THE UNIVERSITY OF QUEENSLAND
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Evaluating Auditory Function in Primary School Children with Learning Difficulties in Australia

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Abstract

Children who experience poor academic performance at school have been described as having learning difficulties (LD). These children are thought to show reduced performances in reading, written language and numeracy, and to be inactive and inefficient learners. Hearing is one of several factors thought to influence a child's learning at school with students spending at least 45% of their classroom activities that require listening and 45 to 75% of their time in the classroom comprehending their teachers' and classmates' speech. Hearing impairment can include loss of hearing sensitivity and/or impaired auditory processing (AP). While rates of peripheral hearing loss (PHL) in the Australian primary school-aged population is estimated to be between 3.4% and 12.8%, rates of impaired AP in this population are not available in Australia.

Children with PHL and/or impaired AP often show behaviours similar to those reported in children with LD, suggesting that LD and hearing impairment could be related in primary school child populations. The present thesis aimed to investigate LD and hearing impairment in a school-aged child population in the greater Brisbane region of Queensland, Australia. The thesis considered two main research questions: (1) Do children with LD have higher rates of impaired hearing and/or impaired AP compared with typically developing (TD) children?; and (2) What models might best explain any relationships between LD and hearing impairment?

The first study chapter conducted a systematic review where the rate of PHL in the general primary school child population in Australia was considered. A search of five electronic databases yielded three studies that had quantitatively reported the PH results of screening and follow-up assessment of hearing in primary school children in Australia. The review concluded that the overall rate estimate of PHL in the primary school child population in Australia was between 3.4% and

12.8%. The review also compared this rate to other high-income countries and concluded that primary school children in Australia had higher rates of PHL primarily due to higher rates of conductive hearing loss.

The second study chapter investigated the rates of impaired hearing and AP in a large, non-clinical sample of children with LD and TD children. A total of 486 children, aged 7.7 to 10.8 years and attending years three and four in six primary schools, were classified as having an LD (n = 67) or being TD (n = 419). This classification was based on a Learning Score generated from their school report results and National Assessment Program – Literacy and Numeracy (NAPLAN) scores. All children attempted a conventional hearing assessment (CHA) involving pure-tone audiometry, tympanometry, acoustic reflexes (AR), and otoacoustic emissions (OAEs). Children returning pure-tone audiometry results within normal limits also attempted an auditory processing assessment (APA) including dichotic digits (DD) and low-pass filtered speech (LPFS) tests. This study's results showed that, compared to TD children, children with LD were 2.4 times more likely to fail CHA, and 2.1 times more likely to fail APA, and 2.0 times more likely to fail the overall hearing assessment (OHA). In children who had completed the OHA, multiple linear regressions showed average AR thresholds, DD scores and LPFS scores explained 13 to 18% of the variance in the Learning Score.

The third study chapter investigated the performance of children with and without LD referred for AP assessment on six tests of AP. Fifty children (aged 7.67 to 10.75 years) referred for AP assessment on the basis of having failed the school-based APD screening tests were classified as having an LD (n = 14) or TD (n = 36) based on the Learning Score. All children completed basic audiometry and an AP assessment consisting DD, LPFS, frequency patterns with linguistic report (FP_{lin}), competing sentences (CS) and two subtests from TAPS-R: Auditory Number Memory – Forward (ANM_F) and Auditory Word Memory (AWM). All participants had normal hearing

thresholds (≤ 15 dB HL from 0.5-4 kHz). Compared to the TD children, children with LD performed significantly worse on FP_{linR} and FP_{linL}, DD_R, and ANM_F. For all children combined, significant correlations were observed between learning score and DD_R, FP_{linR}, FP_{linL} and ANM_F and a multiple linear regression model returned FP_{linR} DD_R and ANM_F as significant predictors explaining 50% of the variance in Learning Score.

The thesis concludes by reporting that children with LD do have higher rates of impaired hearing and/or impaired AP compared with TD children. Any relationships between LD and hearing impairment might best be explained by risk factor models, association models, and not explained by single distal cause models. The practical implications of these findings for personnel in the health and educations sectors are continued screening for PHL, and a possible expansion of current school-based hearing screening to include AP tests. Future research will need to examine the feasibility of such a screening program, and the possibility of a trans-disciplinary approach to subsequent referral and rehabilitative pathways.

Declaration by Author

This thesis is composed of my original work and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications Included In This Thesis

Peer-Reviewed Papers

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This paper is incorporated as chapter 4 in this thesis.

Contributor	**State of contribution**
Choi, S.M.R. (Candidate)	Study design (80%) Data collection (100%) Data analysis (100%) Wrote the paper (80%) Edited the paper (70%)
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Contributions by Others to the Thesis

Significant and substantial inputs were made by others in the research, work and writing represented and/or reported in the thesis.

- Associate Professor Wayne Wilson played a major role in all aspects of this research. This included substantial input in the research design, data analysis and interpretation, and critical revisions of written work.

- Associate Professor Joseph Kei played a major role in all aspects of this research. This included substantial input in the research design, data analysis and interpretation, and critical revisions of written work.

Statement of Parts of the Thesis Submitted to Qualify for the Award of another Degree

No works submitted towards another degree have been included in this thesis.

Research Involving Human or Animal Subjects

Ethical clearance has been granted from the Behavioural & Social Sciences Ethical Review Committee, The University of Queensland (Approval number: 2015000218) for the project. The project will adhere to the Guidelines of the ethical review process of The University of Queensland in accordance with the National Health and Medical Council's guidelines. A copy of the approval is included in Appendix A.

Ethical clearance has also been granted by Education Queensland (Approval number: 550/27/1566). The project will comply with the National Health and Medical Research Council's National Statement on Ethical Conduct in Human Research. A copy of the approval is included in Appendix B.

The thesis must be comprised only of research undertaken while enrolled in the HDR program unless otherwise approved by the Dean, Graduate School in advance of submission.

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Keywords

Hearing impairment, *hearing loss*, *auditory processing disorder*, *primary school children*, *Australia*, *learning difficulties*.

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List of Abbreviations Used in the Thesis

(C)APD	Central Auditory Processing Disorder
AAA	American Academy of Audiology
ACARA	Australian Curriculum Assessment and Reporting Authority
ACER	Australian Council for Educational Research
ADHD	Attention Deficit Hyperactivity Disorder
ANMF	Auditory Number Memory – Forward
AP	Auditory Processing
APA	American Psychological Association
APA	Auditory Processing Assessment
APD	Auditory Processing Disorder
AR	Acoustic Reflexes
ASD	Autism Spectrum Disorder
ASHA	American Speech-Language-Hearing Associations
AUSPELD	Australian Federation of the Specific Learning Difficulties Association
AWM	Auditory Word Memory
BSA	British Society of Audiology
CANS	Central Auditory Nervous System
CHA	Conventional Hearing Assessment
CHC	Cattell-Horn-Carrol
CHL	Central Hearing Loss
CN	Cochlear Nucleus
CS	Competing Sentences
Cth	Commonwealth
dB HL	Decibels in Hearing Level
DD	Dichotic Digits

DDT	Dichotic Digits Test
DSM-5	Diagnostic and Statistical Manuel of Mental Disorders
EAP	Education Adjustment Program
ECV	Ear Canal Volume
ESL or ESD	English as a Second Language or Dialect
fMRI	Functional Magnetic Resonance Imaging
FP_{lin}	Frequency Patterns with the Linguistic Report
FPT	Frequency Pattern Test
IC	Inferior Colliculus
ICC	Inferior Colliculus Central Nucleus
ICP	Inferior Colliculus Pericentral Nucleus
ICX	Inferior Colliculus External Nucleus
LD	Learning Difficulties
LiSN-S	Listening in Spatialized Noise Sentences
LPFS	Low-pass Filtered Speech
LSOC	Lateral Superior Olivary Complex
MNTB	Medial Nucleus of the Trapezoid Body
MRI	Magnetic Resonance Imaging
MSOC	Medial Superior Olivary Complex
NAPLAN	National Assessment Program – Literacy and Numeracy
NDS	Neurodevelopmental Syndrome
NGP	NAPLAN Grammar & Punctuation
NHMRC	National Health and Medical Research Council
NHL	Neural Hearing Loss
nLL	Lateral Lemniscus
NN	NAPLAN Numeracy

NR	NAPLAN Reading
NS	NAPLAN Spelling
NW	NAPLAN Writing
OAEs	Otoacoustic Emissions
OHC	Outer hair cells
OM	Otitis Media
PAT-M	Progressive Achievement Tests in Mathematics
PAT-R	Progressive Achievement Tests in Reading
PE	Pressure Equalisation
PHL	Peripheral Hearing Loss
PON	Periolivary Nuclei
PROBE	Prose Reading Observation, Behaviour & Evaluation of Comprehension
SC	Static Compliance
SD	Standard Deviation
SE	School Report English
SHL	Sensory Hearing Loss
SM	School Report Mathematics
SOC	Superior Olivary Complex
SpLDs	Specific Learning Difficulties
SR	School Report
TAPS-R	Test of Auditory Perceptual Skills - Revised
TD	Typically Developing
TEOAEs	Transiently Evoked Otoacoustic Emissions
TPP	Tympanometric Peak Pressure
USA	United States of America
USOE	United States Office of Education

VIII CN	Vestibulocochlear Nerve
WHO	World Health Organisation

Chapter 1: Introduction

1.1. Introduction

Children who experience poor academic performance at school have been described as under-achieving by teachers and assessors, with the label *learning difficulties* (LD) being used to describe these children. Despite the ubiquitous use of the term *LD*, other associated terms such as *learning disability* are currently also being used in the literature (Watson & Boman, 2005). This may be due to the concept of LD being derived from research on the brain-behaviour relationship and reading disabilities in Europe in the 1800s (Hallahan & Mercer, 2001), while the concept of learning disabilities primarily developed in the United States of America (USA) in the 1920s. Since the introduction of learning disabilities as a concept into Australia from the USA in the early 1960s, the discussion and evolution of the terms LD and learning disabilities has focussed on *difficulty* versus *disability*. While the Australian Government (2017) has attempted to provide a clear distinction and definition of LD and learning disabilities, most States and Territories in Australia have struggled to consistently apply the terms LD and learning disabilities at the operational level. This has resulted in schools and state governments (e.g., the Queensland Government) attempting to identify children with LD using a range of systematic tests, school-based assessments and classroom teacher monitoring system (Australian Council for Educational Research, 2013, 2014; Australian Curriculum Assessment and Reporting Authority, 2017; Pool, Parkin, & Parkin, 2002). To avoid confusion, in this thesis, the term LD has been used to describe students who underachieve academically for a variety of reasons including sensory impairment (weaknesses in vision or hearing), severe behavioural, psychological or emotional issues, English as a second language or dialect (ESL or ESD), high absenteeism, ineffective instruction or inadequate curricula, but excluding intellectual impairment, that is, IQ less than 75 (Schalock, 2012).

Many factors can influence a child's learning at school; however, the factor targeted in this research is hearing deficit. In this regard, two hearing pathways are involved, with the peripheral hearing pathway being responsible for the initial processing of sound up to the cochlea, and the central hearing pathway being responsible for further processing of sound up to the auditory cortex.

In this research, peripheral hearing loss (PHL) refers to hearing deficit due to a disorder of the outer, middle and/or inner ear (Bess & Humes, 2008a). PHL can be described in terms of the degree and type of hearing loss. The degree of hearing loss includes mild, moderate, moderately severe, severe to profound. The type of hearing loss includes as conductive, sensory or mixed depending on the site of lesion (Goodman, 1965; Humes, 2018; J. Jerger & Jerger, 1980; Northern & Downs, 2002). From a clinical perspective, a battery of audiometric tests (otoscopy, pure tone audiometry, immittance tests and speech audiometry) is used to diagnose peripheral hearing loss (J. Jerger & Hayes, 1976). In Australian children attending state primary schools, the estimated rate of PHL was between 3.4% and 12.8%, with the majority of these children having a conductive hearing loss due to outer/ middle ear dysfunction (Choi, Kei, & Wilson, 2016).

Central hearing loss (CHL) refers to hearing deficit due to a disorder along the auditory pathway beyond the cochlea. One of the well-known CHL is Auditory Processing Disorder (APD). APD is thought to be a deficit in the processes performed on sound signals by central hearing structures. The cause of APD is complex and is often multi-factorial. APD lacks a universally accepted definition (W. J. Wilson & Arnott, 2013). Several approaches to APD have been proposed by various authors, including audiological (J. Jerger, 2009), psychoeducational (J. Jerger, 2009), language acquisition and learning (J. Jerger, 2009), modality specificity (Cacace & McFarland, 2013), auditory attention (Moore, Ferguson, Edmondson-Jones, Ratib, & Riley, 2010), hierarchical testing (Dillon, Cameron, Glyde, Wilson, & Tomlin, 2012), clinical entities (Vermiglio, 2014), and neural networks (Friel-Patti, 1999). These approaches have been described in detail by W. J. Wilson (2018).

The most cited and used approach is that from the American Speech-Language Hearing Associations (ASHA, 2005) and the American Academy of Audiology (AAA, 2010). ASHA (2005) defines APD as “a deficit in the perceptual processing of auditory information in the central auditory nervous system (CANS) and the neurobiological activity that underlies that processing and gives rise to electrophysiological auditory potentials" (ASHA, 2005). APD may affect one or more of the following auditory skills: sound localisation and lateralization; auditory discrimination; auditory pattern recognition; temporal aspects of audition, including temporal integration, temporal discrimination (e.g. temporal gap detection), temporal ordering and temporal masking; auditory performance in competing acoustic signals (including dichotic listening); and auditory performance with degraded acoustic signals (ASHA, 2005). This definition is also endorsed by AAA (2010). Similar to the peripheral hearing loss, APD is diagnosed using a battery of tests, with diagnostic outcomes significantly being influenced by the criterion applied (J. Jerger & Musiek, 2000; W. J. Wilson & Arnott, 2013). As a result, given the lack of consensus on the definition of APD and its criteria for diagnosis, an accurate estimate of the prevalence of APD in the general paediatric population cannot be reliably made.

While the potential relationship between PHL and/or CHL and learning are poorly understood, the impact of PHL and CHL on learning have been well reported in the literature. In general, school-aged children with PHL have shown higher rates of delayed language development, academic underachievement, social isolation, higher risk of injuries and increased poverty (Olusanya, Neumann, & Saunders, 2014; World Health Organization, 2016). Similarly, school-aged children with CHL often show behavioural characteristics such as difficulty comprehending speech in competing or reverberant environments, difficulty following complex auditory information, inattentiveness and distractibility (ASHA, 2005; DeBonis & Moncrieff, 2008).

1.2. Overview and Aims of This Research

This thesis investigates LD and hearing impairment in a school-aged child population in the greater Brisbane region of Queensland, Australia. Two main research questions were considered: 1) do children with LD have higher rates of impaired hearing and/or impaired AP compared with typically developing children, and 2) what models might best explain any relationships between LD and hearing impairment?

1.3. Significance of Research

The results of the thesis will shed light on the hearing ability of children with and without LD. These results will influence the management of children with LD who have hearing deficits by driving the development and implementation of appropriate and effective educational and audiological support for these children in the classroom.

1.4. Organisation of the Thesis

This thesis is presented as a series of chapters including journal articles both published articles and currently under review for publication. While each journal article is presented as a separate chapter with an introduction to illustrate its place in the larger thesis, some repetition of concepts and citations does occur as the introduction, methods, results and discussion format of the journal articles overlaps with the content of other chapters within the thesis.

Chapter one (the current chapter) introduces the thesis both in topic and structure.

Chapter two discusses the definitions of LD in Australia and internationally. It considers the origin of LD and its evolution as a concept and its identification, prevalence and aetiology. The chapter concludes by proposing the operational definition of LD for use in this thesis.

Chapter three considers hearing impairment as a factor that can influence a child's learning at school. Peripheral and central hearing pathways and their common pathophysiologies are briefly discussed. The chapter concludes by discussing the possible association between hearing impairment and LD.

Chapter four presents a systematic literature review of the rate of PHL in the primary school children in Australia. It estimates this rate and compares it to similar estimates around the world, and considers the problems created by disparities in definitions of normal hearing thresholds in children and the use of screening versus diagnostic measures when determining rates of PHL in school-aged children.

Chapter five presents the data from a large, nonrandomized, cross-sectional, single measure school-based study that examined the rates of impaired hearing and AP in 67 children with LD and 419 typically developing (TD) children. It reports on the higher rates of impaired hearing found in children with LD and considers models best suited for explaining result relationships between impaired hearing and children with LD.

Chapter six presents the data from a smaller, non-randomised, cross-sectional, single measure clinic-based study that examined the performance of 14 children with LD and 36 children without LD referred for AP assessment on six tests of AP. It reports on the higher rates of AP difficulties found in children with LD and attempts to determine the contribution of AP to learning scores in the sampled children.

Lastly, chapter seven discusses the thesis as a whole and offers final conclusions as to the possible relationships between hearing impairment and LD and the models that might best explain these relationships. Chapter seven also considers the strengths and limitations of the thesis as well as its implications for education and clinical practice and future research.

All chapters that contain works submitted for publications have been formatted to be consistent with the style of the thesis with regards to layout, terminology and referencing style. The thesis uses Australian English and adheres to the American Psychological Association (APA) guidelines, 6th edition (APA, 2009). All studies adhered to the guideline of the ethical review process of Education Queensland, The University of Queensland and the National Statement on Ethical Conduct in Human Research and were granted ethical clearance by Education Queensland and the University of Queensland Behavioural and Social Sciences Ethics Review Committee.

Chapter 2: Learning Difficulty

2.1. Introduction

Children who experience poor academic performance at school have been described as underachieving by teachers and assessors. These children may require additional educational support in their early schooling, with this need potentially increasing in later schooling as a result of poor social, emotional and educational development (Hill, Comber, Louden, Rivalland, & Reid, 1998; Rohl, Milton, & Brady, 2000). In Australia, the term *learning difficulties* (LD) is most commonly used to address such children (Elkins, 2002; Louden et al., 2000). The definition and causes of LD have been much debated, making its identification and management difficult. This has partly been due to arguments around the definition of LD versus terms such as *learning disability*.

This chapter begins by considering types of definitions as a precursor to discussing definitions of LD offered in Australia and internationally. It then attempts to define LD by considering the origin of LD and its evolution as a concept before considering the identification, prevalence and aetiology of LD and concluding with the definition of LD to be used in this thesis.

2.2. Defining Definition

Before the history of LD and associated terms such as learning disability are considered, the concept of *definition* itself must be examined. A definition is a semantic device that uses words for descriptive purposes. A definition should be able to describe the parameters of the condition in question and provide a precise and unencumbered statement describing its characteristics (Kavale & Forness, 2000). The goal of a definition is to convey factual information as well as meaning (Miller, 1980). To understand the meaning, the fundamental and basic qualities of a condition need to be interpreted and translated into words. This interpretation depends on the perception as well as the physical properties of a condition and the resulting description may not be an accurate representation of a condition.

