Putkinen et al., 2012), newborns (Leppänen & Lyytinen, 1997; Dehaene-Lambertz & Peña, 2001; Winkler et al., 2003), and even in fetuses (Huotilainen et al., 2005). The morphology of the response is quite similar in children and adults but the scalp topography of children's P3a is more anterior than that of adults (Määttä et al., 2005). It seems that the processing of acoustic novelty in childhood closely resembles that in adulthood, although some underlying neural networks still continue to develop (for a review, see Kushnerenko et al., 2013a).

The P3a has been shown to be often biphasic (Escera et al., 2000; Friedmann et al., 2001). Two phases, early and late, have been identified in children as well (Gumenyuk et al, 2001, 2005; Määttä et al., 2005), as early as age two (Kushnerenko et al., 2002). Early P3a (eP3a) was suggested to reflect automatic detection of a violation of the neural model of the existing stimulus environment and thus to represent the orientation of attention (Yamaguchi & Knight, 1992). It is maximal at vertex and diminishes posteriorly and laterally (Escera et al., 1998). The late P3a (lP3a), which is maximal frontally, was suggested to reflect the actual attention switch (Escera et al., 1998). The eP3a and lP3a may have different maturational trajectories. The eP3a might mature earlier than lP3a, which continues to enhance frontally during development (Čeponienė et al., 2004).

Atypical P3a responses have been connected to affected involuntary attention; for example, it is well established that P3a correlates with distraction in behavioural tasks (Escera, 1998, 2000; Gumenyuk et al., 2001). Furthermore, involuntary attentional mechanisms have been connected to the forming of stable phonemic representations (Hari & Renvall, 2001). Atypical P3a responses were found in children with increased distractibility (Gumenyuk et al., 2005; Lepistö et al., 2004), which can lead to problems of language development by disturbing a child's engagement with linguistic stimuli.

2.4.5 LN

In adults, P3a is followed by reorienting negativity (RON) (Schröger & Wolff, 1998). A counterpart of this response in children was suggested to be the late negativity (LN, also called Negative component, Nc) (Gumenyuk et al, 2001, 2005; Kushnerenko et al., 2002; Määttä et al., 2005; Wetzel et al., 2006). This response to novel sounds is proposed to reflect reorienting of attention back to the primary task after recognizing and evaluating a distracting stimulus (Escera et al., 2001; Näätänen, 1992). The LN peaks maximally at fronto-central scalp areas at around 400–700 ms after the onset of a novel stimulus (Wetzel et al., 2006). The LN latency reflects reorienting time (Wetzel et al., 2006) and its amplitude reflects the neural effort given to reorienting (Schröger & Wolff, 1998) or attention paid to the surprising event (Määttä et al., 2005).

The LN has been detected already in newborns (Cheour-Luhtanen et al., 1995, 1996), and in infants and toddlers (Kushnerenko et al., 2002). There are also studies of its developmental changes. During maturation, the development of inhibitory mechanisms of distraction was suggested to be reflected by a diminishing amplitude and decreasing latency of LN (Čeponienė et al, 2004; Määttä et al., 2005).

2.5 Auditory processing and consonant acquisition in children with OM

The following sections review earlier studies on sound encoding, auditory discrimination, auditory attention, and consonant acquisition in children with OM. It should be noted that the definitions of OM differ across the studies. The detailed methods, such as OM history, and the main outcomes of these studies are presented in Table A1, in Appendix.

2.5.1 Sound encoding and auditory discrimination in children with OM

Neurophysiological methods have not been widely used in studying the effects of OM (for a review, see Whitton & Polley, 2011). Auditory brain stem responses (ABR) in children with a history of OM were shown to have signs of immaturity in neural integrity but no actual auditory neuropathy (e.g. Hall & Grose, 1993; Gravel et al., 2006; Maruthy & Mannarukrishnaiah, 2008). So far the only study utilizing the cortical auditory ERPs in investigating effects of OM was that of Maruthy and Mannarukrishnaiah (2008). They found that at three years of age children with a history of OM had abnormally long ABR latencies elicited by non-speech click stimuli, whereas the latencies of cortical obligatory responses for the same clicks were decreased. This finding may reflect possible compensatory changes at the higher level of central auditory system due to a longer conduction time at the level of brain stem. At four and five years of age, however, no significant differences in these responses were found between the children with a history of OM and the controls indicating that the earlier changes observed may be reversible. To the best of my knowledge, cognitive ERPs have not been reported in children with OM.

Behavioural measurements have, however, suggested that the discrimination of speech sounds is affect by childhood OM. Polka and Rvachew (2005) found that when tested with head-turning responses at the time of MEE, 6–9-month-old infants had difficulties in discriminating /bu/ and /gu/ syllables even when the sounds were presented to them with a 10 dB stronger sound pressure level than to control infants. Furthermore, 6–9-month-old infants with a history of OM but with healthy ears at the time of the study were also poorer in this discrimination task than infants with no history of OM. At the age of two years, children with a history of OM were shown to have difficulties discriminating between words with or without a fricative in word-final position (Petinou et al., 2001). Also 5-year-old children with a history of OM managed worse than their controls in the fricative discrimination task and in the same-different task for word pairs differing in their initial consonants (Nittrouer & Burton, 2005). Deficient auditory discrimination of consonants in children with a history of OM has been established even at school age, years after the OM episodes have resolved (Mody et al., 1999; Zumach et al., 2011). These results, indicating difficulties with auditory discrimination and being congruent from infancy to school-age, give support to the assumption that OM in early childhood is a risk factor for language development. Consonant discrimination is a pivotal part of language acquisition, and deficits in it can affect language development (Kraus et al., 1996; Benasich et al., 2006).

2.5.2 Studies of auditory attention in children with OM

Studies of auditory attention in young children with OM are scarce, probably due to the poor co-operation skills of toddlers in behavioural tasks. In the study of Feagans et al. (1994), toddlers with OM showed reduced attention during book reading and their mothers rated them as easily distractible. At school age, there is evidence for elevated distractibility in children with a history of OM in a school environment. Roberts et al. (1989) found that school-children with a history of OM were less task-oriented, as rated by their teachers. However, this was not evident in the study of Minter et al. (2001). Decreased resistance to distraction in the children with a history of OM was further proposed by Dhamani et al., (2013). They used a target identification task, where 10–15-year-old children had to discriminate and identify a target syllable from a string of five syllables in the presence of speech babble. Participants with listening difficulties and a history of OM showed longer time to re-orient their attention from distraction back to the task than did their peers.

A dichotic listening task, where two different CV syllables are presented simultaneously and directed to different ears through headphones, can be used to study auditory attention in children with adequate skills to co-operate. Asbjørnsen et al. (2000, 2005) and Klausen et al. (2000) investigated school-aged children and found that selective auditory attention was deficient in children with OM history. Children with a history of OM showed the right ear advantage, like their controls, when repeating syllables freely or repeating what they heard while attending to the right ear. However, when participants were asked to attend to and repeat syllables presented to the left ear, the children with a history of OM could not repeat more syllables presented to the left than the right ear like their controls. To summarize, earlier studies on children with OM have indicated deficits of auditory attention at the behavioural level, but the neural mechanisms underlying these findings are still unknown.

2.5.3 Consonant acquisition in children with OM

To date, the studies on the effects of OM on consonant inventories have focused on English-speaking children. The study groups have been small and children have had a heterogeneous background of OM. The consonant inventories of Finnish-speaking children with OM have not been studied previously. However, Kunnari (2000) investigated the typical phonological development in Finnish-speaking children and noted that three of ten children in her study had had recurrent middle ear infections, which she suggested had delayed their acquisition of words and phonemes. Abraham et al. (1996) studied 2-year-old children with OM during the first year of life. They found that these children produced fewer word-initial consonants and had problems in the production of consonants with back-placed articulation. Otherwise, phonological development seemed to follow a similar course to that of the control children. In the study of Petinou et al. (1999), highly visible bilabial plosives were found to be preferred in the babbling of 10–14-month-old children who had a history of OM. Miccio et al. (2001) followed up six 12–48-month-old children who had OM at least 2.5 months per year between the ages of 12–36 months. They found that the early phase of consonant acquisition was delayed but these children reached the typical range at the end of the follow-up period, except for one child with the most severe OM and hearing loss. However, all of these children showed delayed or atypical fricative acquisition.

In addition to these studies, there is an interesting case study by Donahue (1993), who reported her daughter’s lexical and phonological development at the age of 9–22 months. This child had chronic otitis media during the first year of her life. During the first phase (9–17 months) her speech production was characterized by vowels and nasals and she seemed to use words which had a distinct prosodic shape. At the later phase she showed a clear preference for bilabials and avoidance of velars in the words she produced.

Hence, OM can be suggested to result in delayed or atypical acquisition of consonants in English speaking children. However, these results might not be applicable to Finnish speaking children with different language specific patterns of phonology. The Finnish language, for example, largely lacks the contrast of voiced and voiceless consonants and the number of fricatives is very restricted compared to English (Suomi et al., 2006). Therefore, it is important to study the effects of RAOM on the acquisition of Finnish consonants.

3 AIMS OF THE STUDY

This thesis focuses on investigating central auditory processing and acquisition of phonology in 2-year-old children with RAOM. For the first time the study aimed to examine the possible effects of RAOM on different stages of central auditory processing by using auditory ERPs elicited by speech-syllable and novel stimuli. Furthermore, it aimed to investigate consonant inventories reflecting acquisition of phonology for the first time in Finnish children with RAOM.

Study I aimed to examine sound encoding and preattentive discrimination of sound features in children with RAOM and their matched controls. Sound encoding and auditory discrimination crucial for language development were investigated with the multi-feature paradigm by recording ERPs elicited by speech-syllables. It was hypothesized that RAOM would not have an effect on obligatory P1 and N2 reflecting sound encoding, but MMNs elicited by vowel, consonant, vowel duration, frequency, and/or intensity changes in Finnish syllables and reflecting preattentive discrimination of sound features, which would be affected in children with RAOM. Especially, it was supposed that children with RAOM would show a decreased or in other ways atypical MMN elicited by consonant changes in these syllables.

Study II aimed to examine involuntary auditory attention mechanisms in children with RAOM and their matched controls. To this end, the P3a and LN responses elicited by novel sounds in the multi-feature paradigm were compared between the groups. Children with RAOM were hypothesized to show atypically enhanced and/or short-latency P3a reflecting greater distractibility for the attractive novel sounds and to have enhanced and/or long-latency LN indicating more effort and longer time paid to the re-orientation of attention than their peers.

Study III aimed to investigate acquisition of phonology in children with RAOM and their matched controls. At the age of two years, phonology can be well studied by examining the acquisition of consonants. Spontaneous speech samples were used to compare the sizes of consonant inventories and the place and manner of articulation of consonants produced between the groups. It was suggested that the affected auditory processing in children with RAOM would result in restricted consonant inventories at this age, and especially as atypical fricative production.

4 MATERIALS AND METHODS

4.1 Research composition

4.1.1 Participants and ethics

The original study group consisted of 24 children with RAOM (at least three AOM per six months or four AOM per one year) and 22 control children with two or less episodes of AOM. During a 1-year period in 2009–2010, all children aged 22–26 months who came for tympanostomy tube insertion at the Ear, Nose and Throat clinic of Oulu University Hospital and fulfilled the criteria of this study were recruited to participate in this study. The lifetime history of AOM episodes in children with RAOM was collected from the medical records (Table 3). Children with RAOM were expected to have normal hearing with healthy, effusion free ears at the time of the measurement. The age-matched control children were recruited through public advertisements. All the families were volunteers. An informed written consent was obtained from the parents and they were paid 15 € for travel costs. A non-written assent was obtained from the children and their possible dissent from measurements was respected. The study was conducted in accordance with Declaration of Helsinki and the ethics committee of Northern Ostrobothnia Hospital District approved the study design.