The nature of any definition is complex as several types of definitions can co-exist (R. Robinson, 1954). Real definitions are hypothesised ideals that are not often achieved. Conceptual definition describe a set of characteristics gathered from the formal activity of concept formation that have been theoretically validated (Hempel, 1952). Formal definitions, more correctly known as stipulative definitions, are those definitions where consensus has been reached among a group. Formal definitions do not need to be true, only useful (Rantala, 1991). In this context, they can be used in areas such as funding and legislative purposes in government. Most definitions offered by various researchers, organisations and government agencies fall into a formal class of definition. While formal definitions are useful in the sense that they are generic, their application is challenged by their potential lack of validity. Formal definitions need to be transformed into an operational definition to be used in practice. Operational definitions are defined by a set of operations, rules or parameters that can be used to test for a certain condition (Benjamin & Lathrop, 1955). Operational definitions are not without pitfalls. First, they are easily influenced by the operational indicators chosen. Second, the theoretical validity of operational indicators can result in the definition exhibiting little relationship to what is stated in the formal definition. However, it is equally as necessary to formally verify the elements stipulated in informal definitions. Despite these challenges, operational definitions can server practical purposes, such as diagnosis and classification.

Most of the definitions of LD that will be discussed in this chapter fall into the formal class of definitions. With the exception of the definition provided by the Australian Federation of the Specific Learning Difficulties Association (AUSPELD, 2014), the current definitions of LD in Australia are challenged by the failure to provide significant insight into the nature of the condition as these definitions outline the concept of LD but don't describe the specific condition of LD.

2.3. Origin of LD: Learning Disability in the USA

While the concept of LD began as research on brain-behaviour relationships and reading disabilities in Europe in the 1800s (Hallahan & Mercer, 2001), the primary development of the concept of LD can be traced to the concept of learning disabilities in the USA. By about the 1920s in the USA, increased awareness of children who had extreme difficulty in language, reading, perception, perceptual-motor abilities, and/or attention was raised by clinicians and researchers from disciplines such as psychology, special education and medicine (Elkins, 2002; Hallahan & Mercer, 2001). These children, who did not appear to have any obvious impairment, struggled to learn to read and spell and were initially labelled as having dyslexia, minimal brain damage, and minimal cerebral dysfunction (Hallahan & Mercer, 2001). During this period, researchers such as Orton (1925), Monroe (1928) and Fernald (1943) studied children with reading disabilities, while others such as Werner and Strauss (1940) and Cruickshank, Bucem, and Wallen (1957) studied children with hyperactivity, low intellectual ability, or cerebral palsy. These researchers offered various terms to describe these children that included *word-blindness* (Orton, 1925), *reading disabilities* (Fernald, 1943; Monroe, 1928), *mentally retarded* (Werner & Strauss, 1940), *specific brain injury* or *hyperactivity* (Cruickshank, Bentzen, Ratzeburg, & Tannhauser, 1961). These terms and their accompanying definitions formed the basis of the development of the contemporary concept of LD.

From about the 1960s, these terms were changed to *learning disability* in order to shift attention from physical impairment to children's educational needs (Kirk, 1962). Most authorities in the USA credited Samuel Kirk as the originator of the term learning disabilities (Hallahan & Mercer, 2001). Kirk (1962) defined learning disabilities as:

> "…a retardation, disorder, or delayed development in one or more of the processes of speech, language, reading, writing, arithmetic, or other school subject resulting from a psychological handicap caused by a possible cerebral dysfunction and/or emotional or behavioural disturbances. It is not the result of mental retardation, sensory deprivation, or cultural and instructional factors (Kirk, 1962, p. 263)."

In 1965, Bateman built on Kirk's definition and put an emphasis on using discrepancy between achievement and potential as a way of formally identifying children in this group. Bateman offered the following definition of learning disabilities:

> "Children who have learning disorders are those who manifest an educationally significant discrepancy between their estimated potential and actual level of performance related to basic disorders in the learning process, which may or may not be accompanied by demonstrable central nervous system dysfunction, and which are not secondary to generalized mental retardation, educational or cultural deprivation, severe emotional disturbance, or sensory loss (Bateman, 1965, p. 220)."

Towards the end of the 1960s, the U.S. Office of Education (USOE) formed a committee to propose a formal definition of learning disabilities that was to be used as a basis for legislation and for funding programs. The committee offered a definition similar to Kirk's 1962 definition:

> "Children with special (specific) learning disabilities exhibit a disorder in one or more of the basic psychological processes involved in understanding or in using spoken and written language. These may be manifested in disorders of listening, thinking, talking, reading, writing, spelling or arithmetic. They include conditions which have been referred to as perceptual handicaps, brain injury, minimal brain dysfunction, dyslexia, developmental aphasia, etc. They do not include learning problems that are due primarily to visual, hearing or motor handicaps, to mental retardation, emotional disturbance, or to environmental disadvantage (USOE, 1977, p. 34)."

It was not until 1975 when the Congress of USA passed Public Law 94-142, the Education for All Handicapped Children Act, that learning disabilities finally achieved official status as a category eligible for funding for direct services. For use in the implementation of the Public Law 94-142, the term *learning disabilities* was changed to *specific learning disabilities* and USOE's definition was adapted to the following formal definition:

"…a disorder in one or more of the psychological processes involved in understanding or in using language, spoken or written, which may manifest itself in an imperfect ability to listen, speak, read, write, spell, or to do mathematical calculations. The term includes such conditions as perceptual handicaps, brain injury, minimal brain dysfunction, dyslexia and developmental aphasia. The term does not include children who have learning disabilities which are primarily the result of the visual, hearing, or motor handicaps, or mental retardation, or emotional disturbance, or of environmental, cultural, or economic disadvantage (USOE, 1977, p. 65083)."

Since its official status as a fundable category, the term and definition of *specific learning disabilities* has changed to *specific learning disorder,* which is considered a diagnosable condition in the *Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition* (DSM-5) (American Psychiatric Association, 2013) and is defined as:

"Specific learning disorder is now a single, overall diagnosis, incorporating deficits that impact academic achievement. Rather than limiting learning disorders to diagnoses particular to reading, mathematics and written expression, the criteria describe shortcomings in general academic skills and provide detailed specifiers for the areas of reading, mathematics, and written expression (American Psychiatric Association, 2013)."

Following the introduction of the term *specific learning disabilities* and its early conceptual definition developed in the USA, many countries including Australia followed the definition proposed by USOE in 1977 (Sideridis, 2007). Countries such as Canada chose to retain the term specific learning disabilities and adopted the following definition:

"Learning Disabilities refer to a number of disorders which may affect the acquisition, organization, retention, understanding or use of verbal or nonverbal information. These disorders affect learning in individuals who otherwise demonstrate at least average abilities essential for thinking and/or reasoning. As such, learning disabilities are distinct from global intellectual deficiency. Learning disabilities result from impairments in one or more processes related to perceiving, thinking, remembering or learning. These include, but are not limited to: language processing; phonological processing; visual-spatial processing; processing speed; memory and attention; and executive functions (e.g. planning and decision-making) (Learning Disabilities Association of Canada, 2002).".

Other countries such as the United Kingdom have changed the term to *specific learning difficulties* and adopted the USA's definition as follows:

"Specific Learning Difficulties (or SpLDs) affect the way information is learned and processed. They are neurological (rather than psychological), usually run in families and occur independently of intelligence. They can have a significant impact on education and learning and on the acquisition of literacy skills. SpLD is an umbrella term used to cover a range of frequently co-occurring difficulties, more commonly: Dyslexia, Dyspraxia / DCD, Dyscalculia, and A.D.D / A.D.H.D. SpLDs can also co-occur with difficulties on the autistic spectrum such as Asperger Syndrome (British Dyslexia Association, 2018)."

Countries such as Portugal and Spain adopted the term *learning disabilities* but did not propose a specific definition. Due to lack of uniformity in terms, concepts and definitions to describe children who do not meet the minimum academic requirements at school, just which group of children the researchers and countries are referring to continues to be debated globally (Grünke & Cavendish, 2016).

2.4. Evolution of LD: From Learning Disability to LD in Australia

The conceptual definition of *learning disability* from the USA was introduced into Australia in the early 1960s to describe students who had difficulties with learning at school, despite normal school experiences and no evidence of intellectual, physical, sensory, emotional or social problems (M. M. Robinson & Deshler, 1995). Children with learning disabilities defined in this manner were thought to struggle to learn due to minimal brain injury that could not be detected with available technology (Jenkinson, 2006).

Following the introduction of the term *learning disabilities* into Australia in the early 1960s, opposition began to grow against its definition as resulting from minimal brain injury. To voice their opposition, parent groups formed in each state in the late 1960s and linked together nationally as the AUSPELD (the Australian Federation of SPELD Associations, where the SPELD associations are Australian State or Territory organisations Supporting People Experiencing Learning Difficulties) (Elkins, 1983). AUSPELD remained a national not-for-profit organisation that provides advice and services to children and adults with learning difficulties, and those who care for, teach and work with them (AUSPELD, 2014). The members include parents, teachers, psychologists, speech pathologists and other professionals that work with the learning difficulties population. By the mid-1970s, AUSPELD had raised a considerable public awareness about the needs of children who were experiencing difficulties acquiring basic skills but did not have a diagnosed disability that affected learning (Elkins, 1983). To improve services for these children at school, AUSPELD lobbied the Australian House of Representatives to re-examine the term and definition of learning disabilities (Elkins, 1983). This saw the term LD first coined by the Select Parliamentary Committee of the House of Representatives (Cadman, 1976). The members of the Committee were unconvinced that the difficulties experienced by a learning-disabled child of constitutional impairment represented a diagnosed disability or impairment that would justify the use of the term *disabilities* rather than *difficulties* (Cadman, 1976). Thus, the Committee recommended the use of the term LD to describe children whose learning needs were not adequately met (Cadman, 1976). The Committee could not reach consensus on a definition of LD and therefore decided at the time not to create a precise definition of this term (Cadman, 1976). As a result of the inquiry, use of the term learning disabilities in Australia was discouraged in favour of the term LD.

In the 1990s, the National Health and Medical Research Council (NHMRC, 1990), Australia's leading body promoting the development and maintenance of public and individual health standard, attempted to make clear distinctions between LD versus learning disabilities by proposing formal definitions of both. NHMRC (1990) described LD as a generic or umbrella term to include all children experiencing difficulties in their learning while learning disabilities referring to a smaller sub-group of children within LD. According to NHMRC (1990), LD is:

> "…a generic term which refers to the substantial proportion (10 – 16%) of children and adolescents who exhibit problems in developmental and academic skills. These difficulties are considered to result from one or more of the following factors: intellectual disability, physical and sensory defects, emotional difficulties, inadequate environmental experiences, lack of appropriate educational opportunities (NHMRC, 1990)."

NHMRC (1990) defined learning disabilities as:

> "…a smaller proportion (2 – 4%) of children and adolescents who exhibit problems in developmental and academic skills which are significantly below expectation for their age and general ability. The disabilities, which often include severe and prolonged directional confusion, sequencing and short-term retention difficulties, are presumed to be intrinsic to the individual, but they are not considered to be the direct result of intellectual disability, physical and sensory defects or emotional difficulties. Nor do they appear to derive directly from inadequate environmental experiences, or lack of appropriate educational experiences (NHMRC, 1990)."

The definitions proposed by NHMRC (1990) have been the basis of the Australian Disability Discrimination Act 1992 (Cth) and, subsequently, of the Australian Disability Standards for Education 2005 (Cth). However, these definitions lack clarity in several areas. First, it is unclear how a generic problem and a significant developmental discrepancy is measured and identified. Similarly, the definition of learning disabilities comments on a child's learning ability being significantly below expectation; however, no standard or severity level is outlined to accompany the phrase. Second, while both definitions describe potential factors contributing to LD and learning disabilities, the factors appear to be contradicting the definition of each term. The definition of LD includes intellectual disabilities as a potential factor, while the definition of learning disabilities excludes this. According to the Australian Disability Discrimination Act 1992 (Cth), a disability is a broad term that includes intellectual disabilities. As such, intellectual disabilities should be included as a factor in learning disabilities, not LD. Nevertheless, the definition proposed by NHMRC (1990) served as a foundation for the Australian Disability Discrimination Act 1992 (Commonwealth) and the Australian Disability Standards for Education 2005 (Cth).

In 2000, Elkins, one of the leading researchers at the time in the field of LD, added to NHMRC's (1990) definition and argued that learning disabilities should be viewed as a sub-set of LD. Elkins (2002) noted that some children with LD:

> "…don't respond to the usual classroom and additional supportive teaching that schools provide. Thus the term 'learning disabilities' should be restricted to these 'hard to help' students where it seems reasonable to assume that their limitations in learning might stem from a constitutional impairment (even though usually we can't identify it) [Elkins, 2002, p. 12]."

The definition of LD proposed by NHMRC (1990) was not challenged, with Elkins (2002) agreeing that learning disabilities should be seen as a sub-set within the umbrella of LD. Similar to NHMRC's (1990) definition, this definition lacks precision and clarity. Although Elkins acknowledges that children with learning disabilities are "hard to help" children, it is unclear what constitutes a hard-to-help child. Similarly, it is ambiguous to what a reasonable response is to the classroom and additional support. While the definition eluded to potential factors, the phrase "constitutional impairment" lacks precision with respect to aetiology as well as wide latitude with respect to the origin of *learning disabilities*.

2.5. Current Definition of LD in Australia

Despite the recommendation by the Select Parliamentary Committee of the House of Representatives (Cadman, 1976) and the distinction and formal definition proposed by NHMRC (1990) and Elkins (2002), the Australian States and Territory education systems, with an exception of Education Queensland, continued to use the terms and definitions of LD and learning disabilities interchangeably (Watson & Boman, 2005). The lack of comparable terminologies and definitions led to uncertainty in identifying and providing these children with appropriate instruction and intervention (Watson & Boman, 2005).

To address these issues, AUSPELD (2014) proposed operational definitions of LD and learning disabilities to assist teachers in identifying children in these two groups. From 2016, this definition has been endorsed by the Australian Government to be accessible to all registered teachers in Australia (Australian Government, 2017). AUSPELD (2014) built upon NHMRC's (1990) differentiation of LD and learning disabilities and proposed the following operational definition of the former:

> "Students with learning difficulties underachieve academically for a wide range of reasons, including factors such as: sensory impairment (weaknesses in vision or hearing); severe behavioural, psychological or emotional issues; English as a second language or dialect (ESL or ESD); high absenteeism; ineffective instruction; or, inadequate curricula. These students have the potential to achieve at age-appropriate levels once provided with programs that incorporate appropriate support and evidence-based instruction (AUSPELD, 2014, p. 4)."

On the other hand, children with learning disabilities were those who:

> "…have difficulties in specific areas of academic achievement as a result of an underlying neurodevelopmental disorder, the origin of which is an interaction of genetic, epigenetic and environmental factors. One of the defining features of a specific learning disability is that the

difficulty continues to exist, despite appropriate instruction and intervention (AUSPELD, 2014, p. 4)."

Despite AUSPELD's (2014) and the Australian government's (2017) attempt to provide a clear distinction between and national definitions of LD versus learning disabilities, it appears that most states and territories in Australia continue to lack such clarity when dealing with these terms. For instance, while the state of Victoria refers to AUSPELD's definition (Department of Education and Training Victoria, 2017), the state of Queensland does not appear to provide a definition nor a clear distinction between the two terms (Education Queensland, 2018). Thus, the debate around LD and learning disabilities continues in Australia with no single definition being universally accepted.

The operational definitions of LD and learning disability provided by AUSPELD (2014) appeared to be more specific, with acknowledgement to the multifactorial nature of both conditions. Unlike previous definitions, the definition of LD proposed by AUSPELD (2014) acknowledged that children with LD possess the potential to achieve at age-appropriate levels when provided with the necessary support, while children with learning disabilities may not. The potential factors are outlined clearly with specific examples. However, the phrases "academic underachievement" and "appropriate support" lack clarity, with no specific parameters of severity level being outlined. While the exclusion clause is stipulated in the formal definition provided by NHMRC (1990), it is not outlined in the operational definition. Similar to the formal definitions, the requisite severity level necessary to identify a child as having either a learning difficulty or learning disability remains unclear.

A consequence of LD not having a universally accepted definition in Australia is the resulting effect on public funding support (e.g., Australian Government, 1992; Education Queensland, 2017). This effect can be seen across Australia in the manner in which all childhood difficulties and disabilities are identified. To use the State of Queensland as an example, its program for supporting children facing educational challenges is called the Education Adjustment Program (EAP). EAP acknowledges only six impairment areas as being funded by the Education Queensland. Those areas are Autism Spectrum Disorder, hearing impairment, intellectual disability, physical impairment, speech-language impairment, and vision impairment (Education Queensland, 2017). LD is not included as a fundable impairment, making it difficult for children with LD to receive appropriate and timely support and intervention.

2.6. Review of Definitions of LD

A key element of the above discussion of the history and evolution of the terms LD and learning disabilities has been around difficulty vs disability. In Australia, the current definitions of these terms suggest that the point of difference lies in the presence or absence of an underlying neurodevelopmental disorder. In this regard, LD describes a larger group of children whose difficulty lies in underachieving academically for a wide range of reasons whereas learning disabilities describes a smaller group of children (possibly a sub-group) whose difficulty in specific academic areas is due to an underlying disability.

While definitions of LD and learning disabilities remain imprecise, some agreement exists for some aspects of its definition. The primary diagnostic factor of LD and learning disabilities appears to be an academic failure, with the difference between LD and learning disabilities being the degree of academic failure. Despite this degree of agreement, existing definitions of LD still fail to provide an answer to the basic question: “What is LD?” Beyond vague observations, definitions of LD only appear to provide a description of generalized learning failure. The elements for determining eligibility for either the LD or learning disabilities are only implied through informal or operational definitions. This poses a difficulty when using these definitions in practice where teachers are required to distinguish between children with LD versus children with learning disability. One of the implications of the absence of a formal diagnosis of LD is reflected in the system by which state governments in Australia financially support children with this diagnosis. In most states, children with LD receive financial support via a formal diagnosis that closes matches with their academic difficulties or behaviours, such as dyslexia or ADHD.

Despite definitions of LD evolving throughout the years, children with LD appear to present with similar characteristics consistently. The most prevalent area of concern for children with LD is poor academic performance. In particular, the most common difficulty reported is with reading (van Kraayenoord, 2005; Westwood, 2003) followed by written language and numeracy (van Kraayenoord, 2005; van Kraayenoord & Elkins, 2004). Difficulty in reading can result in poor academic performance at school as mastery of basic reading skills is needed to understand concepts presented in written format (Twomey, 2006). Similarly, children who experience difficulty in written language can struggle to articulate ideas in sentence format, have reduced vocabulary and are liable to make significant errors in spelling, grammar and punctuation (Van Kraayenoord, 2005). Finally, lack of sufficient mathematical skills can result in confusion in basic concepts such as addition, subtraction, multiplication and division (Rhine, 1996; Twomey, 2006). As a result, children with LD often struggle academically at school in a manner that can lead to reduced scholastic attainment and the poor self-esteem and socio-emotional behaviour (Ashman & Elkins, 2002; Treuen, van Kraayenoord, & Gallaher, 2000; Westwood, 2004).

2.7. Prevalence and Identification of LD in School

The prevalence of LD cannot be accurately estimated due to the lack of universal consensus on the term and its definition. Accurate estimates of prevalence are also made difficult by the heterogeneity of LD with its variety of characters and abilities across many skill areas (Twomey, 2006).

The NHMRC (1990) estimated that the prevalence of LD varied between 10 to 16 percent. It is not clear how this value was obtained in the absence of supporting data. Louden et al. (2000) favoured the definition proposed by NHMRC (1990) and estimated that the prevalence of LD as reported by teachers varied between 6 to 30 percent. However, this estimate may not be accurate as it may have been confounded by sampling constraints, non-response bias and definition confusion. Given that this rate was based solely on teacher report from 377 schools only (out of a national population database of 8199 Australian primary schools), further bias may affect the accuracy of the estimate. AUSPELD (2014) favoured their own operational definition and estimated the prevalence of LD to be between 15 to 20 percent. Similar to the NHMRC's (1990) estimate, it is unclear what this value is based on as no data supported this estimate.

The identification of children with LD in Australia occurs both inside and outside the school system, with practices of identification varying from state to state. However, it is common to use national (involving standardized tests), school-based (e.g., Prose Reading Observation, Behaviour & Evaluation of Comprehension [PROBE], Progressive Achievement Tests in Reading [PAT-R], Progressive Achievement Tests in Mathematics [PAT-M]) and classroom-based methods to identify children with LD (van Kraayenoord & Elkins, 2004).

Nationally, systematic tests such as National Assessment Program – Literacy and Numeracy (NAPLAN) are used to test the skills that are essential for every child to progress through school and life, such as reading, writing, spelling and numeracy (Australian Curriculum Assessment and Reporting Authority [ACARA], 2017). Since 2008, every year on the same day, all Australian primary school students in years three and five complete tests of reading, writing, language conventions (spelling, grammar and punctuation) and numeracy. Each child's score on each skill is expressed as a number between 1 and 10 (to one decimal place) with group statistics provided by the ACARA (2017) allowing for these to be converted to z-scores. While the NAPLAN is deemed a valid and reliable national assessment of literacy and numeracy in Australia, it remains a standardised test that has been criticised for its limited ability to compare individual scores across schools and regions (Thompson, Adie, & Klenowski, 2018).

School-based assessments such as PROBE (Pool et al., 2002), PAT-R (Australian Council for Educational Research [ACER], 2008) and PAT-M (ACER, 2013) are often used in schools to measure and track student achievement by providing teachers with objective information for setting realistic learning goals and planning effective programs (ACER, 2013). These assessments have tests appropriate for a range of year levels that assess various skills in literacy and numeracy. A score in each area is given to a child based on the normative reference data that is based on a sample of schools across Australia, which is meant to represent all systems and states (ACER, 2014). Results from school-based assessments are often used for monitoring purposes so that appropriate intervention can be planned for an individual child (ACER, 2014). While anecdotal, the scores from these assessments, in conjunction with teacher observation of individual student's progress in literacy and numeracy, appear to form the basis of a school report.

In addition to the above, classroom teachers in Australia monitor student progress and behaviour through day-to-day observation. The results of this monitoring over a period of time, in combination with school-based assessment, are typically presented as a school report at the end of each school semester (Education Queensland, 2017). Although susceptible to teacher and school bias, the school reports do provide longitudinal observation and monitoring of a child's academic progress rather than offering a snapshot of standardised test results such as in the case of NAPLAN (Education Queensland, 2017). Thus, systematic and school-based and/or classroom-based assessments assist each other in identifying children with LD.

2.8. Definition of LD Used in this Thesis

The definition of LD used in this thesis is an operational definition that is built upon other definitions proposed by NHMRC (1990), Elkins (2000) and AUSPELD (2014).

In this thesis, the term 'LD' has been used to describe children who underachieve academically for a wide range of reasons, including sensory impairment (weaknesses in vision or hearing); severe behavioural, psychological or emotional issues; English as a second language or dialect (ESL or ESD); high absenteeism; ineffective instruction; or, inadequate curricula, but excluding intellectual impairment (IQ less than 75) (Schalock, 2012). These students have the potential to achieve at age-appropriate levels once provided with programs that incorporate appropriate support and evidence-based instruction. In addition to the current definition, I have addressed the problem of identifying children with LD by describing cut-off criteria based on the NAPLAN and the school-based reports. The developmental and academic underachievement was defined by a learning score derived from the child's school report (SR) and NAPLAN assessments.

2.9. Summary

Since the introduction of learning disabilities from the USA to Australia in the early 1960s, several iterations of its terms and definitions have been proposed in Australia. Despite numerous attempts by various government organisations, researchers and non-profit organisations attempting to establish a universal term and definition of LD (NHMRC, 1990; Elkins, 2000; AUSPELD, 2014), various schools, states and territories continue to use the terms LD and learning disabilities interchangeably. Thus, determining the prevalence and identification of children with LD has been difficult. To overcome these challenges, an operational definition of LD was proposed to be used throughout this thesis.

Chapter Three: Hearing and Learning

3.1. Overview

The previous chapter discussed LD and the debate around its definition in Australia, with an operational definition of LD built upon previous definitions was proposed for use in this thesis. Many factors can influence a child's learning at school, such as inadequate classroom environment, emotional or behaviour problems or sensory impairment of vision or hearing (Chan, 1998; Cheng, 1998; Westwood, 2003). While each of these factors warrants substantial investigation, the factor that has been targeted in this thesis is the impact hearing impairment may have on the learning ability of children with LD.

This chapter discusses peripheral and central hearing impairment and their possible causes. It concludes by discussing the possible association between hearing impairment and LD.

3.2. Human Auditory System

The human auditory system consists of two parts: the peripheral and central. The peripheral hearing pathway is responsible for collecting and processing of sound up to the cochlea, while the central hearing pathway is responsible for further processing of sound from the cochlear nerve to the auditory cortex.

3.3. Peripheral Hearing Pathway

The peripheral hearing pathway consists of the outer ear, middle ear, inner ear, and the vestibulocochlear nerve (Bess & Humes, 2008b).

The outer ear is an acoustic chamber consisting of two parts: the pinna and the external auditory canal (Wright, 2001). The pinnae facilitate the ability to localise sound in space. They also protect the auditory system by providing a cushion against physical impact to the head (Wright, 2001). The pinna collects, modifies and channels sound towards the external auditory canal. As a sound enters the external auditory canal, its acoustic spectrum is altered as some frequencies are amplified while others are suppressed (Keefe, Bulen, Arehart, & Burns, 1993). This results in distinct spectral shaping of the incoming sounds by the outer ear that enhances the aspects of sounds that are important to human behaviour and speech communication (Eluredge & Miller, 1971).

After passing through the outer ear, sound sets the tympanic membrane at the end of the external auditory canal into vibration, transferring its energy to the middle ear. The middle ear is an air-filled cavity (also called tympanic cavity or tympanum) that consists of three parts: the tympanic membrane, ossicles (consisting of three bones, malleus, incus and stapes) and the Eustachian tube. The middle ear not only acts as an impedance matching device between the low-impedance of the air-filled outer ear and the high impedance of the fluid-filled inner ear (Bess & Humes, 2008b), it also provides limited protection to the inner ear against very loud sounds by way of an acoustic reflex that increases the middle ear impedance in response to loud sounds (Lawerence, 1960). The Eustachian tube attempts to maintain the pressure in the middle ear cavity at atmospheric pressure (Honjo, Okazaki, & Kumazawa, 1979) to maintain the equal air pressure necessary on both sides of the tympanic membrane to maximise the transfer of sound energy from the outer ear to the middle ear (Honjo et al., 1979).

Anatomically, the inner ear consists of three main anatomical elements: the semicircular canals, the vestibule, and the cochlea. Physiologically, the inner ear consists of two major elements: the cochlea and the vestibular system. The cochlea contains the auditory organ (organ of Corti) while the vestibular system contains the sensory organs in the semicircular canals (Cristae ampullaris) for detecting head rotation, and sensory organs in the vestibule (Macular organs in the saccule and utricle) for detecting linear motion of the head and head tilt in relation to gravity (Davis, 1957).

The primary function of the organ of Corti in the cochlea is to perform mechano-electrical transduction, i.e., to convert the mechanical energy of the motion of the stapes into electrochemical impulses in the hair cells (Lim, 1986). This mechanical energy is transferred to the motion of the fluids in the cochlea, resulting in a travelling wave moving along the basilar membrane (Lim, 1986).

The basilar membrane is arranged tonotopically, responding differently to sound stimuli of different frequencies (Engström & Engström, 1972). The inner hair cells in the organ of Corti transduce the mechanical energy of the basilar membrane vibration into what will eventually become electrical impulses (or more correctly, trans-membrane ionic potentials) in the auditory nerve fibres (Engström & Engström, 1972). Outer hair cells (OHC) act primarily as electromechanical transducers that enhance the mechanical motions inside the inner ear. The OHCs are susceptible to biological factors such as ageing (e.g., Dayal & Bhattacharyya, 1986) and environmental factors such as noise damage (e.g., Falk, Cook, Haseman, & Sanders, 1974).

In summary, the outer ear functions to collect and channel sound towards the middle ear (Eluredge & Miller, 1971). The middle ear acts to overcome the impedance mismatch created by the air of the outer ear and the fluid of the inner ear (Eluredge & Miller, 1971). The inner ear performs the mechano-electrical transduction needed to convert the mechanical energy of sound into electrical energy for transmission along the auditory nerve to the brain (Davis, 1957). The vestibulocochlear nerve (VIII CN) functions to relay information about the frequency, intensity, and phase/timing of sound from the cochlea to the auditory brainstem (Phillips, 2014).

3.4. Peripheral Hearing Loss

In this thesis, peripheral hearing loss will be used to describe a partial or total inability to hear due to genetic or acquired disorders affecting the peripheral auditory pathway (outer, middle and inner ear). In children, peripheral hearing loss is of increasing concern globally. The World Health Organization (WHO) estimates that 32 million children (0 to 14 years) are living with disabling hearing loss defined as a hearing loss greater than 30 dB HL in the better hearing ear in children (World Health Organization, 2016). Unilateral hearing loss in school-aged children has shown to contribute to increased rates of grade failures, need for additional educational assistance, and percieved behavioural issues in the classroom (Daud, Noor, Rahman, Sidek, & Mohamad, 2010; Lieu, 2004). Similarly, children with lesser degrees of hearing loss (less than 30 dB HL) are at higher risk for academic, speech-language, and social-emotional difficulties than their normal hearing peers (Bess, Dodd-Murphy, & Parker, 1998; Bovo, Martini, Agnoletto, & Beghi, 1988; Kiese-Himmel, 2002; Oyler, Oyler, & Matkin, 1988).

Peripheral hearing loss can be classified into (degree severity) and types. Degree of peripheral hearing loss is useful in estimating its impact on an individual's ability to recognise speech (Schlauch & Nelson, 2009). Types of peripheral hearing loss allows differentiation of outer and/or middle ear disorders (conductive hearing loss) from inner ear disorders (sensory hearing loss), neural disorders (neural hearing loss), or inner ear and neural disorders (sensorineural hearing loss) (Schlauch & Nelson, 2009).

3.4.1. Diagnosis of peripheral hearing loss

Peripheral hearing loss can be diagnosed using a battery of audiometric tests. A test battery approach to assess auditory function not only allows the detection of disorders along the peripheral auditory pathway (Hanley, 1986), but it also permits cross-checking of all test results before making a diagnosis (J. Jerger & Hayes, 1976). The use of multiple tests can also increase the accuracy of the diagnosis (Turner, 2003).

The most commonly used battery of tests for assessing peripheral auditory function consists of pure tone audiometry, speech audiometry, tympanometry, acoustic stapedial reflex (Wiley & Fowler, 1997), and more recently, otoacoustic emission. In children younger than 4 years old, and/or older children who fail to follow instructions, auditory brainstem response (ABR) is the most common evaluation test for assessing peripheral auditory function (Arslan, Turrini, Lupi, Genovese, & Orzan, 1997; Despland & Galambos, 1980; Tas et al., 2007). Play audiometry is also used instead of pure tone audiometry in pre-school children (2 to 4 years old) to assess peripheral auditory function (Thompson, Thompson, & Vethivelu, 1989). Using these tests, the severity and degree of hearing loss can be determined along with the site(s)-of-lesion.

A number of authors have proposed a schema for the classification of degree of hearing loss (Goodman, 1965; Humes, 2018; J. Jerger & Jerger, 1980; Northern & Downs, 2002) with preferred schema differeing from clinic to clinic and from country to country. Table 3.1 shows the classification of hearing loss by four authors. While the most cited of the classification in this table is Goodman (1965), Northern and Downs (2002) suggestion of using 15 to 25 dB HL as a slight hearing loss category has attracted some favour for paediatric populations. Arguments over a slight hearing loss category can be seen to extend to different authors proposing different cut off values for normal hearing. Unsurprisingly, some children may be assessed to have normal hearing acuity despite having subtle middle ear pathologies which can have a negative impact on their communication abilities (Bess, Dodd-Murphy, & Parker, 1998).

More recently, Humes's (2018) classification of hearing loss incorporates the functional aspects of communication in relation to the degree of hearing loss, as pure-tone thresholds do not accurately represent the impairment an individual may be experiencing in their day-to-day activities. According to Humes (2018), normal hearing corresponds to no or very slight hearing problems in a quiet and noisy environment, while a mild hearing loss corresponds to difficulty following a conversation in a noisy environment, but no difficulties in a quiet environment. A moderate hearing loss corresponds to a possible hearing difficulty in a quiet environment when listening to a speaker speaking at a normal conversational level, as well as difficulty with conversation in noise (Humes, 2018). A moderately severe hearing loss corresponds to difficulty in a quiet environment even with raised speech levels, as well as great difficulty hearing in noisy environments (Humes, 2018). A severe hearing loss corresponds to difficulty with loud speech being spoken directly in an individual's ear in a quiet environment, as well as having great difficulty understanding speech in a noisy environment (Humes, 2018). Finally, a profound hearing loss corresponds to not being able to hear or understand a shouted speech in both quiet and noisy environments (Humes, 2018).

Table 3.1. Classification of degree of hearing loss by various authors (Units in dB HL).

Degree of hearing loss	Goodman (1965)	Jerger and Jerger (1980)	Northern and Downs (2002)	WHO (Humes, 2018)
Normal	<26	<21	<16	<20
Slight			16-25	
Mild	26-40	21-40	26-30	20-34
Moderate	41-55	41-60	30-50	35-49
Moderately Severe	56-70			50-64
Severe	71-90	61-80	50-70	65-79
Profound	>91	>80	>70	80-94

3.4.2. Types of peripheral hearing loss and commonly associated pathologies

Peripheral hearing loss can be categorised into five types: conductive, sensory, neural, sensorineural, or mixed. Conductive hearing loss results from a disorder in the conductive pathway (outer and middle ear). The conductive condition reduces the intensity level of the sound before it reaches the inner ear (J. Robinson, 2001). In children, conductive hearing loss is the most prevalent type of hearing loss, probably due to upper respiratory tract infection and otitis media (OM) (Bess & Humes, 2008a). Conductive hearing loss can also arise from other causes such as occlusion of the ear canal due to cerumen or foreign bodies, perforation or scarring of the tympanic membrane (TM), cholesteatoma or ossicular chain disruption due to trauma (Kramer, 2008). Congenital conductive conditions such as atresia, ossicular chain fixation and cleft lip and palate can result in a conductive hearing loss. Children with syndromes such as Down syndrome and Turner syndrome may also have a conductive condition.

OM is the most common cause of conductive hearing loss in pre-school and school-aged children (Roberts et al., 1989). OM is an accumulation of fluid in the middle ear cavity and can be a result of Eustachian tube dysfunction (Luxford & Syms, 2003) and/or bacterial and viral infection (Coates, 2003). Several types of OM can occur, ranging from acute OM (fluid infected with bacteria), purulent OM (fluid becomes thickened, with or without active bacteria) to chronic OM (fluid remains in the middle ear for an extended period). Some cases of OM may resolve without medical intervention. However, for chronic or reoccurring OM, a pressure equalisation (PE) tube or grommet may be inserted into the tympanic membrane to allow fluid to drain into the outer ear and maintain equal air pressure between the outer and middle ear. The insertion of PE tubes can reduce the occurrence of acute OM and chronic OM and improve hearing acuity (Browning, Rovers, Williamson, Lous, & Burton, 2010; Mandel, Rockette, Bluestone, Paradise, & Nozza, 1992; Rosenfeld, 2000; Rosenfeld et al., 2000). Acute OM affects up to 80% of children prior to the age of three years, with a peak incidence of OM occuring between six and 24 months of age (Teele, Klein,

& Rosner, 1989; Vergison et al., 2010). Chronic OM is less frequent; however, it is an important cause of preventable hearing loss, especially in low-income countries (Berman, 1995).

Sensorineural hearing loss refers to disorders located within the cochlea and its contents, and of the auditory nervous systems. This term has been used when sensory and neural hearing losses co-exist of cannot be correctly distinguished. This term also continues to be used, particularly in medical contexts, to describe hearing losses that though modern testing can be identified as being sensory losses only. This is mostly a historical artefact of the previous usage of term sensorineural hearing loss when older testing did not allow for such differential diagnosis of site-of-lesion. Where possible, attempts have been made to differentiate sentory and neural losses in this thesis.

Sensory hearing loss (SHL) results from a disorder of the cochlea that reduces the sound being transmitted to the auditory nervous system (J. G. Clark & Martin, 2013). While less common than conductive hearing loss, sensory hearing loss in school-aged children can arise from congenital, genetic and acquired causes. Congenital conditions such as cytomegalovirus infection and congenital rubella are rare but can result in SHL (Watkin, 2001), with sensorineural hearing loss being observed in around 10% of infants infected with CMV (Yamamoto et al., 2011). More than half of neonates with sensory hearing loss have inherited hearing loss due to genetic conditions, with 75 to 80% being due to simple mendelian recessive inheritance (Smith, Bale, & White, 2005). Autosomal dominant (about 20%), X-linked (2 to 5%), and mitochondrial (about 1%) also result in sensory hearing loss (Smith et al., 2005). For instance, Pendred syndrome is often present from birth and has been linked to mutations in the *PDS* gene that also causes enlarged vestibular aqueduct syndrome and represents between 4.3% and 7.5% of all causes of childhood hearing loss(Coyle et al., 1996). Children with Pendred syndrome often have Mondini dysplasia that further exacerbates sensory hearing loss (Nance, 2003). In pre-school and school-aged children, acquired causes of sensory hearing loss include bacterial meningitis, mumps and measles, and head trauma (Brookhouser, 1996). Bacterial meningitis is one of the common causes of acquired sensory hearing loss, accounting for about 6%

of all cases of sensorineural hearing loss in children (Drake, Dravitski, & Voss, 2000; Fortnum & Davis, 1993). It is caused by Haemophilus influenza or by meningococcal or pneumococcal infection (Drake et al., 2000). While early diagnosis and treatment can result in full recovery in a small percentage of children, suppurative destruction of the organ of Corti can cause severe permanent sensory hearing loss (Drake et al., 2000).

Neural hearing loss (NHL) results from a disorder of cochlea nerve which reduces and distorts the sound being transmitted to the central auditory nervous system (J. G. Clark & Martin, 2013). While less common than conductive and sensory hearing losses, neural hearing loss in school-aged children can arise from congenital, genetic and acquired causes. Congenital conditions such as auditory neuropathy spectral disorder that desynchronizes firing of cochlear nerve fibres to sound can result in NHL, with around 0.2% of children being diagnosed with this disorder (Rance et al., 1999; Madden et al., 2002). Genetic conditions such as Neurofibromatosis Type II, linked to mutations in the gene that gives rise to a peptide called Merlin or Schwannomin may also result in a neural hearing loss, with 20% of children displaying hearing loss or tinnitus as initial symptom (Evans, Birch, & Ramsden, 1999; Neff & Welling, 2005). In pre-school and school-aged children, acquired causes of neural hearing loss include infections and head trauma (Nance, 2003).