Only Finnish-speaking, monolingual families were invited to the study. All the children were full-term born with normal birth weight. They had typical cognitive and motor development and no congenital hearing or visual abnormalities according to the parental questionnaires and the clinical examinations at the family and health care visits during their early childhood. All children were screened with the standardized Finnish version of Reynell Developmental Language Scales III, the Comprehension scale (Edwards et al. 1997; Kortesmaa et al., 2001) in order to exclude developmental language disorders. This test was selected because it is applicable to the screening of comprehension problems which can indicate other problems of cognitive development not connected to the history of OM (see Paradise et al., 2000, 2003, 2005, 2007; Roberts et al., 1995, 2004). Reynell III takes into account the large variation of language development at the age of two years but still detects comprehension problems with a possible cognitive background. The test was applied before or after the EEG registration at the Neurocognitive unit or, if a child was too tired, within a week at the child’s home. All the tests were performed by an experienced speech and language pathologist and they were also video recorded. Children with a family history of speech and language disorders, other developmental impairments, or severe neuropsychiatric diseases were excluded.

Before the EEG recording, an otolaryngologist examined all the children and verified that they had clinically healthy ears. To disclose possible sensory neural hearing losses at the time of this study, transient evoked otoacoustic emissions (TEOAE; MADSEN AccuScreen® pro, GN Otometrics; nonlinear click sequence 1.5 to 4.5 kHz, 73 dB SPL, pass/refer result) were checked before or right after the EEG recording. TEOAE measurements of four children with RAOM and six control children failed due to lack of co-operation but all had passed a TEOAE screening at a postnatal period in Oulu University Hospital.

Table 3. The history of middle ear infections in children with recurrent acute otitis media (RAOM)

Child	**Gender**	**Number of diagnosed AOM episodes before TTI**		**Number of diagnosed AOM per ear**		**First AOM diagnosed (months)**
		UNILAT	BILAT	RIGHT	LEFT	
1	M	2	2	4	3	2
2	M	8	1	5	5	1
3	M	7	5	3	3	5
4	F	0	4	4	4	9
5[a]	M	4	2	4	4	3
6[a]	M	7	0	11	6	5
7	F	8	1	0	7	11
8	F	3	1	5	6	8
9	M	4	2	4	1	4
10	M	2	3	4	4	10
11	F	5	1	4	4	1
12	M	3	4	6	4	7
13	F	0	3	3	3	14
14	M	0	3	4	4	15
15	F	2	3	5	4	14
16	M	1	2	3	3	17
17	M	1	4	3	2	14
18	F	0	4	3	4	19
19[b]	M	1	3	2	4	18
20	F	4	1	4	4	18

Note. AOM: acute otitis media; UNILAT: unilateral; BILAT: bilateral; F: female; M: male
a: a statistical outlier in Study II due to enhanced P3a responses
b: an affected speech sample in Study III

Table 4 summarizes the research composition and the final groups in each part of the study. In the RAOM group, reasons for exclusion due to the above-mentioned criteria were as follows: one child had a family history of dyslexia, one child showed signs of a developmental language impairment according to the Reynell III and a further examination of a speech and language pathologist, and the families of two children did not arrive for the EEG registration at the appointed time. In Study II, the analysis indicated abnormally enhanced P3a responses in two children with RAOM, and statistical analyses indicated they were outliers. Because it was hypothesized that the RAOM group would have enhanced P3a responses, these children were excluded from further analysis in the study to avoid any bias in the results. Considering Study III, transcription of the spontaneous speech sample of one child with RAOM was not possible because a sibling masked the sample. In the control group, a reason for the exclusion of one child was a diagnosed AOM at the time of the measurement. Considering Studies I and II, two control children showed a low signal to noise ratio caused by alpha activity in their EEG and they were excluded from the ERP analyses.

4.1.2 Electrophysiological measurements

EEG registration

The EEG registrations in Studies I–II were carried out in an electrically shielded and sound-attenuated chamber, reverberation time and background noise being 0.3 seconds and 43 dB, respectively. The children sat in a chair or in their parent’s lap and watched voiceless cartoons or children’s books or played with silent toys in order to ignore the auditory stimuli (passive condition). The parents were requested to be as quiet as possible. Brain Vision BrainAmp system and software and ActiCAP 002 (Brain Products GmbH) with 32 channel active-shielded Ag-AgCl electrodes placed according to the international 10/20 system were used for EEG registration at frequencies of 0.16–1000 Hz with a sampling rate of 5000 Hz. The FCz electrode served as an online reference. Impedances were kept below 20 kΩ. Electro-oculogram was registered with additional electrodes placed above the outer canthus of the right eye and below the outer canthus of the left eye with a bipolar montage.

During recording, the child was camera monitored and an experienced EEG technician followed the quality of the EEG signal. Breaks with refreshments were allowed when necessary. In addition, every other stimulus sequence was presented with background noise, reported by Niemitalo-Haapola et al. (2015). The total EEG registration time was approximately 45 minutes. In those children with RAOM, EEG registration was done on average 33 days (range 20–56 d) after the tympanostomy tube insertion to ensure healthy ears at the time of the EEG recording.

Table 4. Research composition

	Study I		Study II		Study III	
Theme	Sound encoding and preattentive auditory discrimination of speech features		Involuntary auditory attention switch		Consonant acquisition	
Subjects	**RAOM**	**Controls**	**RAOM**	**Controls**	**RAOM**	**Controls**
	N = 20	N = 19	N = 18	N = 19	N = 19	N = 21
Mean age in months (min-max)	24 (22–26)	24 (22–26)	24 (22–26)	24 (22–26)	24 (22–27)	24 (22–26)
Gender	8 F 12 M	8 F 11 M	8 F 10 M	8 F 11 M	8 F 11 M	9 F 12 M
Mother's education*	4 low 15 m-h	2 low 17 m-h	4 low 13 m-h	2 low 17 m-h	4 low 15 m-h	2 low 19 m-h
Method	Electrophysiological measurements Linguistic multi-feature paradigm with novel sounds				Behavioural assessment Spontaneous speech sample	
Measures	P1, N2, MMN		eP3a, lP3a, LN		Vocabulary size Consonant inventory size Place and manner of articulation	

Note. RAOM: recurrent acute otitis media; F: female; M: male; m-h: middle or high
* Based on years of education after nine years of elementary school; low: 0–3 years; middle or high: 4 years or more. The educational information of one mother in the RAOM group was not available. No significant group differences in age, gender, or mothers' education were observed.

Auditory stimuli

The linguistic multi-feature paradigm with Finnish syllable stimuli was used for stimulus presentation. The multi-feature paradigm was shown to be a fast and eligible method for obtaining several ERPs reflecting different stages of auditory processing in adults ("Optimum-1"; Näätänen et al., 2004; Kujala et al., 2006; Pakarinen et al., 2009; Sorokin et al., 2010), school-aged children (Lovio et al., 2009, 2010; Kujala et al., 2010) and toddlers (Putkinen et al., 2012; Niemitalo-Haapola et al., 2013). In the multi-feature paradigm, a standard sound and several types of deviant sounds alternate in succession. In the deviants, only one sound feature (e.g. vowel or frequency) of the standard stimulus is changed at a time while the other features remain the same and strengthen the memory representation of the standard stimulus. To study attentional mechanisms, occasional distracting novel sounds may also be embedded in the same sound stream (Sorokin et al., 2010; Putkinen et al., 2012; Niemitalo-Haapola et al., 2013). The sound variability of this paradigm resembles the natural speech listening situation and may thus increase the ecological validity to identify auditory processing difficulties in clinical groups (Kujala et al., 2006).

The syllables were semisynthetic CV syllables, the standards being /ke:/ or /pi:/ and the deviants being five different syllables with changes of vowel, consonant, vowel duration, frequency, and intensity (Alku et al., 1999). Distracting novel sounds were embedded among these repeating syllables. They were non-synthetic, environmental human (e.g. coughs and interjection) or non-human (e.g. door slam and telephone ring) sounds (Sorokin et al., 2010). More detailed description of these stimuli is presented in Table 5.

The stimuli were presented with a sound pressure level of 75 dB via two loudspeakers (Genelec® 6010A, Genelec Ltd.) in front of the child. The two loudspeakers were symmetrically positioned at a distance of 1.3 m and in a 40 degree angle from the child's head. Stimuli were presented quasi-randomly so that every other stimulus was a standard and every other was one of the deviants or novels but the same deviant or novel sound never occurred before and after a standard stimulus. Probability of the standard stimulus was 0.5 and those of each deviant and novel sound 0.08. SOA was 670 ms. In the present study, three to four stimulus sequences of about 6 minutes were presented to each participant. Each sequence started with 10 standards and included 540 stimuli.

4.1.3 Behavioural assessments

In Study III, a semi-structured free play situation of 15 minutes with a box of selected toys and picture books was used to collect spontaneous speech samples. Toys and books were assessed to be appropriate for 2-year-old children and suitable for eliciting a wide variety of different kinds of words as well as all Finnish phonemes. A child played with one parent, who was told to interact with the child as normal. Most of the parents were mothers, but there were also two fathers in the RAOM group and three fathers in the control group.

The play situation was video recorded and a high-quality microphone (Sony ECM-55B) was placed on the floor near the child and moved during the recording as necessary. The recordings were carried out in the quiet room at the Neurocognitive unit after the EEG registration. If any child was too tired at that moment, the play situation was recorded with the same equipment and procedure within a week at the child's home. Video recording of nine children in the RAOM group and six children in the control group was carried out at home.

4.2 Data analysis

4.2.1 ERP data

The offline analysis of EEG was carried out using Brain Vision Analyzer 2.0 (BrainProducts, GmpH). Data were down sampled to 250 Hz and re-referenced to the mathematical average of the mastoid electrodes. This re-referencing provides a good MMN signal to noise ratio (Kujala et al., 2007) and enables hemispheric differences to be addressed (Luck, 2005). Because of the young age of the participants, data were filtered at first with band pass of 0.5–45 Hz, 24 dB/octave (zero phase shift -filter) to decrease signals which did not originate from the brain and, furthermore, to avoid aliasing (Luck, 2005).

All the data were visually inspected to check their quality and to remove large artefacts. Data of Fp1, Fp2, PO9, PO10, O1, Oz, and O2 electrodes included extracerebral artefacts and were disabled from further ERP analysis. Next, the blink artefacts were reduced by applying an independent component analysis. The F7 and F8 electrodes and additional EOG electrodes were used to identify horizontal and vertical eye movements. After that, the voltage exceeding ± 150 µV and ± 50 ms around it at any electrode was determined as extracerebral artefact and removed. Then, the data were filtered with band pass of 1–20 Hz, 48 dB/octave (zero phase shift -filter).

The continuous EEG was segmented based on the stimulus triggers. The epochs were -100 ms prestimulus to 500 ms after stimulus onset in Study I and -100 ms prestimulus to 670 ms after stimulus onset in Study II. The data were baseline corrected according to the -100 ms to 0 ms prestimulus. The first 10 standard stimuli at the beginning of each recorded sequence and the standard stimuli right after the novel stimuli were not taken in the analysis. The epochs containing ERPs to the standards and to the vowel, consonant, intensity, and frequency deviant were clustered, respectively. Next, the epochs were separately averaged for standards, each deviant type (Study I), and novel sounds (Study II). The mean numbers of accepted trials for each stimulus type are presented in Table 5. A two-tailed independent samples *t* test indicated no significant differences between the groups within the means of accepted trials.

The peak detection for each ERP response was done individually for each child. The P1 and N2 responses were identified from the ERP waveform for standard stimuli, the MMN from the deviant minus standard difference waveform, and eP3a, lP3a, and LN from the novel minus standard difference waveform. The selection of time windows and electrode for the peak detection was based on the literature of ERP measurements in children (see Čeponienė et al., 2002; Määttä et al., 2005) and visual inspection of the grand average difference waves. Table 5 presents these parameters for each response. The peak latency was determined from the most positive (P1, eP3a, and lP3a) or the most negative (N2, MMN, and LN) peak in those windows. The mean peak amplitudes were calculated from a ±24 ms time window around peak latencies for the P1, N2, and MMN responses (Study I) and from a ±20 ms time window around the peak latencies for the eP3a, lP3a, and LN responses (Study II).

4.2.2 Behavioural data

Spontaneous 15 minute-long speech samples collected from the child-parent play situation were transcribed by using the International Phonetic Alphabet (IPA). The author of this thesis performed all the transcriptions. Blinded for groups, a trained under-graduate student made additional transcriptions for cross-checking of ten children (25% of the sample). The inter-rater agreement for consonant transcriptions was 83%.

Identification of words

Firstly, the meaningful words were identified from the samples using the criteria of Vihman and McCune (1994). These criteria have been used earlier in the studies of phonemic inventories in Finnish speaking children (Kunnari, 2003; Kunnari et al., 2006). It was observed that onomatopoeic words (e.g. voices of animals and vehicles) constituted a large proportion of children’s vocabulary at this age. Hence, they were taken into account. Nonetheless, at the age of two years children already have an advanced ability to correct their productions according to a model. For that reason, words immediately imitated after a parent’s pronunciation were excluded. A number of meaningful words were counted for each child so that inflected forms of the same word were counted as one.

Identification of consonants

In Study III, only words with a meaning were used for defining consonant inventories. Consonants occurring in any word position (AWP) and in specific positions of words, namely word-initial (WI), word-medial (WM), and word-final (WF), were defined separately. To be counted in the inventory, a consonant had to occur in two different words (AWP inventory) and likewise, in two different words in a specific position (WI, WM, and WF inventories). If a consonant occurred once, it was classified as a marginal phoneme. The same method has been used in previous studies on Finnish (Kunnari, 2003; Kunnari et al., 2006) and in other studies of phonemic inventories (e.g. Dyson, 1988; Stoel-Gammon, 1985, 1987; Morris, 2009). Double consonant phonemes (geminates; e.g. /kukka/, ‘flower’), which are characteristic of Finnish in a word-medial position, were counted as one because the place and manner of articulation do not change within a geminate and also because there is no absolute duration length for geminates (Karlsson, 1983, p. 72). The Finnish consonant system includes only one sibilant, /s/, and one trill, /r/, which are known to be difficult to learn to produce accurately for Finnish children, and even for some adult speakers (Saaristo-Helin, 2009). This allows a degree of variation among speakers. In this study, /s/ and /r/ were accepted in the inventory if the child made a clear distinction between these phonemes and others by using their own allophonic variant, which could not be confused with another phoneme (e.g. /kissa/ as [kiʃʃa], ‘cat’; /karhu/ as [kaʀhu], ‘bear’). Higher phonological abilities are implicated when a child uses an allophonic variant for the target phoneme and does not merely omit it or submit it with another phoneme (Saaristo-Helin, 2009).

In addition to sizes of consonant inventories, place (labials, dentals/alveolars, palato-velars, and glottal) and manner (stops, fricatives, lateral, trill, nasals, and semivowels) of articulation for the consonants were also determined. The consonants produced by the majority (60%) of children in both groups were also determined.

Table 5. Parameters of ERP measurements (Studies I and II)

	Stimulus	ERP response	Electrode	Time window for peak detection (ms)	Accepted trials per participant Mean (min–max) [SD]	
					RAOM	**Controls**
Study I	**Standard** /ke:/ or /pi:/ F0 101 Hz duration 170 ms	**P1**	Cz	80–200	685 (374–856) [125]	728 (534–859) [88]
		N2	Cz	200–300		
	Deviant					
	Vowel from /ke:/ to /ki:/ and from /pi:/ to /pe:/	**MMN**	Cz	150–300	138 (73–170) [24]	146 (108–175) [18]
	Consonant from /ke:/ to /pe:/ and from /pi:/ to /ki:/		Cz	150–300	136 (74–169) [26]	145 (110–169) [17]
	Vowel duration from syllable length of 170 ms to 120 ms		Cz	200–400	138 (76–172) [24]	146 (100–169) [18]
	Frequency F0 +/- 8%		C4*	150–300	136 (77–173) [24]	147 (105–170) [17]
	Intensity +/- 7 dB		Cz	150–350	137 (76–171) [25]	145 (108–171) [17]
Study II	**Standard** /ke:/ or /pi:/ F0 101 Hz duration 170 ms				675 (373–856) [131]	719 (517–856) [91]
		eP3a	Cz	180–300		
	Novel sound human or non-human environmental sound duration 200 ms	**lP3a**	Fz	300–440	133 (75–170) [27]	143 (99–171) [19]
		LN	Fz	420–600		

Note. * The frequency deviant elicited no significant MMN at Cz but clearly right hemispheric lateralized MMN; F0: fundamental frequency; SD: standard deviation

4.2.3 Statistical analysis

ERP data

The obligatory (P1 and N2) and MMN responses (Study I) were statistically analysed from six electrodes, F3, Fz, F4, C3, Cz, and C4, because those responses are known to be largest at fronto-central electrodes (Čeponienė et al., 2002; Cheour et al., 2000; Kujala et al., 2007). The P3a and LN (Study II) were analysed from nine electrodes, F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4, as commonly used in investigating these responses (Gumenyuk et al., 2001, 2005; Määttä et al., 2005). At first, the existence of each ERP response (P1, N2, MMN, eP3a, lP3a, and LN) was determined by comparing whether its amplitude differed from zero with a two-tailed *t* test.

The group differences in amplitudes and amplitude scalp distributions of all responses were examined by repeated measures analysis of variance (ANOVA) with a group [RAOM, control] as a between-subject factor. For the P1 and N2, within-subject factors of a 3-way ANOVA were anterior-posterior (AP) [F3-Fz-F4, C3-Cz-C4] and right-left (RL) [F3-C3, Fz-Cz, F4-C4] electrode locations. In the MMN analysis, 4-way ANOVA included within-subject factors as follows: deviant type [vowel, consonant, vowel duration, frequency, intensity] and AP [F3-Fz-F4, C3-Cz-C4] and RL [F3-C3, Fz-Cz, F4-C4] electrode locations. The eP3a, lP3a, and LN analyses were performed with a 3-way ANOVA and the within-subject factors were AP [F3-Fz-F4, C3-Cz-C4, P3-Pz-P4] and RL [F3-C3-P3, Fz-Cz-Pz, F4-C4-P4].

The group differences of the latencies of all responses were studied with one-way ANOVA. The P1, N2, and MMN latencies were inspected at the Cz electrode, except for the MMN elicited by the frequency deviant, which was determined at the C4 electrode. This was done because the MMN elicited by frequency deviant was right-side lateralized and did not reach a significance at the Cz electrode. The eP3a latency was also compared at the Cz electrode. The lP3a and LN latencies were inspected at the Fz electrode. For all ANOVA analyses, the Huynh–Feldt correction was applied if it was appropriate and the partial eta squared (ηp^2) was calculated for the effect-size estimation.

Behavioural data

In investigating the consonant inventories (Study III), non-parametric tests were used for the statistical analyses because the sample size was small and not all variables were normally distributed. A Chi square test and Fisher's exact test were used for the comparison of categorical variables. The group differences in the number of words produced, sizes of consonant inventories, and the place and manner of articulation were inspected with a Mann-Whitney U test. Within the groups, the Wilcoxon signed rank test was used to compare the size of WI and WM consonant inventory in the related samples. The correlation between the number of words produced and the size of consonant inventory was studied with Spearman’s rho correlation coefficient.

5 RESULTS

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5.1 Obligatory ERPs (Study I)

The standard syllables /ke:/ and /pi:/ (combined in the analysis) elicited an ERP wave including clearly identifiable and statistically significant P1 and N2 responses in both those children with RAOM and their controls (Figure 1). The detailed information of these responses is presented in Table 6. There were no group differences in the amplitude, amplitude scalp distribution, or latency of P1 and N2.

Table 6. The mean amplitudes and latencies of obligatory ERPs elicited by the standard stimuli in the children with recurrent acute otitis media (RAOM) and the controls

	Electrode	Group	Amplitude µV Mean (SD)	p*	Latency ms Mean (SD)
P1	Cz	**RAOM**	8.6 (3.7)	0.001	139 (13)
		Controls	8.8 (3.1)	0.001	137 (11)
N2	Cz	**RAOM**	-2.0 (3.4)	0.001	247 (23)
		Controls	-2.2 (2.4)	0.001	252 (24)

Note. *Two-tailed t test, difference from 0 µV; SD: standard deviation

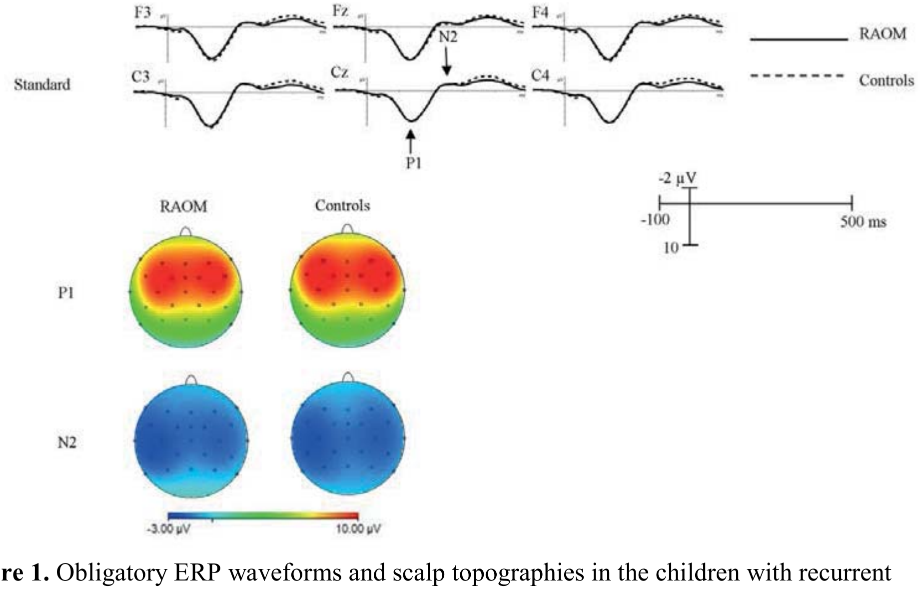

Figure 1. Obligatory ERP waveforms and scalp topographies in the children with recurrent acute otitis media (RAOM) and the controls

5.2 MMN (Study I)

All deviant stimuli elicited statistically significant MMNs in both those children with RAOM and their controls (Figure 2). The amplitudes, latencies, and statistical information of MMNs are presented in Table 7. It was found that the vowel duration deviant elicited a stronger MMN response than the other deviants in both groups (A 4-way ANOVA; Deviant main effect F(4,148) = 5.55, $p = 0.0003$, $\eta p^2 = 0.13$, LSD post hoc $p \leq 0.02$, Huynh-Feldt corrected).

For the MMN amplitudes, there was a significant Group x Deviant x AP x RL interaction (A 4-way ANOVA; F(8,296) = 2.46, $p = 0.01$, $\eta p^2 = 0.06$). According to the LSD post hoc test, the MMN amplitude for the vowel deviant was enhanced in those children with RAOM at all electrodes except at C3 ($p \leq 0.05$, Huynh-Feldt corrected). An enhanced MMN amplitude for the frequency deviant was found at C3 and Cz in the RAOM group ($p \leq 0.04$, Huynh-Feldt corrected). Furthermore, the LSD post hoc test showed several group differences in the MMN amplitude scalp distribution. Firstly, the MMN elicited by the consonant change was evenly distributed in those children with RAOM, while its amplitude was strongest at the left side electrodes in the controls ($p =$ 0.01–0.07, Huynh-Feldt corrected). Secondly, the RAOM group had a left-hemispheric lateralization for the frequency MMN. It was strongest at the C3 electrode ($p < 0.03$, Huynh-Feldt corrected). The control group, in turn, had a stronger frequency MMN amplitude at the right (C4) than left scalp (C3) ($p = 0.05$, Huynh-Feldt corrected). Thirdly, the RAOM group had frontally and centrally evenly distributed MMN amplitude for the intensity change whereas in the control group it was centrally strongest ($p < 0.01$, Huynh-Feldt corrected).

The only MMN latency difference between the groups was found for the MMN elicited by the frequency deviant. It was found to be faster in those children with RAOM than in the controls (One-way ANOVA; F(1,38) = 4.25, $p = 0.05$, $\eta p^2 = 0.10$).