Mixed hearing loss arises when the disorder of either the external and/or middle occur alongside disorders of inner ear and/or cochlear nerve (Bess & Humes, 2008b). Mixed hearing loss is less common in school-aged children, with congenital mixed hearing loss comprising only a small subset of congenital hearing loss (Bess & Humes, 2008b). However, conditions such as the CHARGE syndrome and congenital cretinism can result in a mixed hearing loss (Morimoto et al., 2006). Genetic conditions such as Treacher Collins syndrome can start with a CHL, followed later in life by the development of a high-frequency sensory hearing loss, and resulting in a mixed HL (Nance, 2003). Acquired conditions of mixed HL can result from an acute OM infection in a child with an existing sensorineural hearing loss.

3.4.3. Prevalence of peripheral hearing loss in primary school children

Peripheral hearing loss in children is of increasing concern globally. The WHO (2016) estimates that 32 million children live with disabling peripheral hearing loss, the consequences of which include delayed language development, academic underachievement, social isolation, higher risk of injuries and increased poverty (Olusanya et al., 2014). To assess the extent of the hearing problem in children, many countries have sought to identify the rates of hearing loss in their paediatric populations.

The prevalence figures for peripheral hearing loss in primary school children have been reported in many, but not all, countries around the world. These reports have been reviewed by authors such as Stevens et al. (2011), who calculated a figure of 7.57% for the prevalence of any hearing loss in children aged five to 14 years for all reporting countries. This was based on prevalence values (with 95% confidence intervals) of 6.22% (4.61–8.81%) for mild hearing loss (20-34 dB HL), 1.07% (0.77–1.69%) for moderate hearing loss (35-49 dB HL), 0.21% (0.15–0.34%) for moderately severe hearing loss (50-64 dB HL), 0.05% (0.04–0.08%) for severe hearing loss (65-79 dB HL), 0.01% (0.01–0.02%) for profound hearing loss (80-94 dB HL), and 0.01% (0.01–0.02%) for complete hearing loss (≥95 dB HL). These prevalence values were seen to differ by region with the higher prevalence reported in South Asia and sub-Saharan Africa and lower prevalence reported in the Middle East, North Africa and East Asia. While prevalence of unilateral and/or milder degrees of hearing loss were not reported, children with such hearing loss experience increased rate of grade failures, need for additional educational assistance, and perceived behavioural issues in the classroom than their normal hearing peers (Bess et al., 1998; Bovo et al., 1988; Daud et al., 2010; Kiese-Himmel, 2002; Oyler et al., 1988).

When compared with other disorders that could impact a child's learning in school, such as vision disorder, the reported rates of PHL is high. According to WHO reports, vision disorders in low-income countries were reported to be 0.15%, and 0.03% in high-income countries (Gilbert &

Foster, 2001). However, when compared to neuro-behavioural disorders such as attention-deficit/hyperactivity disorder (ADHD) with the prevalence estimate of 7.2%, the rate of PHL is similar, if not slightly higher (Thomas, Sanders, Doust, Beller, & Glasziou, 2015). While Stevens et al. (2011) and others (e.g., Pascolini & Smith, 2009) summarised the prevalence of hearing loss in primary school children by region and/or country, these summaries did not include data from Australia.

3.4.3.1. Prevalence of peripheral hearing loss in Australian primary school children

The systematic review of rates of peripheral hearing the loss in primary school children in Australia is reported as Chapter 4 in this thesis. A brief summary of this review is presented below to maintain content continuity within the present thesis chapter.

To determine the rate of peripheral hearing loss in Australian primary school children, Choi et al. (2016) conducted a search of five electronic databases that yielded three studies that had quantitatively reported the peripheral hearing results of screening and follow-up assessment of hearing in primary school children in Australia. A follow-up assessment was deemed to have occurred if the researchers performed a second, more thorough, assessment of the hearing of those children who failed an initial screening (Choi et al., 2016). Studies were excluded from this review if they reported on data already presented elsewhere or if the children were sampled from restricted populations such as coming from a single site, clinical referral and/or presenting with only selected disorder (Choi et al., 2016). Studies that had investigated Aboriginal Australian populations were not included in this review due to the identified complexities around hearing and hearing health in this population (Burns & Thomson, 2013).

The systematic review concluded that the overall rate estimate of peripheral hearing loss in primary school children in Australia was between 3.4 and 12.8%. Detailed rates degree and laterality of hearing loss are described in Chapter 4, Table 4.2. These rates were drawn from three potential estimates reported by various authors. Driscoll, Kei, and McPherson (2001) had reported an overall rate of hearing loss of 4.7% [95% CI: 3.4% - 6.1%, n = 940] when a normal hearing was defined as hearing thresholds ≤25 dB HL. Cone, Wake, Tobin, Poulakis, and Rickards (2010) had reported a rate of 12.0% [95% CI: 11.2% - 12.8%, n = 6240] when normal hearing was defined as hearing thresholds ≤15 dB HL, and Keogh, Kei, Driscoll, and Khan (2010) had reported a rate of 10.2% [95% CI: 8.4% - 12.0%, n = 1071] when normal hearing was defined as hearing thresholds ≤20 dB HL. The highest rate of the type and degree of hearing loss was reported to be a mild, conductive hearing loss (Cone et al., 2010; Driscoll et al., 2001; Keogh et al., 2010), while the lowest rate of the type and degree of hearing loss was reported to be mixed and sensorineural hearing losses (Cone et al., 2010; Keogh et al., 2010).

Estimates of the rates of type, degree and laterality of peripheral hearing loss in primary school children in Australia were more difficult to determine. Driscoll et al. (2001) reported the highest rate for mild, conductive hearing loss and lower rates for mixed and sensorineural hearing losses. The higher rate of conductive hearing loss was generally supported by similar data from Cone et al. (2010) and Keogh et al. (2010). The lower rate of sensorineural hearing loss was supported by Cone et al. (2010), but the lower rate of mixed hearing loss was not supported by Cone et al. (2010). Reports on the rates of laterality were variable across Driscoll, Kei and McPherson (2001), Cone et al. (2010) and Keogh et al. (2010) for conductive hearing losses, were reported as being equal by Driscoll et al. (2001) for sensorineural hearing loss, and were under-reported for mixed hearing loss.

Compared to other high-income countries, primary school children in Australia had higher rates of hearing loss, primarily due to higher rates of conductive hearing loss (Choi et al., 2016). While possible reasons for this higher rate of conductive hearing loss were not obvious from the data reviewed, this could be due to higher rates of OM in Australian school-child population. A systematic review conducted by Mahadevan et al. (2012) showed that in non-Aboriginal Australian school-child population, OME was more prevalent compared to other developed countries such as New Zealand

and Japan. Nevertheless, this highlighted the need to detect and manage conductive losses using existing health resources in Australia (Gunasekera, O'Connor, Vijayasekaran, & Del Mar, 2009).

The estimate of hearing loss provided in this systematic review was affected by disparities in definitions of what constitutes normal hearing thresholds in children and the use of population distributions of hearing thresholds in adults to define normal hearing thresholds in children (Choi et al., 2016). The review also highlighted the need to base any reporting of rates of hearing loss on the results of follow-up diagnostic hearing assessments and not on hearing screenings (Choi et al., 2016).

3.5. Central Hearing – Auditory Processing

The central auditory pathway consists of the structures beyond the cochlea and cochlear nerve. It includes the auditory brainstem and auditory cortex and is often referred to as the central auditory nervous system (CANS). The auditory brainstem begins processing the spectral and temporal features of sound (Phillips, 2014). The auditory cortex continues this processing and provides the listener with much of the conscious perception of sound (Phillips, 2014). This auditory processing proceeds from simpler processes such as identifying what the sound was, when it occurred, and where it came from; to more complex processes such as listening to speech, listening to multiple sound sources, and listening in noise (J. Jerger & Musiek, 2000).

The processing of sound in the central hearing structures begins when the cochlear nerve fibres synapse in the cochlea nucleus at the dorsal-lateral aspect of the medulla-pons junction (Rhode, 1991). Each fibre of the cochlear nerve branches on entering the cochlea nucleus to innervate cells in the dorsal, antero-ventral and postero-ventral cochlear nuclei (Rhode, 1991). The main function of the dorsal cochlea nucleus is thought to be to process the spectral and temporal features of a sound. The main function of the antero-ventral cochlear nucleus is thought to be to relay the signal with high fidelity to higher auditory nuclei in the brainstem (Phillips, Hall, & Boehnke, 2002).

From the cochlear nucleus, the auditory brainstem is thought proceed along two main pathways, monaural and binaural. The monaural or "what" pathway is thought to process the spectral and temporal features of a sound and therefore focuses on sound identification and classification (Alain, Arnott, Hevenor, Graham, & Grady, 2001; Kraus & Nicol, 2005). This pathway predominantly consists of the cochlear nucleus (with an emphasis on the dorsal CN), the contralateral nucleus of the lateral lemniscus (nLL) and contralateral inferior colliculus (IC). The binaural pathway or "where" pathway is thought to process the binaural features of the stimulus to identify the origin of the sound (Alain et al., 2001; Kraus & Nicol, 2005). This pathway predominantly consists of the cochlear nucleus (with an emphasis on the antero-ventral cochlear nucleus), both superior olivary complexes and both inferior colliculi (Alain et al., 2001; Kraus & Nicol, 2005).

The superior olivary complex (SOC) is located in the caudal portion of the pons and forms a multinucleated complex with four divisions: medial superior olive (MSO), lateral superior olive (LSO), medial nucleus of the trapezoid body (MNTB), and the periolivary nuclei (PON). The main function of the SOC is to encode binaural cues for the spatial location of sounds by executing interaural stimulus comparisons (Scharf, Magnan, Collet, Ulmer, & Chays, 1994).

The lateral lemniscus (LL) is a tract of axons travelling from cochlear nucleus and SOC to the IC, with some of its fibres synapsing with the nuclei of the lateral lemniscus (nLL) in the pons.The nLL has two distinct regions: the dorsal nLL and ventral nLL. The primary function of the nLL is thought to be the processing of temporal features of sound as its cells have better temporal resolution compared to other cells rostral to the cochlear nuclei (Masterton, Jane, & Diamond, 1967; Tollin, 2003).

The inferior colliculus (IC) is located on the dorsal aspect of the midbrain and contains three morphologically distinct nuclei: a central nucleus (ICC), a pericentral nucleus (ICP) and an external nucleus (ICX). The ICC is the mandatory synaptic station for all auditory sensory information ascending beyond the auditory midbrain and is thought to carry out multiple functions (Phillips, 2014). The main function of the IC is to integrate the incoming sound identification and sound localisation information onto a single spatio-tonotopic map, with binaural interactions appearing to be prominent in this area (Casseday, Fremouw, & Covey, 2002). In this regard, the “what” and the “where” auditory pathways are thought to converge in the IC.

The medial geniculate body is the specific thalamic auditory relay site. The main function of the medial geniculate body is to receive information from the inferior colliculus, integrate it, and relay the information to the cerebral cortex (Phillips, 2014). The medial geniculate body is thought to be involved with complex signal processing as well as coding of stimuli with slowly changing acoustic parameters (e.g., vowels and syllables within speech), binaural encoding and feature extraction (Phillips, Vigneault-MacLean, Boehnke, & Hall, 2003).

The auditory cortex consists of a core area, with further surrounding areas called belts. The core lies primarily on the supratemporal plane of the superior temporal gyrus and is referred to as the primary auditory cortex. The largest belt is extended over the lateral border of the temporal lobe, insular cotex and parietal operculum, and is referred to as the auditory association area (Wessinger et al., 2001). The main function of the primary auditory cortex includes, but is not limited to, processing the complex features of sound, subserving sound localisation and the representation of auditory space, being necessary for selective attention to auditory stimuli on the basis of source position, and serving to identify stimuli on an absolute basis. Examples include recognising temporal patterns of sounds and directions of pitch change (e.g., melody, speech etc) (R. J. Zatorre, Belin, & Penhune, 2002). The main function of the auditory association cortex includes, but is not limited to, extracting meanings of sound patterns and associating learned significance with a particular sound pattern (Johnsrude, Penhune, & Zatorre, 2000).

3.6. Central Hearing Loss - Auditory Processing Difficulties or Disorder

The processes performed on sound signals by central hearing structures are referred to as *auditory processing (AP)* (Bamiou, Campbell, & Sirimanna, 2006). Significant deficits in AP have been described as Auditory Processing Disorder (APD), or (Central) Auditory Processing Disorder ([C]APD). While various definitions of APD share some common features (e.g., being predominantly auditory disorder), a single, universally accepted definition remains elusive. (W. J. Wilson & Arnott, 2013). Several approaches to APD have been proposed by various authors, including audiological (J. Jerger, 2009), psychoeducational (J. Jerger, 2009), language acquisition and learning (J. Jerger, 2009), modality specificity (Cacace & McFarland, 2013), auditory attention (Moore, Ferguson, Edmondson-Jones, Ratib, & Riley, 2010), hierarchical testing (Dillon, Cameron, Glyde, Wilson, & Tomlin, 2012), clinical entities (Vermiglio, 2014), and neural networks (Friel-Patti, 1999). These approaches have been described in detail by W. J. Wilson (2018).

The psychoeducation approach to APD was favoured in this thesis as it views APD as a deficit in auditory abilities that are thought to be important to learning, with those auditory abilities being independent of other abilities such as reading/writing (J. Jerger, 2009). This approach does not emphasise the neuroanatomical origin of these abilities. The most comprehensive example of a psychoeducation approach is the Cattell-Horn-Carrol (CHC) theory of cognitive abilities (Flanagan & Harrison, 2012) that is derived from integrated works of the three researchers in its name. The CHC theory of cognitive abilities views AP as one of 16 broad stratum abilities contributing to human intelligence. In the CHC theory, AP is seen as being independent of the other broad stratum abilities.

Other approaches have a different view of APD. For instance, the audiological approach views APD as a disorder due to lesions in the central auditory nervous system (CANS), while the language acquisition and learning approach views APD as a deficit in auditory abilities that are thought to be important to language acquisition and learning (Jerger, 2009). The modality-specific approach views auditory perception as one of many modalities (others include vision, touch, smell, proprioception, etc) and limits APD as being a deficit in the auditory modality only (Cacace & McFarland, 2013). The auditory attention approach views APD as a cognitive rather than an auditory deficit, with APD stemming primarily from a deficit in auditory attention rather than auditory processing (Moore et al., 2010). The hierarchical testing approach does not attempt to define APD, but rather focuses on using hierarchical testing to identify the main feature of a person's listening difficulties (Dillon et al., 2012).

The clinical entities approach argues that the construct of APD does not satisfy the criteria for being a clinical entity and should be abandoned in favour of identifying specific auditory disorders that do not meet these criteria (Vermiglio, 2014). Finally, the network approach views APD as a disruption to the auditory nervous system that is modulated by other systems such as cognitive sensorimotor and reward systems that can benefits from neuroplasticity (Kraus & Nicol, 2005).

While many approaches to explain APD have been taken, the most cited and used approach is that of the American Speech-Language Hearing Association (ASHA, 2005) and the American Academy of Audiology (AAA, 2010). This approach favours the audiological and psychoeducational approaches to the disorder with ASHA (2005) defining APD as “deficit in the perceptual processing of auditory information in the central auditory nervous system (CANS) and the neurobiological activity that underlies that processing and gives rise to electrophysiological auditory potentials” ASHA (2005) go on to state that APD affects one or more of the following auditory skills: sound localisation and lateralisation; auditory discrimination; auditory pattern recognition; temporal aspects of audition, including temporal integration, temporal discrimination (e.g. temporal gap detection), temporal ordering and temporal masking; auditory performance in competing acoustic signals (including dichotic listening); and auditory performance with degraded acoustic signals (ASHA, 2005). This definition is endorsed by the AAA (2010), whose authors have subsequently acknowledged that there are other groups who favour other approaches to APD. One example is the British Society of Audiology (BSA, 2017) that favours the auditory attention approach that emphasises APD as originating from deficits in top-down processes typically associated with cognition over deficits in bottom-up processes more frequently associated with APD (e.g., BSA, 2017; de Wit, Neijenhuis, & Luinge, 2017).

While causes of APD are still debated, some of the potential causes are hereditary developmental abnormalities; maturation delay; antenatal, perinatal and postnatal factors such as prematurity and low birth weight; and auditory deprivation (AAA, 2010; Bamiou, Musiek, & Luxon, 2001; Witton, 2010). Examples of the latter include animal studies showing that auditory deprivation due to OM during critical early developmental periods can result in AP difficulties (Caras & Sanes, 2015); and human studies showing that compared to children with no history of OM, children with past history of OM have significantly impaired binaural speech discrimination in competition and spatial listening ability (Tomlin & Rance, 2014). Musiek et al. (1985) proposed three models of neurological correlates of APD in children. These models are: neuro-morphological disorders, that includes misshaped or misplaced cells, maturation delay of the CNS, and neurological disorders of diseases, including neurodegenerative disorders. Despite these models, the underlying aetiology in most cases of APD remains unknown (Chermak & Musiek, 1997). A small minority of children with AP deficits have demonstrated neurological pathology (Boscariol et al., 2009; Rance, Barker, Sarant, & Ching, 2007; Rance, Ryan, Carew, et al., 2012a; Rance, Ryan, Bayliss, et al., 2012b), however this does not apply to the majority of children suspected of having an APD.

3.6.1. APD Diagnosis

The current recommendations of the ASHA (2005) and the AAA (2010) are for a diagnosis of APD to be made when scores fall two standard deviations (SD) or more below the mean of age-matched peers in one or both ears on at least two or more different behavioural tests in the test battery or if scores fall below at least three SDs on a single test if significant functional difficulty in auditory behaviours are observed (ASHA, 2005; AAA, 2010). This reflects the audiological and psychological approaches that underpin that of the ASHA (2005) and the AAA (2010) and their use of diagnostic criteria drawn from the use of behavioural AP tests to identify site-of-lesion in the CANS.

Diagnostic outcomes are significantly influenced by the criterion applied, with much variability and ambiguity in the literature as to how a diagnosis of APD is reached. Wilson and Arnott (2013) identified nine different criteria to diagnose APD, which included the criterion outlined above by the ASHA (2005). They found that the choice of diagnostic criterion significantly influenced the proportion of children diagnosed with APD, with the rate of diagnosis in the cohort of 150 children varying from 7.3 to 96.0%. As a result, the authors concluded that any diagnosis of APD should be qualified by an explicit statement of the criteria and tests used.

3.6.2. APD Skills and Test Families

As mentioned in the previous sections, AP involves several distinct sub-processes or skills, and hence a breakdown or deficit in any one of these skills or sub-processes can contribute to the development of APD (Baran, 2014; Iliadou, Bamiou, Kaprinis, Kandylis, & Kaprinis, 2009). Similar to diagnosing peripheral hearing loss, relying on a single test or a limited battery of tests may fail to uncover an existing auditory deficit if the deficit is in an area not tapped by the selected test procedure/s (Baran, 2014; Dillon & Cameron, 2015). Similarly, the use of a single test or a battery of tests that assesses CANS function only at one level of the auditory system or within a limited region of the auditory system may fail to uncover compromise within the CANS. Thus, a test battery approach that includes a selection of comprehensive and valid test battery that considers factors and influences such as specific auditory deficits, comorbid disorders or disabilities, age, native language and/or general language ability and motivation have been adopted by most national guidelines for assessing APD (ASHA, 2005; AAA, 2010; BSA, 2017). This approach has led to behavioural tests being categorised into the test families of APD as dichotic listening, temporal sequencing, binaural interaction and monaural low-redundancy speech (ASHA, 2005). The behavioural tests were classified into test families in an attempt to categorise these tests as they differed in terms of the AP that they assess, the types of stimuli used in the tests, the procedures employed, and the level of CANS that is being evaluated. These test categories will be reviewed briefly in the next section. It is noted that only tests involving behavioural or psychoacoustic measures will be discussed. It is acknowledged that electrophysiological measures are also available to assess AP in children.