Table 7. The mean amplitudes and latencies of the MMN responses elicited by the different deviant stimuli in the children with recurrent acute otitis media (RAOM) and the controls

Deviant	Electrode	Group	Amplitude µV Mean (SD)	p*	Latency ms Mean (SD)
Vowel	Cz	**RAOM**	-3.0 (2.0)	0.001	226 (38)
		Controls	-1.3 (2.6)	0.05	233 (30)
Consonant	Cz	**RAOM**	-2.1 (3.1)	0.01	227 (40)
		Controls	-1.7 (1.5)	0.001	242 (39)
Vowel duration	Cz	**RAOM**	-3.2 (2.4)	0.001	180 (16)
		Controls	-4.2 (2.8)	0.001	189 (21)
Frequency	C4	**RAOM**	-2.1 (2.6)	0.01	211 (30)
		Controls	-1.9 (2.6)	0.01	235 (41)
Intensity	Cz	**RAOM**	-2.0 (2.1)	0.001	255 (39)
		Controls	-2.4 (2.3)	0.001	253 (41)

Note. *Two-tailed t test, difference from 0 µV; SD: standard deviation

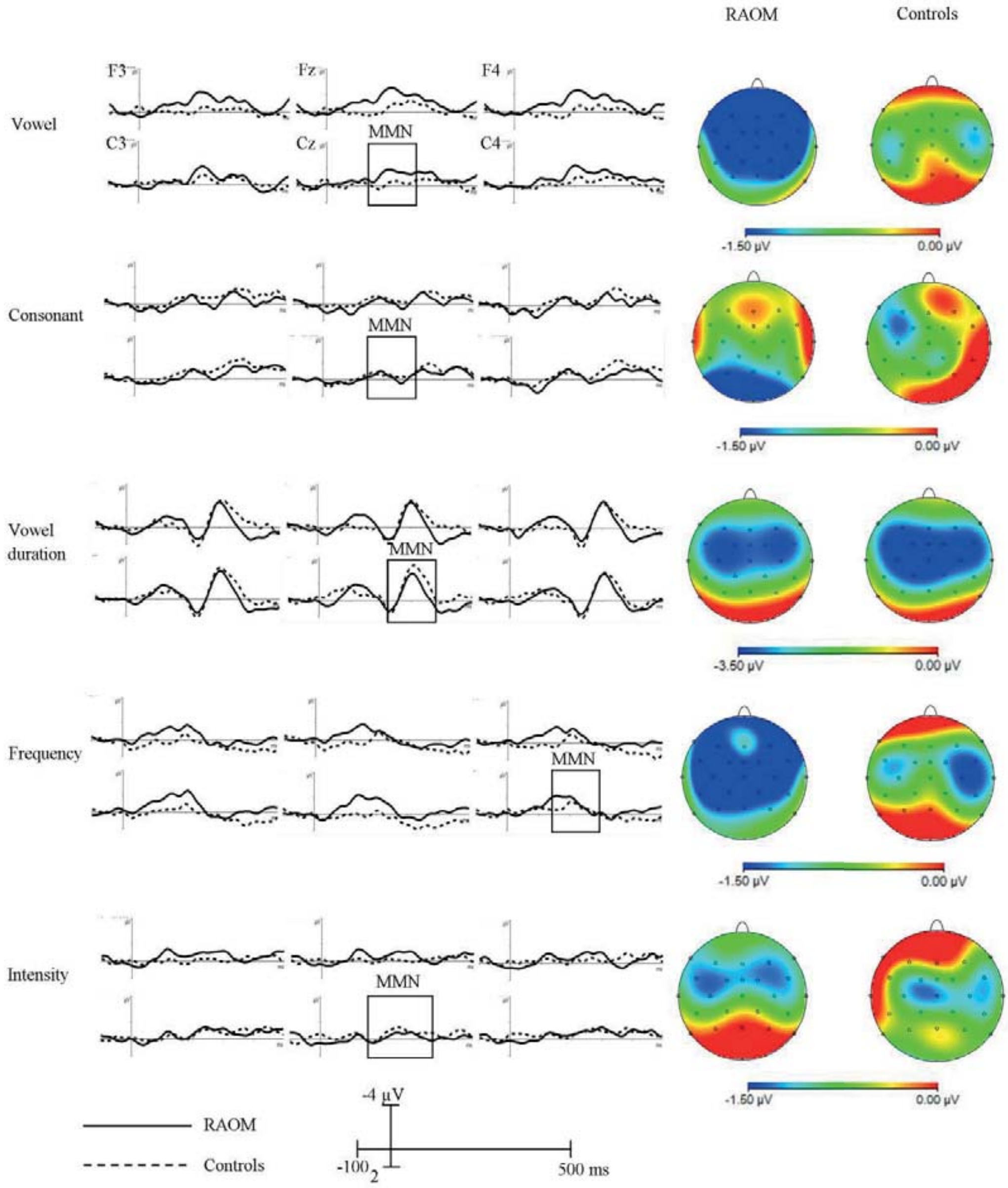

Figure 2. Grand average difference waves (deviant minus standard) and scalp topographies for mismatch negativities (MMN) elicited by the different deviants in the children with recurrent acute otitis media (RAOM) and the controls

5.3 P3a and LN (Study II)

In both groups, eP3a, lP3a, and LN significantly differed from zero (Table 8, Figure 3). With no group difference, a repeated measures ANOVA showed a stronger eP3a at the frontal and central electrodes than at the parietal electrodes (AP main effect; $F(2,57) = 42.09$, $p < 0.001$, $\eta_p^2 = 0.53$; LSD post hoc $p < 0.001$). There were no group differences in the eP3a amplitude, amplitude scalp distribution, or latency.

A repeated measures ANOVA for the lP3a amplitude showed a significant AP x RL interaction with no group difference ($F(4,140) = 4.98$, $p < 0.001$, $\eta_p^2 = 0.13$). At frontal electrodes, RL distribution was even but at central electrodes left hemispheric activation was stronger compared to the vertex and right side electrodes. (LSD post hoc; $p < 0.001$) Furthermore, at parietal electrodes, stronger left- than right-side responses were found (LSD post hoc; $p = 0.03$). A significant Group x AP interaction was found for the lP3a amplitude ($F(2,59) = 3.94$, $p = 0.03$, $\eta_p^2 = 0.10$). According to the LSD post hoc test, the children with RAOM had a more even AP distribution than the control children who had more clearly frontally maximal and posteriorly diminishing amplitude (mean amplitudes frontally 8.99 vs. 9.67 µV, centrally 7.12 vs. 6.04 µV, and parietally 3.64 vs. 2.17 µV in the RAOM and control group, respectively). The latency of the lP3a did not differ between the groups.

A repeated measures ANOVA for the LN amplitude showed a significant AP x RL interaction ($F(4,148 = 2.96$, $p = 0.02$). This was due to the weakest amplitude at F3 (LSD post hoc; $p = 0.001–0.03$) and the strongest amplitude at Cz (LSD post hoc; $p = 0.001–0.002$). There were no group differences in the amplitude or amplitude scalp distribution of LN. The latency of LN significantly differed between the groups (One-way ANOVA; $F(1,37) = 32.76$, $p < 0.001$, $\eta_p^2 = 0.47$). The LN peaked later in those children with RAOM than in the controls.

Table 8. The mean amplitudes and latencies of ERPs elicited by the novel stimuli in the children with recurrent acute otitis media (RAOM) and the controls

Response	Electrode	Group	Amplitude µV Mean (SD)	p*	Latency ms Mean (SD)
eP3a	Cz	**RAOM**	6.66 (4.30)	0.001	244 (26)
		Controls	6.97 (3.44)	0.001	248 (25)
lP3a	Fz	**RAOM**	9.30 (3.69)	0.001	348 (36)
		Controls	9.67 (3.74)	0.001	341 (22)
LN	Fz	**RAOM**	-2.82 (3.38)	0.001	599 (40)
		Controls	-2.34 (3.04)	0.004	526 (43)

Note. *Two-tailed t test, difference from 0 µV; SD: standard deviation

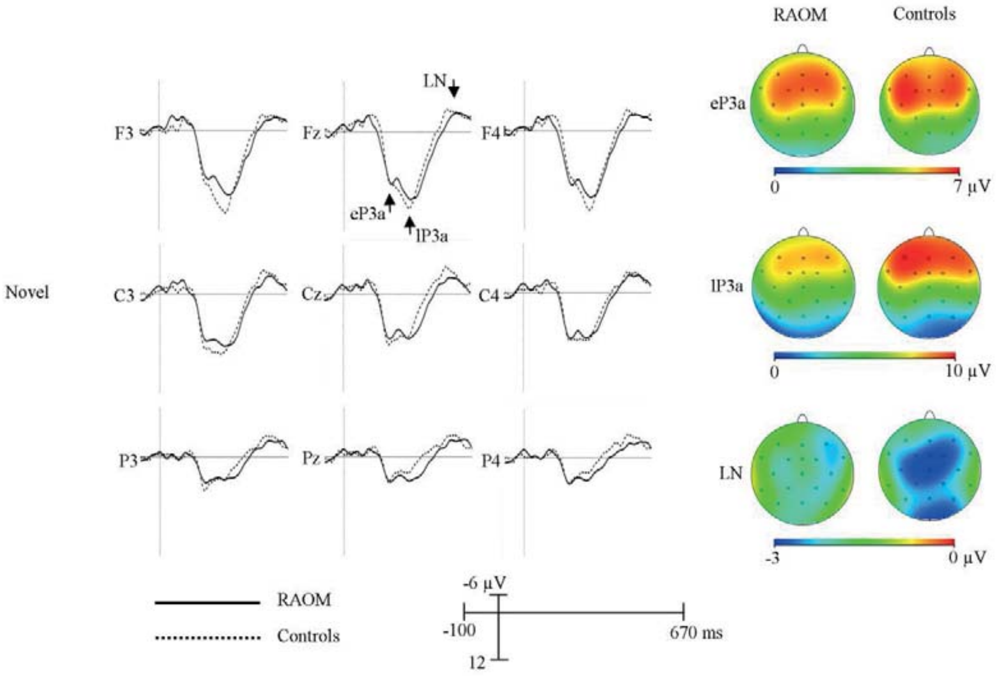

Figure 3. Grand average difference waves (novel minus standard) and scalp topographies for eP3a, lP3a, and LN elicited by novel stimuli in the children with recurrent acute otitis media (RAOM) and the controls

5.4 Consonant inventories (Study III)

Speech sample size

There was a significant group difference in the mean number of words produced in speech samples due to fewer words in the children with RAOM than the controls (Mann-Whitney U = 118.00, $p \leq 0.05$). Figure 4 presents the characteristics of the speech sample sizes and shows a large variation in the control group compared to the more homogeneous RAOM group.

Consonant inventory size

The consonant inventories are presented in Figure 5. The children with RAOM had significantly smaller AWP (Mann-Whitney U = 108.50, $p \leq 0.01$) and WM (U = 109.00, $p \leq 0.01$) consonant inventories than the control children. There was also a trend for smaller WI inventories (U = 131.50, p = 0.065) in the RAOM group than in the control group. In the WF position, just a few consonants were produced in both groups with no group difference; neither were group differences found in the number of marginal phonemes. The control children had more consonants in their WM than in their WI inventory (Wilcoxon signed rank W = 138.00, $p \leq 0.01$), which is a typical developmental feature in Finnish children at this age. In those children with RAOM, this was a trend (W = 72.00, p = 0.057).

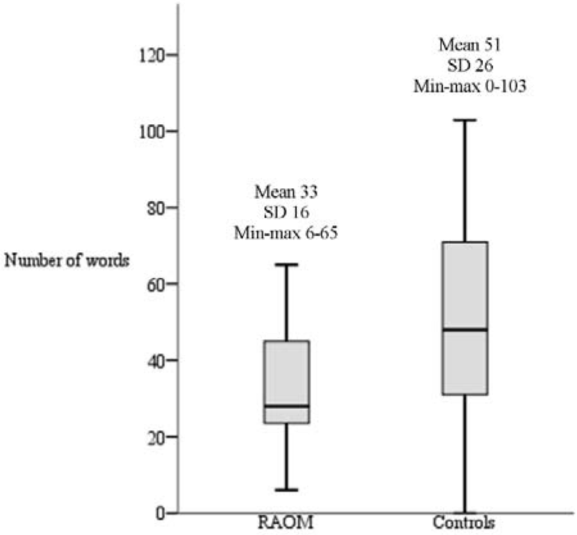

Figure 4. The mean number of words produced by the children with recurrent acute otitis media (RAOM) and the controls. SD: standard deviation

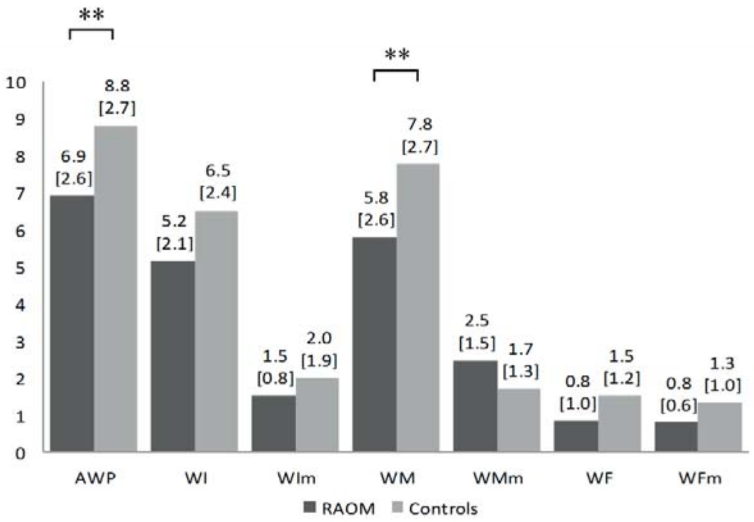

Figure 5. Mean number of consonants produced by the children with recurrent acute otitis media (RAOM) and the controls. Standard deviations are in brackets. **: a significant difference between the groups, $p \leq 0.01$; AWP: any word position; WI: word-initial position; WM: word-medial position; WF: word-final position; m: marginal phonemes.

Correlation for the speech sample size and the consonant inventory size

The correlations for the speech sample sizes and the consonant inventory sizes are presented in Table 9. It was observed that the number of words in the speech sample correlated with the AWP consonant inventory size in both groups. Furthermore, the speech sample size also correlated well with the inventories in different positions of words in both groups.

Table 9. The correlation (Spearman ρ) for the speech sample size and the consonant inventory size in the children with recurrent acute otitis media RAOM and the controls

	Group	AWP	p	WI	p	WM	p	WF	p
Speech sample size	**RAOM**	0.817	0.001	0.928	0.001	0.859	0.001	0.588	0.01
	Controls	0.743	0.001	0.769	0.001	0.797	0.001	0.893	0.001

Note. Inventory sizes were counted for consonants occurring in any word position (AWP), and in word-initial (WI), word-medial (WM), and word-final (WF) positions

The place and manner of articulation

The consonants produced by the children in both groups are presented in Tables 10–12. There was a significant group difference in the place of articulation of the consonants produced. Those children with RAOM produced consonants less frequently in the category of dentals/alveolars than the controls (Mann-Whitney $U = 88.00$, $p \leq 0.01$). The manner of articulation was also found to differ between the groups. Those children with RAOM produced fricatives less frequently than the controls ($U = 104.00$, $p \leq 0.01$). Furthermore, the nasals tended to be less frequently produced in the RAOM than control group ($U = 135.50$, $p = 0.083$).

In the WI position, it was found that those children with RAOM showed a tendency to produce dentals/alveolars less frequently than the controls ($U = 129.50$, $p = 0.057$). In the WM position, the children with RAOM produced significantly less both fricatives ($U = 113.50$, $p \leq 0.05$) and dentals/alveolars ($U = 101.50$, $p \leq 0.01$) and in the WF position, they produced less fricatives ($U = 115.50$, $p \leq 0.05$) when compared to the controls.

Table 10. Percentages for the children with recurrent acute otitis media (RAOM) and the controls producing each Finnish consonant in any word position

Manner of articulation	**Place of articulation**							
	Labials		**Dentals/Alveolars**		**Palato-velars**		**Glottal**	
	RAOM	**Controls**	**RAOM**	**Controls**	**RAOM**	**Controls**	**RAOM**	**Controls**
Stops								
Voiceless	p 94.7%	p 95.2%	t 94.7%	t 95.2%	k 89.5%	k 90.5%		
Voiced	(b) 5.3%	(b) 4.8%	d 0%	d 9.5%	(g) 0%	(g) 0%		
Fricatives	(f) 0%	(f) 4.8%	s, (ʃ) 26.3%	s, (ʃ) 76.2%			h 52.6%	h 71.4%
Lateral			l 68.4%	l 81.0%				
Trill			r 5.3%	r 23.8%				
Nasals	m 84.2%	m 95.2%	n 73.7%	n 90.5%	ŋ 10.5%	ŋ 28.6%		
Semivowels	ʋ 52.6%	ʋ 71.4%			j 31.6%	j 42.9%		

Note. Phonemes in parentheses occur in loan words in Finnish. In this sample, /s/ and / ʃ/ were counted as one phoneme because /ʃ/ is very rare in Finnish and it is a phonetic variant of /s/ in many 2-year-old children. In all cases the target phone was /s/. There was a significant group difference in the production of dentals/alveolars and fricatives (shaded boxes). In individual phonemes, only the production of the fricative /s/ significantly differed between the groups (dark coloured box; $\chi^2(1) = 9.950$, $p \leq 0.01$).

Table 11. Percentages for the children with recurrent acute otitis media (RAOM) and the controls producing each Finnish consonant in word-initial (WI), word-medial (WM), and word-final (WF) positions

Consonant phoneme	WI		WM		WF	
	RAOM	**Controls**	**RAOM**	**Controls**	**RAOM**	**Controls**
p	84.2%	90.5%	68.4%	81.0%	-	-
t	94.7%	95.2%	94.7%	95.2%	15.8%	23.8%
k	84.2%	81.0%	78.9%	85.7%	-	-
(b)	5.3 %	4.8%	-	-	-	-
d	-	-	-	9.5%	-	-
(g)	-	-	-	-	-	-
(f)	-	4.8%	-	-	-	-
s, (ʃ)	15.8%	42.9%	26.3%	71.4%	15.8%	57.1%
h	26.3%	38.1%	42.1%	61.9%	-	4.8%
l	26.3%	47.6%	68.4%	76.2%	-	4.8%
r	-	4.8%	5.3%	23.8%	-	-
m	73.7%	90.5%	57.9%	71.4%	5.3%	-
n	52.5%	71.4%	63.2%	85.7%	47.4%	61.9%
ŋ	-	-	10.5%	28.6%	-	-
ʋ	31.6%	47.6%	36.8%	57.1%	-	-
j	21.1%	33.3%	26.3%	28.6%	-	-

Note. Phonemes in parentheses occur in loan words in Finnish. In this sample, /s/ and /ʃ/ were counted as one phoneme because /ʃ/ is a phonetic variant of /s/ in many 2-year-old children and very rare in Finnish. In all cases the target phone was /s/. The shaded boxes indicate a significant difference of individual phonemes between the groups (WM: χ^2 (1) = 8.120, $p \leq 0.01$; WF: χ^2 (1) = 7.278, $p \leq 0.01$).

Table 12. Consonants produced by the majority (60%) of children with recurrent acute otitis media (RAOM) and the controls in any word position (AWP), word-initial (WI), word-medial (WM), and word-final (WF) positions

Inventory	Group	Consonants produced by 60 % of children
AWP	**RAOM**	[p], [t], [k], [l], [m], [n]
	Controls	[p], [t], [k], [l], [m], [n], [h], [s], [ʋ]
WI	**RAOM**	[p], [t], [k], [m]
	Controls	[p], [t], [k], [m], [n]
WM	**RAOM**	[p], [t], [k], [l], [n]
	Controls	[p], [t], [k], [l], [m], [n], [h], [s]
WF	**RAOM**	-
	Controls	[n]

6 DISCUSSION

6.1 Sound encoding in children with RAOM

Sound encoding was investigated in Study I by measuring obligatory ERPs elicited by standard stimuli, /ke:/ and /pi:/ syllables. These stimuli elicited significant P1 and N2 responses in those children with RAOM and the controls. In both groups, these responses were found to be age-typical (Čeponienė et al., 2002; Kushnerenko et al., 2002; Ponton et al., 2000) and there were no group differences in their amplitude, amplitude scalp distribution, or latency.

Earlier, Maruthy and Mannarukrishnaiah (2008) recorded obligatory ERPs elicited by non-speech click stimuli in children who had OM during their first year of life. At three, four, and five years of age, they found equal amplitudes and equal or even shorter latencies of obligatory responses in children with a history of OM in comparison to the controls. Thus, the findings suggest that early childhood RAOM does not affect the basic encoding of non-speech or speech-like stimuli.

6.2 Preattenttive auditory discrimination in children with RAOM

In Study I, central preattentive auditory discrimination was determined by measuring the MMN in response to five deviations (vowel, consonant, vowel duration, frequency, and intensity) of standard /ke:/ and /pi:/ syllables. All deviants elicited significant MMN responses in both those children with RAOM and the controls. Consistent with a previous study in Finnish-speaking school-aged children using similar stimuli as in the current study (Lovio et al., 2010), the MMN amplitudes were significantly stronger for the vowel duration change than for other deviants in both groups, there being no group difference. The enhanced MMN amplitudes for vowel duration changes in Finnish children might result from the acoustical saliency and the semantically distinctive role of quantity in Finnish language. It seems that this deviant is easily discriminable also for those children with RAOM.

The MMN elicited by the frequency change was stronger and faster in those children with RAOM than in the controls. This refers to an elevated responsiveness (for a review, see Kujala et al., 2013) to frequency changes in children with RAOM. Additionally, an enhanced MMN elicited by the vowel change was found in those children with RAOM. These findings are in accordance with the study of Eapen et al. (2008), suggesting that the development of frequency perception may be affected by childhood OM. Eapen et al. (2008) investigated the effect of removing one of the three frequency bands from sentences on speech perception performance in 5–7-year-old children with a history of OM and tympanostomy tube placement. These children had a significantly poorer speech reception threshold than their peers when middle frequencies (1575–2425 Hz) from sentences were omitted, but they did not differ from the controls when high (3000–5000 Hz) or low (798–1212 Hz) frequencies were removed. This probably indicates that children with a history of OM weighted more the middle-frequency band than their controls to comprehend sentences. It should be noted that the second formants of the Finnish vowels /e/ and /i/ used in the current study are in the region of 2 kHz. According to the frequency weighting theory of Eapen et al. (2008) and the current results of the MMNs elicited by frequency and vowel changes, it is possible that children with RAOM compensate the degraded auditory signal at the level of the central auditory system. They might utilize the frequency content of speech differently than their peers, for example, by processing more efficiently prosodic features of speech to find word boundaries.

Besides the magnitude and speed, the neural origin of processing is an important factor reflecting the efficacy of neural functions (Tervaniemi & Hughdahl, 2003). In Study I, group differences were found in the MMN amplitude scalp distribution suggesting partially distinct neural sources of processing in the two groups. The MMN elicited by the frequency change was left hemisphere preponderant in the RAOM group, whereas in the control group it was right hemisphere dominant as usually reported in healthy adults (Kujala et al., 2007). The left hemisphere dominates the processing of phonetic contrasts and is thought to be specialized in the language specific content of sounds (Tervaniemi et al., 2000; for a review, see Tervaniemi & Hughdahl, 2003). The shift of the frequency-MMN to the left-hemisphere regions in children with RAOM might reflect an enhanced linguistic weight of their auditory system to frequency changes of speech than that of their controls. This finding could also be related to the compensation mechanisms connected with the attenuated auditory signals during RAOM, which was suggested by Eapen et al. (2008), who found that children with a history of OM weighted the frequency content of speech differently than their peers.