In order to ensure a comprehensive and valid test battery is being used, minimum tests in a test battery have been recommended by the Bruton conference consensus statement on APD assessment (J. Jerger & Musiek, 2000). This included a dichotic task, thought to be a sensitive indicator of AP difficulties, a frequency or duration pattern sequence task, thought to be a key measure of auditory temporal processing, and a temporal gap detection task, considered to be a key measure of auditory temporal processing (J. Jerger & Musiek, 2000). Similarly, Musiek, Chermak, Weihing, Zappulla, and Nagle (2011) proposed an efficient APD test battery of dichotic digits and frequency patterns that would maximise the sensitivity and specificity to impaired central auditory pathways. Alternatively, some authors have suggested including tests with specific treatments that are effective for particular types of AP difficulties in a test battery. Examples include a test of spatial processing - the Listening in Spatialized Noise Sentences (LiSN-S) test, and a test of working memory - the memory for digits reversed (Cameron, Glyde, & Dillon, 2011; Dillon et al., 2012). Other suggestions have been that audiologists should select the appropriate test battery on the basis of findings from the case history and interdisciplinary assessments (e.g., results of language and cognitive assessments), as well as being aware of the validity, sensitivity and specificity of each test and the area of CANS to which each test is most sensitive (Chermak, Silva, Nye, Hasbrouck, & Musiek, 2007).

While no single test battery has been agreed upon, some test families from which tests of often chosen to assess for APD are dichotic listening, monoaural low redundancy, and temporal patterning.

3.6.2.1. Dichotic Listening: Binaural Integration & Binaural Separation

Dichotic listening tests involve different sounds being presented to each ear in a simultaneous or overlapping manner. These tests stemmed from the audiological approach to APD and were initially developed to detect the site of lesion in CANS (J. Jerger, 2009). Dichotic speech tests are used as it measures the patient’s ability to process all or selected components of the dichotic stimulus in a manner thought to be sensitive to APD (ASHA 2005; AAA 2010; Jerger & Musiek, 2000; Musiek et al., 2011). Speech stimuli are commonly used in dichotic tests, ranging up from consonant-vowel combinations to digits, words, and sentences.

Dichotic listening tests are considered to be sensitive to lesions of the auditory cortex and the interhemispheric fibres (Baran & Musiek, 1999). With lesions of the auditory cortex, contralateral ear effects are noted; however, binaural deficit can be noted if there is a significant compromise of the left auditory cortex (Keith & Anderson, 2007). With lesions involving the corpus callosum or the interhemispheric pathways, left ear deficits are commonly observed (Kimura, 1967). However, in young children a left ear deficit is seen in the absence of pathology (Keith & Anderson, 2007). This deficit could partially be due to the left auditory cortex acting as the dominant language hemisphere in a majority of people (Keith & Anderson, 2007). Information travelling to the left auditory cortex via the corpus callosum is thought to travel by an indirect pathway compared to the contralateral ear, thereby resulting in a left ear deficit (Kimura, 1967). Improved performance in the left ear with maturation has been reported, consistent with maturation of the corpus callosum in adolescence (Keith & Anderson, 2007). This evidence is in part supported by an inability to recognise stimuli in the left ear in listeners with disconnected hemispheres (Keith & Anderson, 2007).

Dichotic tests can be divided into tests of binaural integration or tests of binaural separation. Binaural integration is the ability of the CANS to take disparate information presented to two ears and to unify and comprehend the auditory information (Keith & Anderson, 2007). Binaural integration tests are currently used as binaural integration deficits have been reported in children with learning and reading disorders (Hynd, Obrzut, Weed, & Hynd, 1979; Moncrieff & Musiek, 2002; Obrzut, Conrad, Bryden, & Boliek, 1988).

One of the most commonly used tests in the binaural integration category is the Dichotic Digits (DD) test (Musiek, 1983). The DD test has been shown to have high sensitivity to CANS lesions in adults (80%) and good test-retest reliability with a specificity of 85% (Musiek et al., 2011) in adults. This test sees two pairs of digits being presented such that each pair is presented simultaneously with each number within each pair being presented to a different ear simultaneously. Scoring is based on the number of correctly repeated digits regardless of the order and is compared to the age-specific norms.

Binaural separation is the ability of the CANS to process the auditory signal presented to one ear while disregarding a disparate message presented simultaneously to the other ear at the same time

(Keith & Anderson, 2007). The acoustic information is often presented in a sentence format and may differ in intensity between ears. Tests that fall into this category are thought to be useful in differentiating brainstem pathology from cortical pathology (S. Jerger & Jerger, 1975). However, when compared with other dichotic measures, binaural separation tests may be less sensitive in identifying cortical lesions (Lynn & Gilroy, 1977; Musiek, 1983). Binaural separation tests that are currently used as tests in this category may be better at investigating neuro-maturation and language processing abilities (Porter & Berlin, 1975; Willeford, 1977).

One of the tests in the binaural separation category is the dichotic competing sentences test (CS) (Musiek, 1983). CS has been shown to have relatively low sensitivity to CANS lesions in adults (75%) but good test-retest reliability with the specificity of 100% (Musiek et al., 2011). This test sees simple sentences of six to seven words presented to each ear separately but simultaneously. The stimulus sentence is presented at a lower intensity level to the test ear and the competing sentence at a higher intensity to the non-test ear. The patient is required to repeat back the softer sentence played to the test ear while ignoring the louder sentence played to the non-test ear. Scoring is based on the number of stimulus sentence portionscorrectly repeated and is compared to the age-specific norms.

3.6.2.2. Monaural Low-Redundancy

Monaural low-redundancy tests involve stimuli that have been degraded by modifying the frequency, temporal or intensity characteristics of the original signal. These tests have stemmed from the audiological and psychoeducational approaches to APD. Within the audiological approach, these tests were initially developed to identify sites-of-lesion with the auditory nervous system. Within the psychoeducational approach, these tests that were initially developed to measure the patient's functional ability to understand degraded speech signals. It is through the psychoeducational approach that monaural low-redundancy tasks draw some face validity as measures of speech reception ability in difficult listening environments such as the classroom settings, despite the audiological approach showing these tests to have lower sensitivity and specificity to lesions of CANS (AAA, 2010; ASHA, 2005; Bellis, 2003; Bellis & Ferre, 1999; Musiek et al., 2011).

Monaural low-redundancy tests are thought to be moderately sensitive to cortical lesions (Baran, 2014). With lesions of the cortex, the contralateral deficit is noted most commonly (Lynn & Gilroy, 1977). In some cases, bilateral deficits may be noted in cases with extensive left hemisphere compromise (Baran & Musiek, 2003) that could be due to compromised auditory areas responsible for speech recognition. Monaural low-redundancy tests are less sensitive to brainstem lesions, with laterality effects differing on the location of the lesion. The performance on monaural low-redundancy tests is not affected by interhemispheric pathway compromise (Baran & Musiek, 1999).

An example of a monaural low-redundancy speech test is the Low-pass Filtered Speech (LPFS) test (Bornstein, Wilson, & Cambron, 1994). Despite its lower sensitivity to APD and lower sensitivity and specificity to lesions of the CANS, the LPFS test is often used due to its face validity as a measure of a child’s ability to hear speech under difficult listening conditions (AAA, 2010; ASHA, 2005; Bellis, 2003; Bellis & Ferre, 1999; Musiek et al., 2011). LPFS tests see low-pass filtered words presented to each ear with scoring is based on the number of words correctly repeated by the listener compared to the age-specific norms.

3.6.2.3. Temporal Patterning

Temporal patterning tests involve stimuli that change in frequency, intensity or duration over time in a manner that creates a temporal pattern. These tests have stemmed from the audiological approach to APD and were initially developed to measure the ability of CANS to integrate information between cortical hemispheres (Musiek, Pinheiro, & Wilson, 1980). Later use of these tests occurred in language acquisition and learning approaches to APD as deficits in temporal patterning were proposed to be related to phonological processing, receptive language and reading development in children (Tallal, Miller, Jenkins, & Merzenich, 1997).

Temporal patterning tests are thought to be sensitive to lesions of the auditory cortex and corpus callosum (Musiek & Baran, 1987; Musiek, Baran, & Pinheiro, 1990; Musiek et al., 1980). The use of verbal versus non-verbal responses (e.g., having the child use words to describe the temporal pattern versus having the child hum the temporal pattern) is thought to improve the test's sensitivity to lesions in the left or right auditory cortices or the corpus callosum (Musiek, Kibbe, & Baran, 1984).

One of the most commonly used temporal patterning tests is the Frequency Pattern Test (FPT) (Musiek & Baran, 1987). The FPT consists of stimuli of three tones of two different frequencies (1122 Hz and 880 Hz). The patient is required to identify the pattern heard by verbally indicating "high" or "low", or by humming in a high or low manner, for each of the three tones. Scoring is based on the number of stimuli correctly reported or hummed against age-specific norms. The FPT has been shown to have good test-retest reliability and high sensitivity (85%) and specificity (100%) to CANS lesion in some adult populations (Musiek et al., 2011; Musiek & Baran, 1987; Musiek, Gollegly, Lamb, & Lamb, 1990).

3.6.2.4. AP or something else?

While many AP tests and test batteries are well entrenched in the APD literature, concerns have been raised about whether these tests assess AP or something else. This section will examine these concerns by considering a series of questions.

What parts of the brain are activated when completing a test of AP? If tests of AP test AP, then it would be expected that completing an AP test would primarily activate areas of the CANS rather than areas outside the CANS. This assumption has not been widely investigated in the AP literature. Bartel-Friedrich, Broecker, Knoergen, and Koesling (2010) conducted functional magnetic resonance imaging (fMRI) on 11 healthy adults (aged between 23 and 31 years) and 14 healthy children (aged between 7 and 10 years) while they completed a phonemic discrimination test (the Hannover phoneme discrimination test), a phonological working memory test (the auditory memory span test), and a dichotic listening test. The fMRI results showed different but overlapping neural activation patterns from these three tests suggesting different but overlapping areas of the brain were responsible for performing these different processes. Similarly, Hugdahl, Thomsen, Ersland, Rimol and Niemi (2003) used fMRI to examine dichotic listening ability and showed that when a focused attention dichotic task was performed on thirteen healthy adults, brain areas associated with attention were activated more than areas associated with AP.

Are tests of AP affected by lesions of the CANS? If tests of AP test the functioning of the CANS, then lesions of the CNS should affect tests of auditory processing. While this assumption has been more widely investigated in the AP literature, these investigations have been mostly limited to the study of adults with known sites-of-lesion in the CANS. An example is Musiek et al. (2011) who performed dichotic digits, competing sentences, frequency patterns and low-pass filtered speech testing on a sample of 20 adults with identified lesions affecting the auditory cortices and 29 adults with no lesions. The authors found that, in general, the tests of AP had good sensitivity, specificity and efficiency for the auditory cortex sites-of-lesion, with the dichotic digits, competing sentences and frequency patterns tests returning individual test efficiencies of over 85%; and the combination of competing sentences and frequency patterns returning the best test battery efficiency of 92%.

Do the results of AP tests correlate with the results of non-AP tests? If AP tests only assess AP, then the results of AP tests should not correlate with the results of non-AP tests. This assumption has been partly supported by AP and non-AP test results being weakly correlated across a number of studies in children (Ahissar, Protopapas, Reid, & Merzenich, 2000). Examples include AP and reading and language results being correlated in children aged 6 to 7 years old with this correlation being lost when controlled for attention (Sutcliffe and Bishop, 2002), auditory temporal sequencing results in children with suspected APD sharing only 10% of variance with attention and memory (Sharma et al., 2009), gap detection and masking level difference test results being unrelated to attention and memory test results (Breier, Fletcher, Foorman, Klaas, & Gray, 2003; Sharma et al., 2009), and SCAN test results being unrelated to attention and memory test results (Riccio, Cohen, Garrison, & Smith, 2005; Rosen et al., 2010).

Do the results of AP tests fall into different statistical factors than the results of non-AP test results? Following on from the correlation argument above, if AP tests only assess AP then the results of AP tests should fall into different statistical factors than the results of non-AP tests. Perhaps the largest consideration of this argument is offered by the CHC Theory of Intelligence (Carroll, 1993; Cattell, 1963; Horn, 1965). This a psychological theory developed using factor analyses of the past 60 to 70 years of literature on the nature, identification and structure of human cognitive abilities (Flanagan & Harrison, 2012). It argues that cognitive ability can be classified into three different strata: narrow, broad and general. AP is classified as one of the abilities in the broad strata, encompassing skills such as speech sound discrimination, resistance to auditory stimulus distortion and maintaining and judging rhythm (Flanagan & Harrison, 2012). Interestingly, these sub-skills show much similarity with the AP skills listed by ASHA (2005) and AAA (2010) in their definition of AP (W. J. Wilson & Arnott, 2012).

Are tests of AP testing AP or speech and language? As many current tests of AP use linguistic stimuli and demand a spoken response, their ability to test AP separate to speech and language processes such as phonetics and syntax has been questioned (Dawes & Bishop, 2009; Keith, 1995; Neijenhuis, 2003). AP tests with heavy linguistic loading, such as competing sentences test, appear to be more influenced by language than tests with lighter linguistic loading, such as dichotic digits. This can be seen in reports of sentence simple sentence repetition tasks being some of the best predictor of language impairment (Conti-Ramsden, Botting, & Faragher, 2001). Some AP test results have also been reported to be correlated with some language test results, with Sharma, Purdy, and Kelly (2009) showing significant correlations between various AP test scores and reading fluency and accuracy in a group of normally hearing children and children with reading disorders. Other studies have disagreed, however, with Rosen, Cohen, & Vanniasegaram (2010) showing only weak correlations between AP and langauge and cognitive test results in 20 normal-hearing children and 28 children with suspected APD; and Tomlin, Dillon, Sharma and Rance (2015) showing only weak correlations between AP test scores and literacy, reading fluency and reading accuracy. These findings can perhaps be summarised by Dawes and Bishop (2009) who noted that as some measures of AP overlap with measures of language, tests of AP can never be completely independent of a child's verbal abilities (Dawes & Bishop, 2009).

Are tests of AP relevant to the larger issue of classroom listening? AP is one of many processes needing to be successfully completed to be able to listen well in the classroom. The relative importance of AP has been questioned against that of processes associated with cognition and language. Tomlin et al. (2015) showed in a clinical sample of 105 children referred for AP assessment on the basis of poor performance in the classroom, 11% showed attention deficits and APD, 6% showing auditory working memory deficits and APD, and 8% showing attention deficit, auditory working memory deficit and APD. Moore et al. (2010) conducted a large population study of 1469 randomly selected children with normal hearing and assessed their cognitive and AP skills and showed that the classroom performance was best predicted by attention (explaining around 20% of the variance) and other areas of cognition such as IQ, language and memory. Other authors such as Riccio et al. (2005) and Tomlin et al. (2015) have also found only weak relationships between AP test results and listening behaviour in school-aged children. In contrast, authors such as Gyldenkærne, Dillon, Sharma, and Purdy (2014) and Sidiras et al. (2019) did not find any relationships with attention. Rather, these authors proposed that while attention and APD may exhibit similar symptoms, they are separate, largely independent conditions.

Overall, the above discussion suggests AP tests and test batteries appear to provide at least a substantial assessment of AP but their results are at least weakly affected by non-AP factors and they may not provide strong predictions of overall listening behaviours in children in the classroom.

3.6.3. Prevalence of APD

Despite the lack of consensus on the definition of APD and its criterion for diagnosis, several attempts have been made to estimate the prevalence of APD in children. In the United States of America (USA), Musiek, Gollegly, et al. (1990) estimated the prevalence of APD in children with learning disability to be between 3 to 7%. Subsequently, Chermak and Musiek (1997) revised this estimate down to between 2 to 3% based on the prevalence of children who had co-morbid disorders such as ADHD. Bamiou et al. (2001) provided a rough prevalence estimate for APD in children in the UK to be 7%. Hind et al. (2011) provided a much lower prevalence estimate of 0.5 to 1% in the same population. Esplin & Wright (2014) estimated the prevalence of APD in children in New Zealand to be 6.2%, based estimates of the prevalence of learning disability and reports of listening difficulties from APD testing (Esplin & Wright, 2014). When compared with other disorders that could impact a child's learning in school, such as vision disorder, the reported rates of APD is high. According to WHO reports, vision disorders in low-income countries were reported to be 0.15%, and 0.03% in high-income countries (Gilbert & Foster, 2001). However, when compared to neuro-behavioural disorders such as attention-deficit/hyperactivity disorder (ADHD) with the prevalence estimate of 7.2%, the rate of APD is similar, if not slightly higher (Thomas et al., 2015).

The wide range of the prevalence figures reported for APD is due in no small part to the lack of agreement on AP test batteries and diagnostic criteria for APD. Many studies report prevalence of APD from a clinical population such as those referred to APD assessment or within a clinic for children with learning disabilities (Dawes & Bishop, 2007; Domitz & Schow, 2000; Iliadou et al., 2009; Sharma et al., 2009). Others attempt to extroplate APD prevalence figures from those offered for comorbid conditions such as learning, attention or reading disorders (Mcfarland & Cacace, 2003). While APD may have a high comorbidity with those conditions, any estimate of APD prevalence from those conditions will depend on factors such as the criteria used diagnosis to diagnose those conditions and the populations from which they were sampled (Chermak & Musiek, 1997; Mcfarland & Cacace, 2003; Sharma et al., 2009; Tomlin et al., 2015).

3.7. Consequences of Peripheral Hearing Loss and APD for Learning

The potential relationship between peripheral hearing loss (PHL) and/or auditory processing disorder (APD) and learning are extremely complex and poorly understood. This is due in no small part to the complexities surrounding each of these areas. When compared with other disorders that could impact a child's learning in school, such as vision disorder, the reported rates of PHL and/or APD is high. According to WHO reports, vision disorders in low-income countries were reported to be 0.15%, and 0.03% in high-income countries (Gilbert & Foster, 2001). However, when compared to neuro-behavioural disorders such as attention-deficit/hyperactivity disorder (ADHD) with prevalence estimate of 7.2%, the rate of PHL and/or APD is similar, if not slightly higher (Thomas et al., 2015).

School-aged children with PHL have shown higher rates of delayed language development, academic underachievement, social isolation, higher risk of injuries and increased poverty (Olusanya et al., 2014; World Health Organization, 2016). Some specific examples in case of PHL include reports of:

- Delayed speech and language (e.g., J. E. Lieu, Tye-Murray, & Fu, 2012; Pittman, Vincent, & Carter, 2009; Yoshinaga-Itano, 1995).
- Delayed phonological and expressive skills in children with mild to moderate degrees of PHL (e.g., Briscoe, Bishop, & Norbury, 2001; Eisenberg, 2007).
- Worse performance in speech comprehension in noise tasks in children with bilateral mild conductive PHL (e.g., Keogh et al., 2010) and in children aided with hearing aids (e.g., Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000).
- Poorer binaural processing tasks in children with a history of conductive PHL (e.g., Graydon, Rance, Dowell, & Van Dun, 2017).

- Less synchronised sustained attention to objects in young children with hearing loss (Chen, Castellanos, Yu, & Houston, 2019)

- Poorer educational outcomes such as being on an education support plan (e.g., J. E. Lieu et al., 2012) or achieving one to four grades lower than normal hearing peers (e.g., McFadden & Pittman, 2008).

- Lower energy levels, poorer communication skills and higher stress level in children with minimal PHL (e.g., Bess et al., 1998).

School-aged children with APD often show behavioural characteristics such as difficulty comprehending speech in competing or reverberant environments and difficulty following complex auditory information, inattentiveness and distractibility (ASHA, 2005; DeBonis & Moncrieff, 2008). While less is known, some specific examples in the case of APD include reports of:

- Listening ability, as rated by the classroom teacher, correlating with a child's academic performance and with reading, writing, and speaking skills (Yalçınkaya, Muluk, & Şahin, 2009).

- Academic difficulties being one of the commonly reported behaviours in children diagnosed with APD (e.g., Chermak, Tucker, & Seikel, 2002).

- Reading fluency and accuracy deficits in children with APD (e.g., Bishop & Snowling, 2004; Ramus, 2003; Sharma et al., 2009; Halliday et al., 2017), with reading difficulties appearing to be one of the typical symptoms of children referred for AP assessment (e.g.,Dawes, Bishop, Sirimanna, & Bamiou, 2008; Rosen et al., 2010).

- Cognitive deficits such as poorer attention and auditory working memory in children with APD (e.g., Moore et al., 2010; Tomlin et al., 2015).

- Literacy and language deficits in children with APD, with deficits in a general AP component posing a higher risk of developing language difficulties (e.g., Halliday et al., 2017; Tallal & Gaab, 2006).

In light of the potential relationship between PHL and/or APD and learning in school-aged children, substantial efforts have been made to identify children with hearing loss for appropriate management and intervention. These efforts have been greater in the case of PHL and include universal neonatal hearing screening (Ching, Oong, & Van Wanrooy, 2006; World Health Organization, 2016) and school-based hearing screening (World Health Organization, 2016). The management options for PHL have included auditory training (e.g., Gravel & O'Gara, 2003) and/or fitting of devices such as hearing aids and/or cochlear implants. Lesser efforts have been observed for APD with children typically not undergoing AP assessement until after they have demonstrated difficulties in learning at school. Once identified, management options for APD remain limited but can include auditory training (e.g., Schochat, Musiek, Alonso, & Ogata, 2010; Veuillet, Magnan, Ecalle, Thai-Van, & Collet, 2007) and devices such as personal frequency modulation (FM) systems (e.g., Johnston et al., 2009; Purdy, Smart, Baily, & Sharma, 2009).

Due to the complexities of the constructs being considered, it is likely that various elements of PHL and APD have a different relationship with certain elements of LD. This thesis will explore various models that could explain these relationships.

3.8. Summary

This chapter discussed peripheral and central hearing impairment, their possible causes, and their possible association between hearing impairment and LD. While hearing impairment appears to be associated with LD, the potential relationship between PHL and/or APD and learning are extremely complex and poorly understood and warrents further investigation.

Chapter 4: Rates of Hearing Loss in Primary School Children in Australia: A Systematic Review.

This chapter was originally published in the peer-reviewed journal of Speech, Language and Hearing (Choi et al., 2016). The content of this chapter is inserted as published, with the exception of formatting changes to headings, tables, figures and references to maintain consistency throughout the thesis.

4.1. Abstract

Objective: To systematically review literature reports of the rates of hearing impairment in primary school children in Australia.

Methods: A search of five electronic databases yielded three studies that had used follow-up diagnostic hearing assessment to examine hearing impairment in primary school children in Australia.

Results: The rate of hearing impairment in primary school children in Australia was estimated to lie between 3.4 and 12.8%. The rates of different types of hearing impairment were estimated as follows: conductive hearing impairment between 2.6 and 7.1%, sensorineural hearing impairment between 0 and 1.19%, and mixed hearing impairment between 0.1 and 4.0%. All estimated rates were affected by the use of different criteria to define the presence of hearing impairment.

Conclusions: The rates of hearing impairment in primary school children in Australia were higher than those reported in other high-income countries, mostly as a result of a higher rate of conductive hearing impairment. The present study's suggestion of higher rates of conductive hearing impairment in primary school children in Australia warrants further consideration as such impairments can be detected and managed using existing health resources.

4.2. Introduction

Hearing loss in children is of increasing concern globally. The World Health Organization (2016) estimates 32 million children live with disabling hearing loss, the consequences of which include delayed language development, academic underachievement, social isolation, higher risk of injuries and increased poverty (Olusanya et al., 2014; WHO, 2016). In response, WHO has recommended all countries strengthen maternal and child healthcare programs, train professionals in hearing care, regulate and monitor ototoxic medicines and environmental noise, make accessible hearing devices and communication therapies, raise awareness to promote hearing care, and implement infant and school-based hearing screening (Olusanya et al., 2014; WHO, 2016).

In response to calls from groups such as WHO, many countries have sought to identify the rates of hearing loss in their paediatric populations. This includes the population of interest in this systematic review, the primary school child (aged six to 12 years), for whom early identification of hearing loss is particularly important. Undetected hearing loss in this population can result in delayed speech and language (Heward, 2003; Wake, Hughes, Poulakis, Collins, & Rickards, 2004), academic difficulties (Bess et al., 1998; Quigley, 1978) and inappropriate labelling such as having a behavioural problem (Flexer, 1994).

The prevalence of hearing loss in primary school children has been widely reported in many, but not all, countries around the world. These reports have been reviewed by authors such as Stevens et al. (2011), who concluded the prevalence of hearing loss in children aged five to 14 years for all countries reporting such data to be 7.57%. This was based on prevalence values (with 95% confidence intervals) of 6.22% (4.61–8.81%) for mild hearing loss (20-34 dB HL), 1.07% (0.77–1.69%) for moderate hearing loss (35-49 dB HL), 0.21% (0.15–0.34%) for moderately severe hearing loss (50-64 dB HL), 0.05% (0.04–0.08%) for severe hearing loss (65-79 dB HL), 0.01% (0.01–0.02%) for profound hearing loss (80-94 dB HL), and 0.01% (0.01–0.02%) for complete hearing loss (≥95 dB HL). These prevalence values were seen to differ by region with the higher prevalence reported in South Asia and sub-Saharan Africa and lower prevalence reported in the Middle East, North Africa and East Asia.

While Stevens et al. (2011) and others (e.g., Pascolini & Smith, 2009) summarised the prevalence of hearing loss in primary school children by region and/or country, these summaries did not include data from Australia. This appears to be the result of at least four factors. First is the absence (to the best of the authors' knowledge) of any large-scale prevalence studies on hearing loss in the primary school child population in Australia. Second is the greater focus of much of the Australian hearing loss literature on neonatal/infant (e.g., Medical Services Advisory Committee, 2008), secondary school/young adult (11 to 35 years) (e.g., Williams, Carter, & Seeto, 2014; D. H. Wilson, Walsh, Sanchez, & Reed, 1998), and elderly populations (e.g., Sindhusake et al., 2001). Third is the reporting of rates of hearing loss for the clinical population of children fitted with hearing aids in Australia rather than the general child population of Australia (e.g., Australian Hearing, 2015). Fourth is the reporting of rates of hearing loss in restricted populations such as those referred for hearing aid assessments (e.g., Wake, Poulakis, Hughes, Carey-Sargeant, & Rickards, 2005) or those with congenital (e.g., Russ et al., 2003) or acquired hearing losses only (e.g., Access Economics, 2006).

In view of the limited data on rates of hearing loss in primary school children in Australia, this study aimed to systematically review the hearing screening and hearing assessment literature to determine if an estimate of the rate of hearing loss in this population can be obtained.

4.3. Method

4.3.1. Search strategy

Five databases were included in the literature search for articles published from 1973 to 2015: *PubMed*, *Cumulative Index of Nursing and Allied Health Literature (CINAHL)*, *EMBASE*, *PsychINFO* and *APAIS-Health*. *PubMed*, *CINAHL* and *PsycInfo* were selected because of their access to large volumes of literature (B. Taylor, Wylie, Dempster, & Donnelly, 2007). *EMBASE* was selected because of its focus on basic science relevant to clinical medicine that may not be indexed in *PubMed* (Wilkins, Gillies, & Davies, 2005). *APAIS-Health* was used to capture additional health and medical literatures published in Australia and New Zealand that were not identified through the other search engines (National Library of Australia, 2016).

The search terms used to search the *PubMed* database were the following MeSH terms: hearing loss OR hearing disorder* OR hearing loss* OR hearing difficulty* AND prevalence OR epidemiology OR incidence AND child AND Australia. For the other databases, the search terms used were the following keywords: hearing loss OR hearing disorder OR hearing loss OR hearing difficulty AND prevalence OR epidemiology OR incidence AND child AND Australia. Abstracts for identified articles were reviewed to select studies that met the inclusion criteria outlined below. In addition, relevant studies were also sought from the reference lists of the papers that met these selection criteria and from personal communication with six researchers in Australia known to the present study's authors. These researchers had completed hearing screening and/or assessment studies on child populations in Australia and were from the National Acoustics Laboratories and the Universities of Melbourne and Queensland. The publication bias induced by only searching databases with published studies is acknowledged.

4.3.2. Inclusion/exclusion criteria

To be included in this review, the selected research had to have quantitatively reported the results of screening and follow-up assessment of hearing using at least pure tone audiometry in primary school children from six to 12 years of age in Australia. A follow-up assessment was deemed to have occurred if the researchers performed a second, more thorough assessment of the hearing of those children who failed the screening. Studies were excluded from this review if they reported on previously reported data and if the children were from restricted populations such as coming from a single site and/or being limited by clinical referral and/or disorder. Studies that had investigated Aboriginal Australian populations were not included in this review due to the identified complexities around hearing and hearing health in this population (Burns & Thomson, 2013). This is a noted limitation of the current review and a separate review of the rate of hearing loss in the Aboriginal Australian population is warranted.

4.3.3. Quality assessment

Studies included in this review were assessed using the Critical Review Form for Quantitative Studies (Letts et al., 2007). This form allowed the researchers to systematically describe the included studies on the basis of nine criteria: study purpose, review of relevant background literature, appropriateness of study design, study biases, appropriateness of sample, frequency of outcome measurements, reporting of results, conclusions offered and limitation stated. The assessment was completed by all three authors who discussed each of the criteria for each of the studies considered until a majority decision was reached. This process was repeated on three occasions to improve the reliability of the authors' decisions. No formal statistical analysis of this process was conducted.

4.3.4. Definition of degrees of hearing loss

In light of ongoing debates surrounding the definition of degrees of hearing loss (Margolis & Saly, 2007), especially regarding the limits of normal hearing (with reported cut-off limits ranging from 15 dB HL to 25 dB HL), this review reported both the descriptions and quantities of degrees of loss as reported by each individual study included in the review. Two considerations are noted here. First is the need to take note of the minor differences in these descriptions and quantities when reviewing the results of the present review. Second is the need to consider the population distribution of hearing thresholds in school-aged children. This consideration could affect definitions of hearing loss in children as many definitions of hearing loss are based on population distributions of hearing thresholds in adults (Standards Australia, 2014).

4.4. Results

Figure 1 shows the results of the search process used in this review. The initial search of databases elicited 59 studies from *PubMed*, six from *CINAHL*, 26 from *ENBASE*, 28 from *PsychInfo*, 118 from *APAIS-Health* and four from personal communication with researchers in Australia. A review of the abstracts of these 239 studies identified six studies that met the inclusion criteria described above. Two of these studies, one conducted by Wake et al. (2006) and Lyons, Kei, and the other by Driscoll (2004) shared the same cohort of school children as Driscoll et al. (2001) and Cone et al. (2010), respectively, and were subsequently excluded. The study conducted by Kei, Brazel, Crebbin, Richards, and Willeston (2007) was also excluded from further analysis due to small sample size (n = 50) and non-representative sample (participants were recruited from a single primary school in the Sunshine Coast, Queensland, Australia). As a result, three independent studies by Driscoll et al. (2001), Cone et al. (2010) and Keogh et al. (2010) were included for further analysis in this review.

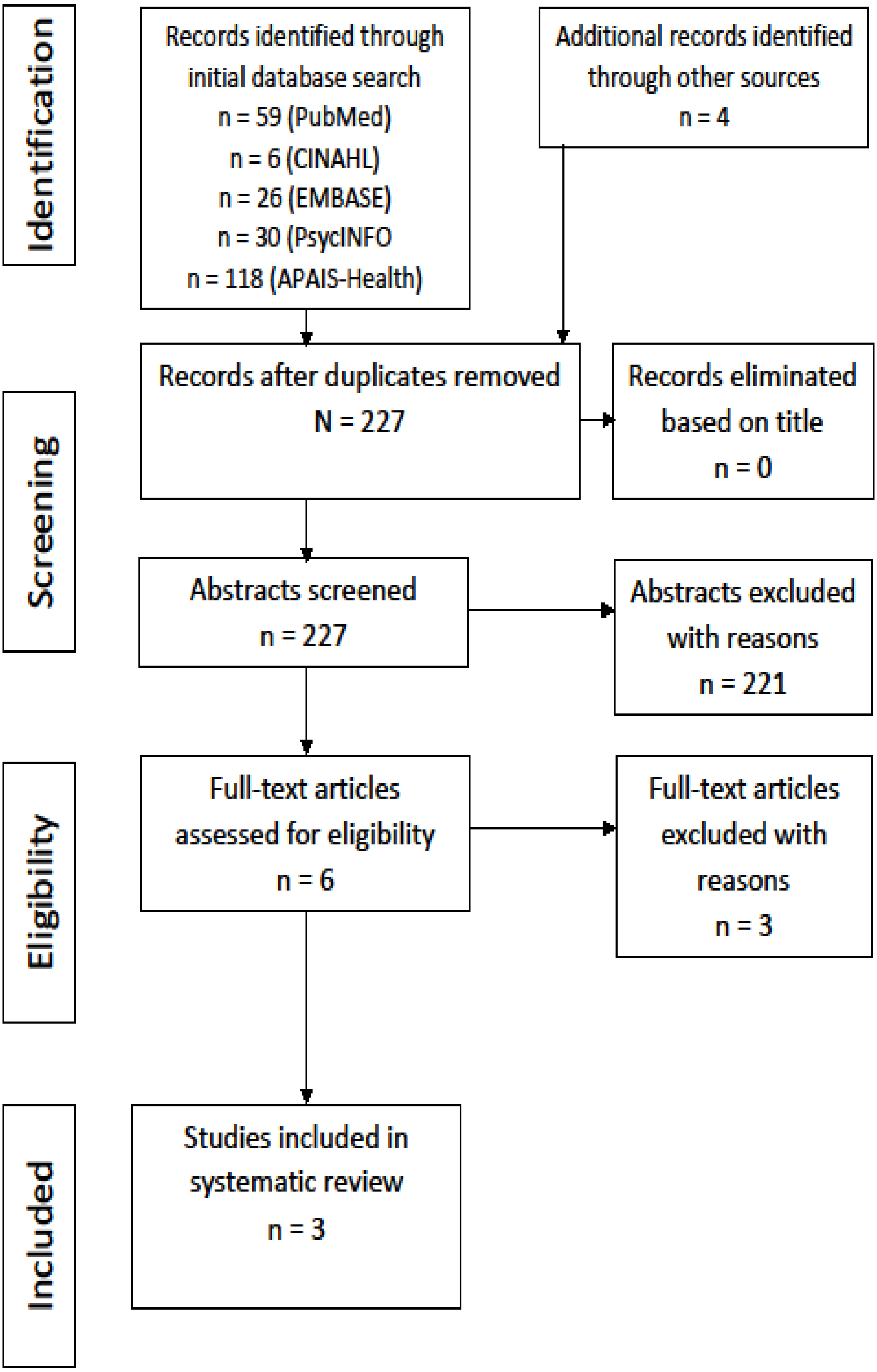

Figure 4.1. The process followed to identify the studies for review.

Table 1 summarises the methods and Table 2 summarises the results of the three studies included in this review (Driscoll, Kei & McPherson 2001; Cone et al. 2010; Keogh et al. 2010). The rate values reported in Table 2 fall into two types. First are the rates of children who failed the hearing screening assessments as reported in each study. Second are the rates of hearing loss by type, degree and/or laterality identified on follow-up audiological assessment as calculated by the present study's researchers. Each of these three papers will now be described in detail.

Table 4.1. Key features of the methods used in each of the reviewed studies.

Study	Period of data collection	Location	Participants	Screening Tests	Follow-up Audiological Assessments	Definition of HI
Driscoll et al. (2001)	March – November 1999 – 2000 (Autumn, Winter, Spring)	Brisbane metropolitan	N= 940, grade 1 students (5.2 – 7.9 years old)	Otoscopy Pure tone audiometry (air conduction: 0.5, 1, 2, 4 kHz) at 20 dB HL Tympanometry (226Hz)	Otoscopy Pure tone audiometry (Full air conduction and bone conduction) Tympanometry (226Hz)	Initial Screening: Pass: 25 dB HL; Fail: >25 dB HL. Follow up: Mild HL: 26 – 40 dB HL Moderate HL: 40 – 55 dB HL Moderately-severe HL: 56 – 70 dB HL
Cone et al. (2010)	Not Stated	Melbourne	N= 6240, grade 1 (mean age 7.1 years) and grade 5 (mean age 11.1 years)	Screening: Otoscopy Pure tone audiometry (air conduction only: 0.5, 1, 2, 3, 4, 6, 8 kHz) at 15 dB HL	Pure tone audiometry (Full air conduction and bone conduction) Tympanometry (226Hz) only for selected children	Slight/mild: 16 – 40 dB HL
Keogh et al. (2010)	March – November 2003 – 2004 (Autumn, Winter, Spring)	Brisbane metropolitan & Sunshine Coast	N= 1071, grade 1-3 students (5.4 – 10.9 years old)	Otoscopy Pure tone audiometry (air conduction only: 0.5, 1, 2, 4 kHz) at 20 dB HL Tympanometry (226Hz)	Pure tone audiometry (Full air conduction) Tympanometry (226Hz)	Pass: 20 dB HL Fail: >20 dB HL

Table 4.2. Rates (in percent) of primary school-aged children who failed a hearing screening assessment and a follow-up diagnostic audiological assessment for all participants in each study. The 95% confidence intervals are shown in brackets.