The MMN elicited by the consonant deviant showed a broader scalp distribution in those children with RAOM than in the controls, whose MMN was left hemispheric preponderant. This left hemispheric lateralization coincides with the typical language organization of the adult brain (Tervaniemi & Hughdahl, 2003), whereas the more even distribution in children with RAOM suggests immature consonant discrimination. This interpretation would be compatible with the findings of Petinou et al. (2001), whose behavioural study suggested that 2-year-old children with OM had difficulties with determining if a word had a fricative in its final position or not. Similarly, consonant discrimination ability was found to be affected in school-aged children in behavioural tasks even years after the OM episodes had been resolved (Mody et al., 1999; Zumach et al., 2011). Consonant discrimination is known to be an important prerequisite for language development and deficits in it can predict atypical language acquisition (Kraus et al., 1996; Benasich et al., 2006). Furthermore, the possible compensatory use of the right hemisphere in the processing of linguistic material found in this study may increase the functional and anatomical symmetry of hemispheres (Liebenthal et al., 2005). This might lead to neurolinguistic resources not optimal for spoken language development or for phonological encoding and decoding associated with written language at school age (Locke, 1997).

For the intensity changes, those children with RAOM showed a broader and more anterior MMN scalp distribution than the controls. This may indicate an attention switch towards the stimuli, because the unattended auditory stimuli predominantly activate the auditory cortex, and broader brain areas are activated when the stimuli are attentively listened to (Degermann et al., 2006). Attention switching towards the intensity changes may indicate that children with RAOM are hypersensitive to sound loudness changes, which is in line with the study of Olsen Widen and Erlandsson (2004), who reported that, compared to their peers, adolescents with OM history are behaviourally more sensitive to the loudness of sound stimuli. Furthermore, hypersensitivity to sounds with normal hearing levels, i.e. hyperacusis, was suggested in some cases to be connected with chronic OM history (Anari et al., 1999).

Taken together, the current MMN results supported the theory that children with a history of OM may utilize the frequency content of speech more efficiently than children without a history of OM (Eapen et al., 2008). Those children with RAOM may also be more sensitive to sound intensity variations. Additionally, they show signs of immaturity of neural organization for the discrimination of small phonetic contrasts, as reflected by the atypical MMNs elicited by consonant changes.

6.3 Consequences of RAOM on involuntary attention switching

In Study II, distracting novel sounds elicited a clearly identifiable P3a with two phases (eP3a and lP3a) and an LN in both those children with RAOM and the controls. In both groups, the morphology of these responses was found to be consistent with earlier findings in children (Gumenyuk et al., 2001, 2005; Kushnerenko et al., 2002; Määttä et al., 2005; Putkinen et al., 2012). However, there were group differences in the topography and timing of these responses, suggesting that neural mechanisms of involuntary attention have a different maturational trajectory in these two groups of children.

Neither the eP3a amplitude, amplitude scalp distribution, nor the latency differed between the groups. This suggests that the automatic detection of a novel stimulus, the orientation of attention (Yamaguchi & Knight, 1992), was similar between the groups. In both groups, the eP3a was larger frontally and centrally than parietally, which is consistent with previous findings in typically developed school-aged children (Čeponienė et al., 2004; Gumenyuk et al., 2001) and in adults (Escera et al., 1998).

In contrast, the lP3a amplitude was found to differ between the groups. It diminished less from frontal to central and parietal areas in those children with RAOM than in the controls. The frontally prominent lP3a is an indicator of a neurally maturated frontal cortex and attention control (Čeponienė et al., 2004; Gumenyuk et al., 2001). For example, an enhanced lP3a at the posterior scalp areas has been described in children with ADHD, who are easily distractible (Gumenyuk et al., 2005). The similar lP3a topography found in the current study and in ADHD might reflect immature neural mechanisms of involuntary attention switching in children with RAOM. In support of this interpretation, Feagans et al. (1994) found that toddlers with a history of OM were rated as easily distractible by their mothers and they showed reduced attention during book reading at the time of MEE. These results refer to the enhanced distractibility in those children with RAOM, which can lead to weak utilization of the auditory information in learning by limiting the ability to ignore irrelevant auditory stimuli (Escera et al., 2007; Gumenyuk et al., 2005).

A longer LN latency was found in those children with RAOM than in the controls, suggesting delayed reorienting back to the ongoing activity (Čeponienė et al., 2004; Määttä et al., 2005). This result corresponds to a behavioural study showing prolonged reorientation time in school-aged children with listening difficulties and a history of OM (Dhamani et al., 2013). The process in which a distracting auditory stimulus is evaluated as being unimportant might be slower in those children with RAOM than in their peers.

Taken together, it is possible that children with RAOM may not have such a resistance to the auditory distraction as the controls. A deficit in attentional mechanisms possibly affects language development by disrupting a child’s engagement in social-communicative actions and sounds critical for language acquisition. It has been shown that attentional mechanisms in infancy guide language acquisition. Kushnerenko et al. (2013b) found that the efficiency of attentional regulation in 6–9-months-old babies predicted speech comprehension at 14–16 months of age. Also Hari and Renvall (2001) proposed that the formation of phonological representations can be affected due to atypical attentional mechanisms. Furthermore, listening in a noisy background, such as day care centres, requires appropriate attention to expected as well as unexpected events and the ability to effectively inhibit distracting stimuli, which are detrimental to language acquisition and communication (see Niemitalo-Haapola et al., 2015).

6.4 Consonant acquisition in children with RAOM

The number of words produced in the spontaneous speech samples was counted in Study III for the consonant analysis. A smaller number of words produced was found in those children with RAOM than in the controls. The number of words produced in the control group was equal, as found earlier in the study investigating 15-minute speech samples of 2-year-old Finnish-speaking children (Kunnari et al., 2006). In addition, the variation in the number of words produced was large in the controls, as found previously (Kunnari et al. 2006). This refers to the typical variation of word acquisition in language development. In contrast, those children with RAOM were a more homogenous group than the controls falling at the lower end of the typical range of development. This indicates some kind of limit to the possible level of advance of the RAOM group.

The sizes of AWP and WM consonant inventories were found to be smaller in those children with RAOM than in the controls. The RAOM group also lagged behind the previous results of consonant inventories in 2-year-old Finnish-speaking children while, in contrast, the results of the controls in the current study were highly consistent with those of Kunnari et al. (2006). Those children with RAOM produced fewer WI consonants than the controls but the group difference was not, however, significant, unlike in the study of Abraham et al. (1996), which reported that 2-year-old English-speaking children with OM history had restricted WI consonant inventories. A possible explanation for the lack of significant differences in WI inventories in the current study may be a language specific pattern of consonant acquisition in Finnish children. Typically developing Finnish children have more WM than WI consonants in the early inventories (Kunnari, 2003; Kunnari et al., 2006; Savinainen-Makkonen, 2007). This preference for WM consonants may be explained by the common WM geminate template for the first words (see Saaristo-Helin et al., 2011) and the typical developmental feature of omission of WI consonants (Savinainen-Makkonen, 2000). Thus, when the number of consonants is smaller in the WI inventories than in the WM inventories, group differences are harder to find in the WI inventories than in the WM inventories, unlike in English speaking children.

The advantage of a WM position for consonant production in Finnish children was also observed in the controls in this study. However, this advantage was only a trend in those children with RAOM. Taken together, this and the finding that the children with RAOM had smaller WM inventories than the controls, lead to a conclusion that the current results suggest particular difficulties with WM consonants in the RAOM group. Phonetic environment may have an effect on this result. Consonants in the WM position are probably harder to discriminate because other phonemes might mask them more than consonants in the WI position. This kind of effect has been found in a study on auditory processing in dyslexic adults (Kujala et al., 2000) who typically have auditory processing difficulties (Ramus et al., 2003). It was shown that dyslexic adults had difficulties in the neural discrimination of changes in the middle of tone patterns but not when the same changes were presented without surrounding sounds. Furthermore, neural discrimination of sound-order reversals was affected in dyslexic participants when an additional sound followed the tone pair but not when the sound preceded the pairs (Kujala et al., 2003).

Comparisons between the groups regarding WF consonants were difficult to make, because the children in both groups had developed only minimally small inventories of WF consonants. This is consistent with the previous study of Kunnari et al. (2006) who showed that most typically developing Finnish children did not even use one WF consonant at two years of age. The acquisition of WF consonants was shown to be slow, also in English (Abraham et al., 1996; Stoel-Gammon, 2011).

The number of words in the speech sample was positively correlated with the size of the consonant inventory overall and in all word positions, being in accordance with earlier studies (for a review, see Stoel-Gammon, 2011). Because the association of early phonological and lexical development is bi-directional, it is not possible to confirm the cause-and-effect relation between the restricted numbers of words produced in the speech samples and the restricted consonant inventories found in those children with RAOM. Small repertoires of phonemes do not support the production of a large number of words (Stoel-Gammon, 2011; Vihman, 1996), but it can also be that the delayed word acquisition leads to delayed consonant acquisition (Locke, 1997). For that purpose, onomatopoeic words, which are highly common among the first words, were included in the analysis to obtain the maximal consonant inventories as well as from children with restricted lexicons. However, it is likely, that RAOM affected the language development of these 2-year-old children by disturbing both the forming of accurate phonemic representations and word acquisition further strengthening the phonemic representations.

In both groups, the most produced consonants were stops, which contain a lot of sound energy and are acoustically easy to discriminate (Liebenthal, et al., 2005). Based on the consonants produced by 60% of children, the RAOM group acquired the same consonants as the controls but the acquisition rate seemed to be slower in all inventories compared to the controls. However, there were group differences in the quality of consonants produced according to the place and manner of articulation. The children with RAOM less frequently produced dentals/alveolars than the controls in the AWP and WM inventories. The most obvious difference was found for fricatives, the weakest sounds in the speech spectrum (Liebenthal et al., 2005), which those children with RAOM produced less often than the controls in the AWP, WM, and WF inventories. This result is in line with the study of Miccio et al. (2001) indicating deficient production of fricatives in children with a history of OM. In Finnish, there are only three fricatives, of which /s/ has an important role in the Finnish lexicon and morphology, and is often the first acquired fricative phoneme in typically developing Finnish children (Kunnari et al., 2006). The only significant group difference in the production of single consonants was found for the fricative /s/ in the WM and WF position. Interestingly, there was no significant difference between the groups for the fricatives in the WI inventories. This might also be influenced by the auditory context. It is possible that the fricative noise in the WI position is more audible than in the WM or WF positions, where it is probably masked more by other phonemes. Additionally, the typical developmental feature of WI consonant omission (Savinainen-Makkonen, 2000) may influence this result.

To summarize, the main findings of Study III suggested limited production of words and restricted consonant inventories in Finnish children with RAOM. The current results support the existing findings of restricted or delayed consonant acquisition in children with OM in early childhood (Abraham et al., 1996; Miccio et al., 2001; Petinou et al., 1999), during which phonological development is critical for further language development. For example, limited production of words accompanied with delayed and/or limited use of consonants has been shown to predict later deficits of language development (Moeller et al., 2007; Vihman, 1996). It has also been shown that the experience of consonant production has an effect on phonological working memory (Keren-Portnoy et al., 2010). Specifically, Keren-Portnoy et al. (2010) found that the longer a child had been producing consonants the better he/she scored in a phonological working memory test. Furthermore, a risk for later deficits in reading and writing may appear as poorer articulatory accuracy of phonemes at the age of 2.5 years (Turunen, 2003).

6.5 General discussion

As was hypothesized, those children with RAOM showed intact sound encoding but atypical preattentive discrimination of multiple speech sound features. Furthermore, these children might be more vulnerable to novel but meaningless sounds as expected on account of previous behavioural studies. These findings of atypical auditory processing obtain support from the restricted consonant inventories shown by previous studies, which were also demonstrated in those children with RAOM in this thesis. In the light of the present study, it can be suggested that RAOM has long term consequences on central auditory processing, because children with RAOM had healthy ears at the time of the measurement.