			Driscoll et al. (2001) n = 940	Cone et al. (2010) n = 6240	Keogh et al. (2010) n = 1071
Rates of Test Failure from Screening Results					
Failed screening overall			18.6 [16.1 – 21.1]	12.0 [11.2 – 12.8]	
Failed screening pure tone audiometry			8.9 [7.1 – 10.7]	12.0 [11.2 – 12.8]	10.2 [8.4 – 12.0]
Failed screening tympanometry			17.9 [15.5 – 20.4]		18.5 [16.2 – 20.8]
Estimated Rates of Type, Degree and Laterality of Hearing Impairment in Whole Sample					
Overall			4.7 [3.4 – 6.1]	12.0 [11.2 – 12.8]	10.2 [8.4 – 12.0]
Conductive	All in sample		3.8 [2.6 – 5.0]	6.2 [5.3 – 7.1]	10.2 [8.4 – 12.0]
	Mild	(26 – 40 dB HL)	3.3 [2.2 – 4.4]		
	Moderate	(40 – 55 dB HL)	0.5 [0.1 – 1.0]		
	Unilateral		2.3 [1.3 – 3.3]	4.2 [3.7 – 4.7]	3.6 [2.52 – 4.8]
	Bilateral		1.5 [0.7 – 2.3]	2.0 [1.6 – 2.4]	6.5 [5.1 – 8.0]
Sensorineural	All in sample		0.3 [0 – 0.7]	1.0 [0.7 – 1.3	
	Slight	(16 – 25 dB HL)		0.6 [0.4 – 0.8]	
	Mild	(26 – 40 dB HL)	0.3 [0 – 0.7]	0.3 [0.2 – 0.4]	
	Moderate	(41 – 55 dB HL)		0.05 [0 – 0.1]	
	Unilateral		0.2 [0 – 0.5]		
	Bilateral		0.2 [0 – 0.5]		
Mixed	All in sample		0.5 [0.1 – 1.0]	3.5 [3.0 – 4.0]	
	Mild	(26 – 40 dB HL)	0.2 [0 – 0.5]		
	Moderate	(41 – 55 dB HL)	0.2 [0 – 0.5]		
	Moderately-severe	(56 – 70 dB HL)	0.2 [0 – 0.5]		
	Bilateral		0.5 [0.1 – 1.0]		

Driscoll et al. (2001) set out to establish test performance measures of transiently evoked otoacoustic emissions (TEOAEs) in grade one pupils in primary schools. They began by recruiting, on a volunteer basis, 940 children (mean age 6.2 years, age range 5.2 to 7.9 years) from 22 primary schools in Brisbane, Australia. All participating children were initially screened in their schools in a quiet room (ambient noise level ranged from 34 to 51 dB A) using otoscopy, pure tone audiometry and tympanometry. For the screening pure tone audiometry, each child was first presented with three consecutive presentations of 20 dB HL at each of the pure tone frequencies of 0.5, 1, 2 and 4 kHz. If the child failed to respond to these presentations at any of these frequencies, the child's hearing threshold was determined at that frequency using the Hughson-Westlake technique (Carhart & Jerger, 1959). If this threshold was greater than 25 dB HL, the child was deemed to have failed the screening pure tone audiometry assessment. For the screening tympanometry, each child was deemed to have failed if they showed type B or C tympanogram. Of the 940 children tested, 175 (18.6%) failed this initial screening [84 (8.9%) failed at screening pure tone audiometry, 168 (17.9%) failed at tympanometry, and an unreported number failed both].

Once Driscoll et al. (2001) had identified the children in their study who had failed the hearing screening, they invited these children to undergo a follow-up audiological assessment at a university-based audiology clinic in sound-treated assessment rooms. The child was deemed to fail full audiometric assessment if the average air conduction pure-tone thresholds at 0.5, 1 and 2 kHz were greater than 25 dB HL and/or air-bone conduction gap was greater than 15 dB HL. One hundred and twelve (64%) of the 168 children who failed the screening assessment attended the follow-up audiological assessment. Of these 112 children, 28 were found to have hearing loss on pure tone audiometry with or without normal tympanometry results (it is worth noting that a further 50 were found to have abnormal tympanometry in the presence of normal hearing thresholds ≤25 dB HL). Driscoll et al. (2001) then reported the types, degrees and lateralities of the hearing losses identified in the 28 children who were found to have hearing loss on pure tone audiometry.

Finally, to calculate the rates of hearing losses for all children in the Driscoll et al. (2001) study, the present researchers took the number of children reported by Driscoll et al. (2001) for each type, degree and laterality of hearing loss and then divided this number by the number of children who had returned to undergo a follow-up audiological assessment at the university-based audiology clinic. Each of these proportions was then used to calculate how many children would have presented with each type, degree and laterality of hearing loss had all 175 children who failed the screening assessment returned for the follow-up audiological assessment. This assumes that the proportions calculated from the 112 students who did return for a follow-up assessment would have been the same if all 175 children who had failed the screening had returned for a follow-up assessment. This assumption is a noted limitation of this review. These predicted numbers of children were then each divided by the total number (940) who had participated in the study to derive the final, predicted rates of hearing loss shown in Table 2. The reported rates of conductive, sensorineural and mixed hearing loss were 3.8%, 0.3% and 0.5%, respectively.

Cone et al. (2010) set out to describe the audiometric and clinical characteristics of children identified with a hearing loss. They began by targeting 7784 grade one (aged seven years) and grade five (aged 11 years) school children from 89 primary schools in Melbourne, Australia. These children were recruited on a volunteer basis. All participating children were initially screened in a portable, single-walled sound booth positioned in their schools using pure tone audiometry, whereby each child was first presented with three consecutive presentations of 15 dB HL at each of the pure tone frequencies of 0.5, 1, 2, 3, 4, 6 and 8 kHz. If the child failed to respond to these presentations at any of these frequencies, they were deemed to have failed the screening assessment and immediately proceeded to a full audiometric assessment including pure tone audiometry at the same test frequencies using the Hughson-Westlake technique (Carhart & Jerger, 1959) and tympanometry. The child was deemed to fail full audiometric assessment if the average air conduction pure-tone thresholds at 0.5, 1 and 2 kHz and 3, 4, 6 kHz were greater than 15 dB HL and/or air-bone conduction gap was greater than 10 dB HL. Seven hundred and fifty (12.0%) children failed the screening pure tone audiometry and immediately completed the follow-up audiometric assessment. Cone et al. (2010) then reported the types, degrees and lateralities of the hearing losses identified in the 750 children who completed the follow-up audiometric assessment.

To calculate the rates of hearing losses for all children in the Cone et al. (2010) study, the present researchers took the number of children reported by Cone et al. (2010) for each type, degree and laterality of hearing loss and then divided this number by the number of children who had participated in the study to derive the final, predicted rates of hearing loss shown in Table 2. The reported rates of conductive, sensorineural and mixed hearing loss were 6.2%, 2.7% and 3.5%, respectively.

Keogh et al. (2010) set out to determine the rate of conductive hearing loss in the primary school population of the Brisbane metropolitan and Sunshine Coast regions of Queensland, Australia. They began by recruiting, on a volunteer basis, 1071 grades one to four (mean age 7.7 years, age range 5.3 to 11.7 years) school children from 19 primary schools in these regions. All participating children were initially screened in their schools in a quiet room (ambient noise levels ranged from 30 to 50 dB A) using otoscopy, pure tone audiometry and tympanometry. For the screening pure tone audiometry, each child was first presented with three consecutive presentations of 20 dB HL at each of the pure tone frequencies of 0.5, 1, 2 and 4 kHz. If the child failed to respond to these presentations at any of these frequencies, their hearing threshold was determined at that frequency using the Hughson-Westlake technique (Carhart & Jerger 1959). If this threshold was >20 dB HL, then the child was deemed to have failed the screening pure tone audiometry assessment. For the screening tympanometry, each child was deemed to have failed if they showed tympanograms with peak tympanometric pressure outside of the range of +50 to -200 daPa, a static compliance outside the range of 0.17 to 1.0 mL, a tympanometric width outside the range of 90 to 180 daPa, and/or an external ear canal volume outside the range of 0.65 to 1.35 mL. One hundred and nine (10.2%) of the 1071 children failed the initial screening pure tine audiometry and were subsequently shown to have bilateral (70 children) or unilateral (39 children) conductive hearing loss. To calculate the rates of these conductive hearing losses for all children in the Keogh et al. (2010) study, the present researchers took the number of children reported by Keogh et al. (2010) for these losses and divided these numbers by the number of children who had participated in the study to derive the final, predicted rates of hearing loss shown in Table 2.

4.4.1. Limitations to the review

The criteria for normal hearing applied by the various studies included in this review differed too greatly to perform a meta-analysis, a problem that was exacerbated by some heterogeneity in how the studies progressed from screening to follow-up diagnostic assessment. None of the reviewed studies were prevalence studies per se with each having other specific aims (such as assessing the sensitivity of TEOAEs to a hearing loss). This saw sampling techniques limited to convenient rather than stratified, and participants limited by age (e.g., Driscoll et al., 2001) only assessed children in grade one) and region (the included studies were conducted in Brisbane, Melbourne and the Sunshine Coast regions of Australia only). These limitations were only partly mitigated by the large sample sizes achieved in each study.

4.5. Discussion

The present systematic review identified three potential estimates of the rate of hearing loss in primary school children in Australia. Driscoll, Kei and McPherson (2001) reported an overall rate of hearing loss of 4.7% [95% CI: 3.4% - 6.1%, n = 940] when normal hearing was defined as hearing thresholds ≤25 dB HL; Cone et al. (2010) reported a rate of 12.0% [95% CI: 11.2% - 12.8%, n = 6240] when normal hearing was defined as hearing thresholds ≤15 dB HL; and Keogh et al. (2010) reported a rate of 10.2% [95% CI: 8.4% - 12.0%, n = 1071] when normal hearing was defined as hearing thresholds ≤20 dB HL.

Estimates of the rates of type, degree and laterality of hearing loss in primary school children in Australia were more difficult to determine. Driscoll, Kei and McPherson (2001) reported the highest rate for mild, conductive hearing loss and lower rates for mixed and sensorineural hearing losses. The higher rate of conductive hearing loss was generally supported by similar data from Cone et al. (2010), and for Keogh et al. (2010) the lower rate of sensorineural hearing loss was supported by Cone et al. (2010) but the lower rate of mixed hearing loss was not supported by Cone et al. (2010). Reports on the rates of laterality were variable across Driscoll, Kei and McPherson (2001), Cone et al. (2010) and Keogh et al. (2010) for conductive hearing losses, were reported as being equal by Driscoll, Kei and McPherson (2001) for sensorineural hearing loss, and were under-reported for mixed hearing loss.

Table 3 shows the rates of hearing loss reported in the present review and a range of countries of high, upper-middle and lower-middle-income [where income was rated by the World Bank (2016)]. This table shows that the rates of hearing loss reported in this review for primary school children in Australia agree less with those reported in countries of high income and more with those reported in countries of lower-middle-income. This finding appears to be driven by the high rates of conductive hearing loss reported by Driscoll, Kei and McPherson (2001), Cone et al. (2010) and Keogh et al. (2010) in the Australian population. Possible reasons for this higher rate of conductive hearing loss are not obvious from the data reviewed.

Table 4.3. Rates (in percent) of hearing impairment reported in the present review and a range of countries of high, upper-middle and lower-middle-income, where income was rated by The World Bank. The 95% confidence intervals are shown in brackets.

Income	Country	Study	Sample Size	Defined Normal Hearing	Rate of hearing impairment (%) with 95% CI			
					Overall	Conductive	Sensorineural	Mixed
High	Australia	Driscoll et al. (2001)	960	≤25 dB HL	4.7 [3.4 – 6.0]	3.8 [2.6 – 5.0]	0.3 [0 – 0.7]	0.5 [0.1 – 1.0]
		Cone et al. (2010)	6240	≤15 dB HL	12.0 [11.2 – 12.8]	6.2 [5.6 – 6.8]	1.0 [0.8 – 1.3]	3.5 [3.0 – 4.0]
		Keogh et al. (2010)	1071	≤20 dB HL	10.2 [8.4 – 12.0]	10.2 [8.4 – 12.0]		
	Saudi Arabia	Al-Rowaily et al. (2012)	2574	≤20 dB HL	1.8 [1.3 – 2.3]	1.5 [1.0 – 2.0]	0.3 [0.1 – 0.5]	
	United States of America	Serpanos et al. (2007)	34979	≤20 dB HL	1.8 [1.7 – 1.9]	0.2 [0.2 – 0.3]	0.02 [0.01 – 0.03]	0.007 [0 – 0.02]
	Sweden	Darin et al. (1997)	86	≤20 dB HL	2 [0 – 5.0]	1.8 [0 – 4.6]	0.2 [0 – 1.1]	
	Finland	Mattila et al. (1986)	40824	≤20 dB HL	2.5 [2.4 – 2.7]	1.0 [0.9 – 1.1]	0.2 [0.16 – 0.24]	
Upper–Middle	China	Lu et al. (2011)	21427	≤20 dB HL	1.4 [1.2 – 1.6]	1.3 [1.2 – 1.5]	0.08 [0.04 – 0.12]	
	Iran	Sarafraz et al. (2011)	785	≤25 dB HL	9.8 [7.7 – 11.9]	5.9 [4.3 – 7.6]	3.9 [2.6 – 5.3]	
Lower–Middle	India	Rao et al. (2002)	855	≤25 dB HL	11.9 [9.7 – 14.1]	9.7 [7.7 – 11.7]		0.4 [0 – 0.8]
	Egypt	Taha et al. (2010)	555	≤20 dB HL	20.9 [17.5 – 24.3]	15.6 [12.6 – 18.6]	5.3 [3.4 – 7.2]	

4.5.1 Implications for public health

The present systematic review's suggestion of higher rates of conductive hearing loss in primary school children in Australia warrants further consideration as conductive losses can be detected and managed using existing health resources in Australia (Gunasekera, O'Connor, Vijayasekaran, & Del Mar, 2009). Such detection and management could mitigate the consequences of such hearing losses which can include delayed language development, academic underachievement, social isolation, higher risk of injuries and increased poverty (Olusanya et al., 2014; WHO, 2016). This would also be consistent with the WHO's recommendation that all countries strengthen child healthcare programs related to hearing (Olusanya et al., 2014; WHO, 2016). It is acknowledged, however, that some conductive hearing loss will persist in paediatric populations despite adequate access to healthcare services.

The use of different criteria to define the presence of hearing loss and its degrees in prevalence and rate studies also needs to be addressed. Currently, the American Speech-Language-Hearing Association (ASHA, 1997), the American Academy of Audiology (AAA, 2011) and the British Society of Audiology (BSA, 2011) all recommend using a hearing threshold of ≤20 dB HL as normal hearing in screening audiometry in children. The European consensus is that hearing loss greater than 20 dB HL for each frequency between 250 and 8000 Hz in both ears may have adverse effects on the development of communication skills, cognitive development and academic achievement (Skarzynski & Piotrowska, 2012; Iliadou et al., 2017). This review found that while most countries adhere to this guideline, ≤ 25 dB HL and ≤ 15 dB HL are still being used as a hearing threshold for normal hearing in screening audiometry in children. In future, researchers should aim to use hearing thresholds ≤ 20 dB HL as normal hearing in paediatric populations. This would allow for a more consistent approach to assessment and intervention in school-aged children with hearing loss. Alternatively, the issue of defining normal hearing thresholds in children could be addressed by using population distributions of hearing thresholds obtained from children rather than adults (as is currently the case in standards such as AS ISO 7029-2003 [R2014] (Standards Australia, 2014).

Finally, any report of prevalence or rates of hearing loss in primary school children should be based on diagnostic hearing test results only. This is because hearing screening results are likely to overestimate the prevalence or rate of hearing loss due to the use of inferior protocols and non-sound treated environments (E. J. Taylor & Emanuel, 2013). The potential for such effects was seen in Driscoll et al. (2001) where only 25% of children who failed the hearing screening in a school room went on to receive a diagnosis of hearing loss on the follow-up/diagnostic assessment in a sound-treated room. In contrast, the use of a sound-treated room by Cone et al. (2010) for both their hearing screening and follow-up/diagnostic assessment could explain why 100% of their children failed both the hearing screening and follow-up/diagnostic assessment. A further consideration in this regard is the time delay between screening and follow-up/diagnostic assessments. While this time was not stated by Driscoll et al. (2001), the immediate progression from screening to follow-up assessments by Cone et al. (2010) could also have contributed to their 100% finding.

4.6. Conclusion

The present systematic review provides a first estimate of the potential rate of hearing loss in primary school-aged children in Australia. This estimate was affected by disparities in definitions of what constitutes normal hearing thresholds in children and the use of population distributions of hearing thresholds in adults to define normal hearing thresholds in children. The present review also highlighted the need to base any reporting of rates of hearing loss on the results of follow-up diagnostic hearing assessments and not on hearing screening.

The rates of hearing loss in primary school children in Australia appeared to be higher than those reported in other high-income countries, mostly as a result of a higher rate of conductive hearing loss. This warrants further consideration as conductive losses can be managed using existing health resources in Australia.

These conclusions are limited primarily by the fact that the studies reviewed were not conducted with the intention of determining rates of hearing loss in the general Australian, school-aged population. Other limitations include the lack of random and/or stratified sampling and variations among studies regarding the criteria used to define normal hearing, the ages of the participants, the regions from which the participants were sampled, and the testing environments. These limitations identified the need for a large-scale prevalence study of hearing loss on the primary school child population to be conducted in Australia.

Chapter 5: Hearing and Auditory Processing Abilities in Primary School Children with Learning Difficulties

This chapter was originally published in the peer-reviewed journal *Ear and Hearing* (Choi, Kei, & Wilson, 2019). The content of this chapter is inserted as published, with the exception of formatting changes to headings, tables, figures and references to maintain consistency throughout the thesis.

5.1. Abstract

Objective: This study aimed to investigate hearing and auditory processing ability in primary school children with LD.

Design: A non-randomised, cross-sectional single measure research design was used. A total of 486 children, aged 7.7 to 10.8 years and attending years three and four in six primary schools, were classified as having an LD (n = 67) or being typically developing (TD, n = 419). This classification was based on a Learning Score generated from their school report results and National Assessment Program – Literacy and Numeracy (NAPLAN) scores. All children attempted a conventional hearing assessment (CHA) involving pure-tone audiometry, tympanometry, acoustic reflexes (AR), and otoacoustic emissions (OAE). Children returning pure-tone audiometry results within normal limits also attempted an auditory processing assessment (APA) including dichotic digits (DD) and low-pass filtered speech (LPFS) tests.

Results: In children with LD, 21/67 (31.4%) failed the CHA, 20/58 (34.5%) failed the APA, and 32/58 (55.2%) failed the overall hearing assessment (OHA) if they failed either or both CHA and APA. In comparison, in TD children, 55/413 (13.3%) failed the CHA, 52/314 (16.6%) failed the APA and 86/313 (27.5%) failed the OHA. Proportionally, children with LD were 2.4 times more likely than TD children to fail the CHA, 2.1 times more likely to fail the APA and 2.0 times more likely to fail the OHA. In children who had completed the OHA, multiple linear regressions showed average AR thresholds, DD scores and LPFS scores explained 13 to 18% of the variance in the Learning Score.

Conclusion: The potential for hearing impairment should be investigated in children with LD. These investigations should begin with CHA; and for children returning normal hearing thresholds, they should continue with measures of AR, DD and LPFS, to ensure these children receive the appropriate auditory support needed to enhance their learning.

5.2. Introduction

Children who experience poor academic performance at school have been described as having LD (Elkins, 2002; Louden et al., 2000). These children may require additional educational support in view of their poor academic achievement in the early schooling, potentially worsening in later schooling and contributing to poor social, emotional and educational development (Hill et al., 1998; Rohl et al., 2000).

The term *LD* has been used in this study to describe children who exhibit developmental and academic problems in the absence of a diagnosed intellectual impairment (an IQ less than 75) (Schalock, 2012). It is noted in the literature that the term LD has been used alongside the term *learning disability*. In Australia, the term LD was first used by the Select Parliamentary Committee of the Australian Government (Cadman, 1976) to describe students whose learning needs were not adequately met. In this context, LD was used as a generic term that included low achievers who exhibited developmental and academic problems. In contrast, learning disability is restricted to students whose limitation in learning may have stemmed from a diagnosed disability or impairment such as hearing, visual or intellectual impairments (Ashman, 2005; Elkins, 1983; National Health and Medical Research Council [NHMRC], 1990; Westwood, 2003). This argument was recently extended to define children with LD as having the potential to achieve at age-appropriate levels with adequate instruction and intervention, while those with a learning disability would not (Australian Curriculum Assessment and Reporting Authority [ACARA], 2017; Australian Federation of The Specific Learning Difficulties Association [AUSPELD], 2014).