Experiences affect development in a cumulative manner, and even transient effects on sensory processes at the critical age may be significant for their further development (Whitton & Polley, 2011). Accurate auditory processing in early childhood helps to create exact memory representations that further allows the discrimination of speech sound features in degraded listening conditions as well (Kuhl et al., 1992, 2006; see Niemitalo-Haapola et al., 2015). Children with a history of OM were shown to have deficient speech in noise listening skills (Gravel & Wallace, 1992; Hogan & Moore, 2003; Zumach et al., 2009), which might be a sign of immature central auditory processing in early childhood as demonstrated in the current study.

However, some studies found no relationship between OM and language development, which, in addition to differences of methods and populations, may be caused by the fact that the development of auditory processing is highly sophisticated and modified by multiple factors (see Moore, 2012). When comparing the current results with those of other studies in children with OM, it should be noted that studies also differ in their definition of the history of middle ear infections. Furthermore, children with RAOM typically suffer from continuously and asymmetrically fluctuating hearing impairment as the status of their middle ears changes with AOM episodes. It is not known whether it is more detrimental to have hearing fluctuation due to numerous shorter or few longer episodes with middle ear effusion.

The results of this thesis are clinically important, as they indicate that early childhood RAOM should be taken as a risk factor for auditory and language development. In health care policy, the preventive interventions, such as counseling of parents, are offered for families of children who have a permanent hearing loss in early childhood. It would be important to also increase the awareness of parents and people working with young children with RAOM on the effects of fluctuating hearing loss on speech perception, as well as to introduce compensatory strategies preventing the influence of degraded auditory input. Preventive actions can be ordinary things in everyday life requiring minimal effort (see also Partanen, 2013; Putkinen et al., 2013; Tallal & Gaab, 2006). For example, one can ensure that a child sees the face of the speaker (e.g. Pascalis et al., 2014), thereby supporting the auditory channel with visual cues. Language environment can be enriched by reading, telling, and singing to and with children (e.g. Leffel & Suskind, 2013). Parents of children with RAOM should be encouraged to use child directed speech, also known as motherese, having properties which help small children to discriminate speech sounds and word boundaries (Floccia et al., 2016; Werker et al., 2007). Finally, family health care clinics should offer systematic counseling of those families with a child affected by early childhood RAOM.

The current results also underline the importance of the identification of children who need intervention in the medical care system before linguistic problems are overt. Early interventions are cost-efficient and may prevent later deficits, for example in reading and writing, which are very sensitive even as regards mild phonological problems (Bishop & Clarkson, 2003). Furthermore, some forms of auditory intervention were found to be beneficial for children with auditory processing deficits (Kujala et al., 2001; Pihko et al., 2007; Lovio et al., 2012). In addition to the clinical implications, the results of this study point to the importance of taking into account the OM history when studying higher level cortical auditory processing in clinical groups or typically developing children.

The possible limitations of this study include the unavailability of detailed information on hearing levels during the AOM periods. This important issue should be taken into account in future studies, with an intensive monitoring of timing, frequency, and duration of AOM episodes and hearing loss. There is a great variance in the time of the disappearance of middle ear effusion (Tapianen et al., 2014) leading to highly individual exposure to the possible hearing loss and feasibleness to evaluate it retrospectively. To be able to assess the direct impact of hearing loss caused by RAOM on central auditory processing, hearing levels should be monitored prospectively during each AOM episode. Furthermore, audiometric testing at the time of ERP measurement was not included in this study, because 2-year-old children have very limited skills with regard to co-operation. However, at the time of the study, hearing levels were assumed to be in the normal range because the children with RAOM had had tympanostomy tubes inserted and severe hearing impairments were excluded by TEOAEs and parental reports. It should also be noted that the perforation of tympanic membrane due to the tympanostomy tubes may attenuate the peripheral transmission and the frequency content of sounds (Voss et al., 2001; see also Zhang et al., 2012), but there is a lack of studies comparing accurately the hearing of children with tympanostomy tubes versus children with intact tympanic membrane. Crucially, no differences in the early cortical sound encoding between the groups were observed, which suggest that the effect of inserted tubes was not reflected at the cortical level. However, further research in this area is necessary.

Regarding consonant inventories, it has to be taken into account that natural speech samples are somehow problematic, as they might not show the full capacity of the child’s spoken language (Edwards & Beckman, 2008). However, the ecological validity of spontaneous speech samples is better than in samples elicited by isolated word-naming tests in toddlers (Stoel-Gammon, 1987). Further studies on the phonology of these children could be supplemented by investigating how children with RAOM use their consonant repertoire to realize the target phonemes (see Saaristo-Helin, 2009). This study did not analyse the geminate production, which is an important feature of phonological development in Finnish children. Geminates are known to be over-selected for production by children learning languages with them (see Vihman & Croft, 2007; Vihman & Velleman, 2000). This thesis found no differences in preattentive discrimination of vowel duration between the groups. However, Richardson (1998) showed that Finnish children at risk of dyslexia require a longer gap to discriminate singletons and geminates at 6 months of age than children not at risk. A common Finnish word template with a geminate in the word-medial position, and the current finding that the children with RAOM produced a smaller number of word-medial consonants than controls highlights the importance of further examination, if RAOM has an effect on discrimination or production of singletons and geminates.

In the future, it would be interesting to study children with RAOM even at the earlier stage of their language development taking into account that word-form recognition can be seen at the end of the first year (Thierry et al., 2003; Vihman et al., 2007), around the time when word production starts. If children with RAOM would not prefer familiar words over phonotactically matched rare words by the same age as the controls, the finding could further elucidate the current results of restricted consonant inventories in those children with RAOM.

Future studies should also longitudinally investigate the neural mechanisms of auditory processing in children with early childhood RAOM. The long-lasting developmental effects of OM have been shown in earlier behavioural studies (Luotonen et al., 1998; Mody et al., 1999; Zumach et al., 2011). The current study indicated that the effects of RAOM on auditory processing are also detectable when the ears are healthy. It would be important to determine whether the changes observed at the neural level at two years of age are transient after hearing is stabilized or persisting at the later stages of development. Furthermore, the effect of the quality of sleep on central auditory and cognitive processing in children with RAOM should be determined. It is possible that the affected auditory attention found in these children is not only due to RAOM itself but related to accompanied sleep problems. An upper airway congestion often found in children with OM is connected to a sleep-related breathing disorder (Gozal et al., 2008). This in turn may weaken the quality of sleep, which has been shown to affect involuntary attention switching (Salmi et al., 2005).

Because the deficient neural mechanisms of involuntary attention and possible distractibility may weaken the child's engagement in social-communicative actions, it would be important to study the social-communicative interaction of these children more intensively. Additionally, this is essential because Yont et al. (2001) found that children with OM had limited nonverbal strategies to overcome communication difficulties. Besides the weakened auditory input, possible alterations in conversational interaction are of significant importance. The amount of joint attention (Tomasello & Farrar, 1986) and mother's responsiveness (Paavola et al., 2005) have a key role in a child's language acquisition. Recently, RAOM was shown to affect families' experiences of their quality of life (Kujala, 2015). For example, crying due to earache may increase caregivers' stress and influence the linguistic interaction between the parent and the child (Locke, 2002). Furthermore, if children with RAOM produce less speech than their peers, they might get fewer verbal responses from caregivers than their peers.

7 CONCLUSIONS

This thesis investigated different stages of central auditory processing in 2-year-old children with early childhood RAOM by using auditory ERPs. Moreover, the consonant acquisition of these children was analysed from spontaneous speech samples. The results suggested that the basic sound encoding was intact in those children with RAOM. In contrast, these children showed aberrant preattentive discrimination of multiple speech sound features and atypical neural mechanisms of involuntary auditory attention. Thus, the fluctuating hearing loss during early childhood caused by RAOM may result in an immature pattern of central auditory processing and attention control. Furthermore, those children with RAOM had restricted consonant inventories. In particular, the acquisition of word-medial consonants and fricatives was delayed. The results of this thesis implicate that early childhood RAOM should be considered as a risk factor for the development of central auditory processing, and the language development of these children would be worthy of much more careful monitoring.

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APPENDIX

Table A1. Studies considering the effects of childhood otitis media (OM) on sound encoding, auditory discrimination, and consonant acquisition

Theme/reference	Subjects	Methods	Main outcomes
Sound encoding			
Hall & Grose, 1993	OM: N = 14 Controls: N = 13 Age: 5.7–8.3 years (mean 6.7) Language: not clearly reported, proposed to be English	**OM history:** Medical records and parental reports **Amount of OM:** OM group: Parents reported multiple episodes of OM HL followed in the clinic 4–6 months prior TTI Controls: no OM episodes **Measurements:** PTA (nomal) Masking level difference (MLD) Click evoked ABRs	The OM group showed reduced MLDs and prolonged waves III and V, and I–III and I–V interwave intervals of ABRs compared to controls. The MLD and delays in absolute wave or interwave intervals did not correlate but interaural asymmetries of the interwave intervals and the MLD correlated. Poorer MLD may be related to atypical brainstem processing in the children with OM.
Gravel et al., 2006	N = 132 Age: 8 years Language: not clearly reported, supposed to be English	**OM history:** Followed prospectively at the age of 0–3 years Pneumatic otoscopy and tympanometry VRA or PA **Amount of OM:** Percentage of time with MEE between 7–39 months A child was considered to have HL when average hearing threshold exceeded the normal range for their cohort **Measurements:** Click evoked ABRs High frequency audiometry Distortion product otoacoustic emissions Acoustic middle ear muscle reflex Speech in noise Binaural processes	High-frequency audiometry, contralateral acoustic middle ear muscle reflex, and the longer latency of the Wave V of ABRs were significantly associated with early hearing loss and OM. Other functional auditory abilities were not significantly related to early hearing loss and OM. It was suggested that normal auditory experiences after early childhood resulted in normal auditory function at school age.

Table A1. Continued

Theme/reference	Subjects	Methods	Main outcomes
Maruthy & Mannarukrishnaiah, 2008	OM: N = 30 Controls: N = 30 Age: 3, 4, and 5 years; in each age group OM: n = 10 Controls: n = 10 Language: Kannada (a Dravidian language spoken in the state of Karnataka in Southern India)	**OM history:** Medical records and/or parental reports **Amount of OM:** OM group: OM episodes at the age of 6–12 months but not after that Duration of MEE (estimated) < 1 month N = 12 3–6 months N = 18 Controls: no episodes of OM **Measurements:** PTA (normal) Tympanometry (normal) Click evoked ABRs Click evoked obligatory ERPs	3-years-old children with OM history had reduced amplitude of I and III waves of ABRs and prolonged ABR latencies. They also had decreased P1, N1, P2, and N2 latencies. At 4- or 5-years of age, there were no differences between the groups. It might be that the consequences of OM on sound encoding are reversible. However, the study was cross-sectional and children were not followed-up.
Auditory discrimination			
Mody et al., 1999	OM: N = 7 Controls: N = 7 Age: 9 years Language: English (some exposed to Spanish)	**OM history:** Followed prospectively every month at the ages of 0–12 months Pneumatic otoscopy **Amount of OM:** OM group: bilateral MEE ≥ 30% of visits (mean 43.3%) Controls: bilaterally healthy ears ≥ 80% of visits (mean 89.4%) **Measurements:** PTA (normal) Acoustic immittance (normal) CV syllable repeating test with standard and variating ISI /sə/ zə/ kə/ gə/ in random order /ba/ /da/ sa /ʃa/ in random order	Children with early OM history were poorer than controls in repeating syllables with variating consonants. Especially /sa/-/ʃa/ difference was hard for them. No group differences in temporal processing. It was suggested that children with OM history are less accurate than controls in their coding of phonetic feature distinctions in working memory. The study indicated long lasting effects of OM in speech perception.

Table A1. Continued

Theme/reference	Subjects	Methods	Main outcomes
Petinou et al., 2001	OM: N = 8 Controls: N = 8 Age: 2 years (26–28 months) Language: English (some exposed to Spanish)	**OM history:** Followed prospectively at 2, 5, 7.5, 10, and 12 months of age Pneumatic otoscopy and tympanometry VRA **Amount of OM:** OM group: MEE ≥ 3/5 of visits (no TTI) Controls: MEE ≤ 1/5 of visits **Measurements:** Tympanometry (4 children in the OM group had abnormal tympanograms and SPL was increased 10 dB for them) Bimodal preferential looking paradigm Word pair discrimination task: 6 monosyllabic novel word pairs differing in their final voiced or voiceless fricative	Controls performed better than the OM group with one phonological and with two morphological targets ending with /s/. Targets with final /s/ were harder than those with final /z/ for the OM group. The fluctuating hearing loss in early childhood was suggested to have a negative impact on fricative perception.
Nittrouer & Burton, 2005	OM: N = 13 Low SES: N = 12 OM + low SES: N = 12 Controls: N = 12 Age: 5 years Language: not clearly reported, proposed to be English	**OM history:** Medical records **Amount of OM:** OM group: ≥ 7 episodes of OME before 3 years of age (estimated MEE ≥ 20% of the time) Controls: ≤ 3 episodes of OME before the age of 3 years **Measurements:** PTA (normal) Tympanometry Speech perception: CV syllables (fricative-vowel /s/ or /ʃ/, /da/-/ta/) Phonological awareness: syllable counting; three choice initial consonant the same: same-different initial consonant Verbal working memory: 3–4 words Comprehension of complex syntax Non-speech temporal processing Tinkertoy task (parental language actions)	In speech perception task, OM and low-SES groups weighted formant transitions more than controls, referring to an undeveloped perceptual strategy. OM group managed weaker than controls in three choice initial task, same-different initial task, and sentence comprehension task. Temporal processing was not affected. According parental language actions, language environment was found to be similar in OM and control group. Delayed perceptual strategies may lead to difficulties to recognize phonetic structure efficiently, to store and retrieve words in working memory, and to comprehend sentences with complex syntax. OM and low-SES groups performed similarly, suggesting that these conditions affect the development similarly.

Table A1. Continued

Theme/reference	Subjects	Methods	Main outcomes
Polka & Rvachew, 2005	Day 1 OM: N = 16 MEE: N = 25 Controls: N = 16 Day 2 OM: N = 10 MEE: N = 10 Controls: N = 10 Age: 6–9 months Language: English, French, and multilingual	**OM history:** Parental reports **Amount of OM:** OM and MEE groups: episodes of OM, amount not reported Controls: no OM episodes **Measurements:** Tympanometry Conditioned head turn procedure Speech sound discrimination task with CV syllables (/bu/-/gu/, phonemic contrast in all languages children were acquiring)	Infants with MEE and infants with a history of OME but normal middle ear function on the day of testing were poorer in a phonetic discrimination task compared to controls. The negative effect of OME on infant phonetic perception persists after MEE has disappeared.
Zumach et al., 2011	N = 54 Age: 7 years Language: Dutch	**OM history:** Followed prospectively every three months at the age of 0–24 months Pneumatic otoscopy and tympanometry VRA **Measurements:** PTA (normal) Speech sound discrimination (same-different) Identification task (7-step continuum between /bak/ and /dak/)	Children with more hearing loss in the first 2 years of life managed weaker both in the identification and the discrimination task. The effect of OM-related hearing loss but not the number of OM episodes was related to categorization of speech sounds at 7 years of age. Hearing loss is a stronger indicator for categorical perception in the long term than the number of OM episodes.

Table A1. Continued

Theme/reference	Subjects	Methods	Main outcomes
Auditory attention			
Roberts et al., 1989	N = 44 Age: 3rd year in elementary school Language: not clearly reported, proposed to be English	**OM history:** Followed prospectively from 6 weeks–3 months to 3 years Once a month and every time when child get illness, every two weeks after OM Pneumatic otoscopy and tympanometry **Measurements:** Cognitive ability Academic achievement Classroom behaviour	OM history and performance on tests of verbal intelligence or academic achievement did not correlate. The number of days with MEE before 3 years of age correlated with teachers' ratings of children's attentional behaviour. Children with more OM tended to be rated as less task-oriented and less able to work independently than children with less OM.
Feagans et al., 1994	N = 35 Age: 12 and/or 18 months OM: N = 23 Controls: N = 12 Age: 24 months Language: English	**OM history:** Followed prospectively each week from < 12 months Pneumatic otoscopy and tympanometry **Amount of OM:** OM group: MEE ≥ 20% of time **Measurements:** 12/18 months: A book-reading task (with and without MEE) 24 months: VRA Language test (SICD) Child behaviour (Goodnes-of-Fit Questionnaire)	No group differences in language test. At the age of 12 and 18 months, children with MEE displayed less attention during book reading and twice as often off-task than controls. At the age of 24 months, mothers rated children with OM history as more distractible and nonattentive than controls.

Table A1. Continued

Theme/reference	Subjects	Methods	Main outcomes
Asbjørnsen et al., 2000	OM: N = 19 Controls: N = 18 Age: 9 years Language: not clearly reported, proposed to be Norwegian	**OM history:** Medical records **Amount of OM:** OM group: OME $\geq$ 1 year with at least one TTI Controls: no history of hearing problems during childhood **Measurements:** PTA (normal) ITPA Speech and language tests Dichotic listening task with CV syllables: free recall, directed right ear, directed left ear	No group differences in speech and language or overall accuracy in reporting CV syllables. OM group showed more pronounced right-ear advantage than controls. Unlike controls, OM group had a lack of left ear advantage during directed left condition. This was suggested to indicate an impaired ability for attentional modulation.
Klausen et al., 2000	OM: N = 19 Controls: N = 19 Age: 8–10 years (mean 9) Language: not clearly reported, proposed to be Norwegian	**OM history:** Medical records and/or parental reports **Amount of OM:** OM group: history of long lasting bilateral OME treated with on average 1.4 TTI Controls: not treated for OME **Measurements:** Articulation test Word and sound discrimination ITPA Boston naming test Dichotic listening task with CV syllables: free recall, directed right ear, directed left ear	OM group managed weaker than controls in the articulation and sound discrimination tests. OM group showed a more pronounced right ear advantage than controls, but a lack of ability to attend to the left ear. It was suggested that attentional modulation may be weakened in the children with OM history.

Table A1. Continued

Theme/reference	Subjects	Methods	Main outcomes
Minter et al., 2001	N = 85 Age: 6 years Language: not clearly reported, proposed to be English	**OM history:** Followed prospectively from 6–12 months to 4 years First 15 months weekly and then biweekly Pneumatic otoscopy and tympanometry VRA/PA **Measurements:** Questionnaires from parents, teachers and clinicians collected in infancy, pre-school age, and at the end of the first grade Behavior Rating Scale of the Bailey Scales 2nd ed. The Parenting Stress Index The Social Skill Rating System The Hyperactivity Index of the Conners' Teacher/Parent Rating Scale	No relationship between amount of OM or hearing loss during first six years and attention and behaviour reported by parents, teachers, and clinicians.
Asbjørnsen et al., 2005	OM: N = 20 OM chronic: N = 19 Controls: N = 20 Age: 9 years Language: not clearly reported, proposed to be Norwegian	**OM history:** Medical records and parental reports **Amount of OM:** OM group: OM episodes, no need for TTI OM chronic: OM episodes and bilateral TTI at least once Controls: no OM episodes **Measurements:** PTA (normal) Language skills and academic achievement (normal) Dichotic listening task with CV syllables: free recall, directed right ear, directed left ear	Focusing of attention to the left ear was weaker in both groups of children with OM history than in controls. Compared to controls, children with OM history showed a lack of attention modulation of dichotic listening performance. This was suggested to indicate impaired development of auditory attentional skills due to OM in childhood.

Table A1. Continued

Theme/reference	Subjects	Methods	Main outcomes
Dhamani et al., 2013	OM*: N = 12 Controls: N = 12 Adults: N = 12 Age: 10–15 years (mean OM 11.4; controls 12.5) Language: Australian English	**OM history:** Parental reports **Amount of OM:** OM group: > 2 episode of OM (mean 2.91) at 2–5 years Controls: no OM **Measurements:** PTA (normal) Target identification task with target syllable /da/ detected as quickly as possible among five CV syllables presented with background noise (speech babble)	In the experimental (OM*) group, hit rates were lower and there were more false alarm rates than in the controls and adults. Also their temporal re-orientation time was longer than that of the controls and adults. It was concluded that the ability to rapidly shift attention in the group of children with persistent listening difficulties was affected compared to their age matched peers.
Consonant acquisition			
Donahue, 1993	Case study N = 1 Age: 9–22 months Language: English	**OM history:** Parental report **Amount of OM:** Chronic OME during the first year of life TTI at 10 months of age **Measurements:** Speech production diary (words)	During the first phase (9–17 months) child’s speech production was characterized by words, which had a distinct prosodic shape. She preferred to use vowels and nasals and there was the absence of obstruents. At the later phase she showed a clear preference for bilabials and avoidance of velars.

Table A1. Continued

Theme/reference	Subjects	Methods	Main outcomes
Abraham et al., 1996	OM: N = 8 Controls: N = 8 Age: 24 months Language: not clearly reported, proposed to be English	**OM history:** Followed prospectively every month at the age of 0–6 months and every two months at the age of 7–12 months Pneumatic otoscopy **Amount of OM:** OM group: bilateral MEE ≥ 30% of visits (mean 40.0%) Controls: MEE ≤ 20% of visits (mean 9.3%) **Measurements:** Spontaneous speech samples: 30-minute play session with caregiver Sizes of consonant inventories Place and manner of articulation Group inventories, Consonant production accuracy, and Phonological error patterns	Groups showed similar tendencies for consonant acquisition but OM group was delayed. OM group had smaller WI consonant inventories than controls. Stops constituted the largest group of WI consonants in both groups but OM group produced fewer of them. OM group produced fewer consonants with a back articulation place and tended to produce less fricatives, liquids, and nasals than controls. Controls showed greater accuracy of WI consonant production than OM group. Same error patterns between the groups but OM group showed them more often. Both groups had minimally developed WF consonant inventories. It was suggested that OM history affects consonant acquisition.
Petinou et al., 1999	OM: N = 8 Controls: N = 8 Age: 10–14 months Language: English	**OM history:** Followed prospectively at 2, 5, 7.5, 10 and 12 months of age Pneumatic otoscopy and tympanometry VRA **Amount of OM:** OM group: MEE mean 62.5% of visits Controls: MEE mean 2.5% of visits **Measurements:** Babbling samples from semi-structured play sessions (10 and 14 months) or from formal language assessments (12 months; PLS-3 and subsections of the CSBS) The rate of vocalizations (consonants produced per minute) Place and manner of articulation	No group differences in vocalization rates. More frontally articulated consonants and fewer consonants with a middle articulation place in the OM group than in the controls. Visible sounds (e.g. bilabial stops) may be more salient for the children with OM. Nasals, which include low frequency energy, were less frequently produced in the OM than control group. Fluctuating hearing loss may affect the perception of low frequencies. It was concluded that the degree of hearing loss influenced children's phonetic inventories.

Table A1. Continued

Theme/reference	Subjects	Methods	Main outcomes
Miccio et al., 2001	N = 6 Age: 12–48 months Language: English	**OM history:** Followed prospectively once a week at 12–36 months Pneumatic otoscopy and tympanometry VRA **Amount of OM:** MEE ≥ 2.5 months per year between 12–36 months **Measurements:** Spontaneous speech samples: 15-minute play session at the age of 12, 15, 18, 21, 24, 30, 36, 42 and 48 months Consonant inventories	Children with OM history showed typical patterns of phonological acquisition but delayed phonological development at the early analyses. Many early inventories were limited to oral stops and glottals and there was a delay in fricatives.

Note. *Experimental group with listening difficulties; ABR: auditory brain stem response; CSBS: Communicative and Symbolic Behavior Scale; CV: consonant-vowel; ISI: inter-stimulus interval; ITPA: Illinois Test of Psycholinguistic Abilities; MEE: middle ear effusion; MLD: masking level difference; PA: play audiometry; PLS-3: Preschool Language Scale 3; PTA: pure tone audiometry; SES: socioeconomic status; SICD: the Sequenced Inventory of Communication Development; TTI: tympanostomy tube insertion; VRA: visual reinforcement audiometry; WF: word-final; WI: word-initial