In Australia, children with LD have been identified through both formal (involving standardised tests) and informal methods (van Kraayenoord & Elkins, 2004). Formally, the most widely used test is the National Assessment Program – Literacy and Numeracy (NAPLAN). Since 2008, every year on the same day, all Australian primary school students in years three and five complete tests of reading, writing, language conventions (spelling, grammar and punctuation) and numeracy. Each child's score on each skill is expressed as a number between one and 10 (to one decimal place) with group statistics provided by the Australian Curriculum Reporting Authority (ACARA, 2017). The raw scores are then converted to z-scores for comparison purposes. While the NAPLAN is deemed a valid and reliable national assessment of literacy and numeracy in Australia, it remains a standardised test that has been criticised for its inability to compare individual scores across schools and regions (Thompson et al., 2018). Informally, classroom teachers in Australia monitor students' progress to identify those who are falling behind in some subject areas. The results of this monitoring over a period of time is typically presented as a school report at the end of each school semester. While susceptible to teacher and school bias, these school reports do provide longitudinal observation and monitoring of a child's academic progress rather than offering a snapshot of standardised test result such as NAPLAN. These two assessments complement each other although they are not always in agreement.

Reports of the prevalence of LD in children in Australia range from 6 to 30% (Andrews, Elkins, Berry, & Burge, 1979; Rohl et al., 2000). Such reports are challenged by LD not being a formal diagnosis in Australia. (However, different regions in Australia recognise different specific impairment areas that attract public funding support. For example, in the State of Queensland, these areas are *Autism Spectrum Disorder*, *hearing impairment*, *intellectual disability*, *physical impairment*, *speech-language impairment*, and *vision impairment*.) These estimates are thought to be conservative as many children continue to remain unidentified (Watson & Boman, 2005). An accurate estimate of prevalence is particularly difficult as children with LD form a heterogeneous group with a wide variety of characteristics and abilities in a range of skills (Twomey, 2006).

Despite differences in definitions, scholars have generally reached some consensus regarding the characteristics typical of students with LD. The most prevalent area of concern for students with LD is reading ability (van Kraayenoord, 2005; Westwood, 2003), followed by written language and numeracy (van Kraayenoord, 2005; van Kraayenoord & Elkins, 2004). In general, children with LD are inactive and inefficient learners, who are often off-task and easily distracted (Ashman & Elkins, 2002; Westwood, 2004). Such children are often unable to integrate prior knowledge and their own experiences into learning. These factors can result in inferior scholastic attainment and development of poor self-esteem and socio-emotional behaviour (Ashman & Elkins, 2002; Treuen et al., 2000; Westwood, 2004).

Many factors can influence a child's learning at school, such as inadequate classroom environment, emotional or behaviour problems or sensory impairment of vision or hearing (Chan, 1998; Cheng, 1998; Westwood, 2003). In particular, good hearing is essential for children's learning in the classroom (Heward, 2003). Research suggests that students spend at least 45% of their classroom learning activities that require listening (Berg, 1993) and 45 to 75% of their time in the classroom comprehending their teachers' and classmates' speech (Rosenberg et al., 1999). Given that classrooms are generally noisy places, children with LD with hearing impairments are at risk of having increased difficulty in discriminating teachers' and classmates' voices from other sources of dynamic classroom noise (Mealings, Buchholz, Demuth, & Dillon, 2015). This could place children with LD who also have hearing problems at even greater risk of falling behind academically at school.

Hearing impairment can include loss of hearing sensitivity and/or impaired auditory processing (AP). Loss of hearing sensitivity is often referred to as a *hearing loss*, the prevalence of which is estimated to be between 3.4 and 12.8% in Australian school-aged children (Choi et al., 2016). Impaired AP is less well defined with causes being much debated (W. J. Wilson & Arnott, 2012). No prevalence data are available for impaired AP in Australia but prevalence estimates for auditory processing disorder in school-aged children in the United States are between 2 and 3% (Chermak & Musiek, 1997).

Children with loss of hearing sensitivity and/or impaired AP often show behaviours similar to those reported in children with LD. These behaviours can include difficulty comprehending speech in competing or reverberant environments, requests for repetition of information, misunderstanding messages, delays in responding and inconsistent or inappropriate responses to oral instructions, difficulty following complex auditory directions, difficulty with sound localisation, inattentiveness, distractibility, and literacy difficulties (American Speech-Language-Hearing Association [ASHA], 2005).

There are similarities in learning behaviours observed in children with hearing impairment and children with LD, which suggests that the two could be related. While such suggestions have been confounded by the inconsistent use of LD versus learning disability (discussed above), children showing poor academic performance are often suspected of having a hearing loss or impaired AP because of their poor communication and listening skills and auditory behaviour (e.g., Kotby, Tawfik, Aziz, & Taha, 2008; Mason & Mason, 2007; Smoski, Brunt, & Tannahill, 1992). Hearing loss alone can have a detrimental effect on learning as it can result in delayed speech development and communication difficulties (Wake et al., 2004). In a speech comprehension noise task, children with bilateral mild conductive hearing loss display significantly worse performance compared to normal hearing or unilaterally hearing-impaired peers (Keogh et al., 2010). Children with mild to moderate hearing loss achieve one to four grades lower than their normal hearing peers, while children with more severe degrees of hearing loss fall behind even further, despite early identification via newborn hearing screening and evidence-based treatment (McFadden & Pittman, 2008). One possible reason for such disparity in educational outcomes with children with hearing loss could be due to the inconsistent use of hearing devices in children that impacts on language development (Walker et al., 2015). Impaired AP can also have a detrimental effect on learning. Children with impaired AP often display reading deficits (e.g., Bishop & Snowling, 2004; Ramus, 2003; Sharma et al., 2009), cognitive deficits (e.g., Moore et al., 2010; Tomlin et al., 2015), literacy and language deficits (e.g., Halliday et al., 2017; Tallal & Gaab, 2006) and poorer academic achievement (e.g., Heine, Slone, & Wilson, 2016). Such findings form part of the psychoeducational approach to impaired AP, which J. Jerger (2009) describes as being built on the premise that a set of primary auditory abilities exist that are likely to affect auditory behaviour and are important for learning, and which support further investigations into LD and auditory processing, particularly in the school-aged population.

In view of the possible resemblance in learning behaviours observed in children with impaired hearing/AP and children with LD, the present study aimed to investigate hearing and auditory processing ability in primary school children with learning difficulties (LD). Two research questions were considered: (1) Do children with LD have a higher rate of impaired hearing/AP compared to TD children?; and (2) To what degree is the variance in learning explained by hearing/AP ability?

5.3. Materials and Methods

5.3.1. Participants

This study adopted a non-randomised, cross-sectional single measure research design to investigate hearing and auditory processing in primary school children. Ethical clearance to conduct this research study was given by Education Queensland and the Medical Research and Ethics Committee of The University of Queensland. Informed consent was received from parents or caregivers to undertake this research. On the day of testing, informed consent from the child was received to undertake this research.

To be recruited into the study, children had to be attending a mainstream state school (equivalent to an elementary school in the USA) in the greater Brisbane area and have no diagnoses of intellectual impairment as confirmed by parental report and school records. Children with other diagnoses such as attention deficit hyperactivity disorder (ADHD), dyslexia, high functioning autism spectrum disorder (ASD) were included in this study as these conditions exist in the general school population and are not exclusive to children with LD, and because of this study's treatment of *LD* as a generic term describing children who exhibit developmental and academic problems in the absence of diagnosed intellectual impairment/s.

A total of 502 children in grades three and four in six state schools participated in the study. Five schools were situated in metropolitan Brisbane and one in the urban region of Ipswich (located 40 km west of Brisbane). This sample of children, though small in size, was deemed to be reasonably representative of children in the state school system in South-East Queensland, Australia. It is acknowledged that this sample did not include children studying in Catholic or independent primary schools.

Years three and four represent the fourth and fifth years of formal schooling, respectively, for children in the state of Queensland, Australia, during which nationally standardised, uniform academic achievement results are available for all students (Education Queensland, 2017). All children attended schools where the only medium of instruction was English. Table 1 shows the demographic data of the participants. Sixteen children were excluded from data analysis due to missing learning outcome measures. This resulted in the final sample of 486 participants, with a mean age of 8.87 ± 0.67 years (range = 7.67-10.75 years).

Table 5.1. Demographic characteristics of the participants (n=486)

Demographic Variable	N (%) – All participants	N (%) - LD	N (%) - TD
Male/Female	236 (48.6)/250 (51.4)	42 (62.7)/25 (37.3)	208 (49.6)/ 211 (50.4)
Caucasian/Non-Caucasian	299 (77.0)/89 (22.9)	42 (85.7)/7 (14.3)	259 (75.7)/ 82 (24.3)
Speaking other languages in addition to English	79 (17.2)	8 (13.1)	71 (17.9)
Parental report of other conditions	64 (13.9)	15 (22.1)	48 (13.1)
Otitis media	13 (20.3)	2 (2.9)	10 (2.5)
ADHD	10 (15.6)	3 (4.4)	8 (2.0)
Dyslexia	6 (9.4)	2 (2.9)	2 (0.5)
High functioning ASD	10 (15.6)	3 (4.4)	6 (1.5)
Receiving speech/language therapy	3 (4.7)	0 (0.0)	2 (0.5)
Vision impairment	3 (4.7)	0 (0.0)	3 (0.8)
Other	19 (29.7)	4 (5.9)	17 (4.3)
Parental concern in reading/writing/numeracy	78 (17.3)/116 (25.7)/76 (16.9)	30 (50.0)/33 (55.0)/26 (43.3)	48 (11.5)/83 (19.8)/ 50 (11.9)
Parental concern in hearing	81 (18.0)	12 (20.0)	69 (16.5)

5.3.2. Learning Outcome Measures

5.3.2.1. Learning Ability

A measure of the child's learning ability was obtained using a combination of their school report and scores on the National Assessment Program – Literacy and Numeracy (NAPLAN) assessment. The use of both school report and NAPLAN scores was thought to mitigate potential bias of using school reports alone.

5.3.2.2. School Report

Written school reports (SR) in the area of English (SE) and Mathematics (SM) were also collected (if available). In Queensland, a school report is issued to parents/caregivers biannually at the end of each semester. The school report shows a student's achievement for each learning area/subject studied in the reporting period, as well as student's effort and behaviour. In years three and four students, the reporting scale ranges from A to E, where 'A' is the highest achieving grade (Education Queensland, 2017). For further analysis of learning ability in the present study, this scale was converted to a numerical scale ranging from 1 to 5, with '1' being the lowest grade E and the '5' being the highest grade A.

5.3.2.3. NAPLAN

NAPLAN results were obtained from the participating schools. The NAPLAN was introduced into Australian primary schools in 2008. Every year, all primary school students in years three and five are assessed in four domains: Reading (NR), Writing (NW), Language Conventions [Spelling (NS), Grammar & Punctuation (NGP)] and Numeracy (NN). The NAPLAN assessment scale is divided into bands of 1 to 10, with band '1' being the lowest. The National Minimum Standards recommends, for each year level, a minimum standard (band) out of a range of bands representing a wide range of the typical skills demonstrated by the students. For instance, the assessment scale for year three students ranges from band 1 to band 6, with band 3 being the minimum standard recommended by the National Minimum Standards. Group statistics for the comparison of performance are also available from the ACARA (2017), allowing results to be converted into z-scores. The child's score is expressed as a number between 1 and 10 to one decimal place, which demonstrates within which band the child's score fell, and the decimal point indicates the child's position within the band.

5.3.2.4. Missing School Report and NAPLAN Scores

Sixty (12.3%) of the 486 children had some missing school report (SR) English (SE) and/or mathematics (SM) scores, or some missing NAPLAN reading (NR), writing (NW), spelling (NS), grammar and punctuation (NGP), and/or numeracy (NN) scores. Six children were missing one NAPLAN score, three children were missing two NAPLAN scores, seven children were missing four NAPLAN scores, 33 children were missing five NAPLAN scores, two children were missing one SR score and three children were missing two SR scores. A Pearson's product moment correlation analysis returned strong correlations amongst all SR and NAPLAN scores (r values ranging from 0.55 to 0.75, $p \leq 0.01$). In light of these results, missing SR or NAPLAN scores were estimated by scores generated from other SR or NAPLAN scores. The estimating process proceeded as per the descriptions below.

For the two children missing one school report (SR) score (SE or SM), their missing SR score was estimated by the remaining SR score. For the three children missing both SR scores (SE and SM), their SR scores were estimated as follows: (1) their report card SE score was estimated by taking the average of their NAPLAN NR, NW, NS and NGP scores (rounded to the nearest whole value) as these scores were related to literacy, with the following corrections for the NAPLAN's 6-item scoring versus the SR's 5-item scoring: NAPLAN score 1 = SR score 1, NAPLAN score 2 = SR score 2, NAPLAN scores 3 and 4 = SR score 3, NAPLAN score 5 = SR score 4; and NAPLAN score 6 = SR score 5; and (2) their report card SM score was estimated by their NAPLAN NN score (as this score was related to numeracy) with the same corrections as listed above.

For the 16 children missing up to four out of five NAPLAN scores, their missing NAPLAN scores were estimated by taking the average of their remaining NAPLAN scores (rounded to the nearest whole value). For the 33 children missing all NAPLAN scores, their NAPLAN scores were replaced as follows: (1) NAPLAN NR, NW, NS and NGP scores were estimated by the report card SE score (as this score was related to literacy) with the following corrections for the SE's five-item scoring versus the NAPLAN's six-item scoring: SE score 1 or 2 = NAPLAN score 2, SE score 3 = NAPLAN score 4, SE score 4 = NAPLAN score 5, SE score 5 = NAPLAN score 6; and (2) their NN scores was estimated by their report card SM score (as this score was related to numeracy) with the same corrections as listed above.

5.3.2.5. Factor Analysis to Generate a Learning Score

To assess the learning capability of each student, the present study generated a learning score derived from the SR and NAPLAN data. A maximum likelihood factor analysis using varimax rotation was carried out on the SR and NAPLAN results of all participating children. This analysis returned a one-factor model with an Eigenvalue of 4.72 that explained 67% of the model variance. No further factors with an Eigenvalue >1.0 were identified. Table 2 shows the factor loadings for this model. The learning score for each child was calculated by multiplying each child's SR and NAPLAN scores by the matching factor loading scores and summing these products.

Table 5.2. Factor loading of seven academic attainment variables in the factor analysis.

Variable	SE	SM	NR	NW	NS	NGP	NN
Factor Loading	.834	.820	.838	.771	.826	.839	.817

Note: SE = school report card English; SM = school report card Mathematics; NR = NAPLAN reading; NW = NAPLAN writing; NS = NAPLAN spelling; NGP = NAPLAN grammar and punctuation; NN = NAPLAN numeracy.

5.3.2.6. Learning Difficulty Classification

To classify children as having an LD or not having an LD (the latter group being typically developing (TD)), it was necessary to assess children's learning ability by their learning score. A cut-off learning score was calculated by determining the learning score that would be obtained by a child who scored values of 3 for all SR and NAPLAN measures. Using this approach, the cut-off learning score was 17.24. There were 67 children with a score less than 17.24 being classified as LD. The remaining 419 children with a score of 17.24 or above were classified as TD.

The above approach to classifying children was chosen to reflect the present authors' decision to use LD as a generic term to describe children who were significantly lagging behind their peers in scholastic attainment. To this end, a cut-off score of 3 (out of 5 for the SR and out of 6 for the NAPLAN) was considered a reasonable and justifiable compromise between SR and NAPLAN assessments. It served to place a child's academic attainment below the minimum pass bracket for those measures, with a score of 3 on the NAPLAN measures and band 3 on SR representing the National Minimum Standard. This approach was also consistent with the descriptions of LD offered in the literature with Elkins's (1983) argument that LD should be used as a generic term that includes low achievers, the NHMRC (1990) description of LD being a generic term to describe children who exhibit developmental and academic problems, Ashman (2005) and Westwood (2003) reporting that LD is generally used with reference to children who experience particular difficulties in achieving at school, and AUSPELD (2014) and the Australian Government (2017) defining children with LD as having the potential to achieve at age-appropriate levels with adequate instruction and intervention.

The classification of children into the LD or TD groups using the learning score described above was compared to the classification of these children by teachers' opinion (data not shown here). These opinions were the verbal responses of 'yes' or 'no' from the teachers to the researchers directly asking them, "Are you concerned about this child's learning?" Agreement was 70% between children classified as having LD using the learning score and teachers' opinion and 82% between children classified as TD using the learning score and teachers' opinion.

Finally, 16 out of 61 (26%) of the parents of children classified as LD and 48 out of 398 (12%) of the parents of children classified as TD reported that their child had a medical diagnosis other than *intellectual disability* (Table 1). The reported presence of such diagnoses was not investigated further due to the diagnoses not being confirmed beyond parental report and because of the present study's use of LD as a generic term describing children who exhibit developmental and academic problems in the absence of diagnosed intellectual impairment.

5.3.3. Overview of Audiometric Test Protocol

Testing was conducted by an Audiology Australia accredited audiologist with the assistance of students completing their Master of Audiology Studies program. These students had completed between one and three semesters of the four-semester audiology program and an eight-hour auditory processing disorder training module, and were closely supervised by the accredited audiologist.

Participants were tested individually in a quiet room within each school during school hours (approximately from 0830 to 1500) from May 2016 to July 2017. Testing was suspended from mid-December 2016 to mid-February 2017 due to summer break. Both ears were tested in no particular order. The entire test battery that included both conventional hearing assessment (CHA) and auditory processing assessment (APA) took approximately one hour (including a short break between CHA and APA testing) to complete. Ambient noise levels ranged from 38.5 to 51.4 dBA (mean = 45.5 dBA, SD = 2.4). Ambient noise levels were measured twice throughout the day of testing using the 'SLA Lite' mobile phone application on an iPhone 6s that had been calibrated against a Brüel & Kjær (B&K) type 2250 sound level meter. Testing was paused on a few occasions where ambient noise level exceeded 50 dBA.

5.3.3.1. Conventional hearing assessment (CHA)

All participating children underwent a CHA. Not all children completed all tests within this assessment due to occasions of equipment fault or children being unwilling to complete parts of the assessment.

5.3.3.1.1. Pure tone audiometry

Pure tone audiometry utilised a Madsen Micromate 304 fitted with ME70 noise excluding headphones. The screening audiometer was calibrated for air conduction testing to AS ISO 389.1-2007 (Standards Australia, 2007). Pure tones of frequencies 0.5, 1.0, 2.0 and 4.0 kHz was presented to each ear at an intensity level of 20 dB HL. If a child failed to respond twice to three consecutive presentations at any frequency at 20 dB HL, the threshold for that frequency would be determined using the Hughson-Westlake procedure (Carhart & Jerger, 1959). Thresholds greater than 20 dB HL at any frequency in either ear were considered a fail result on pure tone audiometry.

5.3.3.1.2. Tympanometry

Tympanometry was performed using a Titan Middle Ear Analyser calibrated according to IEC 60645-5 (2004) (Standards Australia, 2004). Calibration of this analyser using a 2cc cavity was performed daily before testing began. A standard probe tone of 226 Hz at 85 dB SPL was delivered to each participant's ear while the pressure in the external auditory canal was varied from +200 daPa to -400 daPa at a pump speed of 400 daPa/s. The following data were collected from the tympanogram: ear canal volume (ECV), static compliance (SC) and tympanometic peak pressure (TPP). A pass in tympanometry was awarded when the tympanogram was characterised by a SC of 0.3 – 1.6 ml (J. Jerger, Jerger, & Mauldin, 1972), an ECV of 0.9 – 2.0 ml (Wiley et al., 1996) and TPP between +50 and -100 daPa (J. Jerger, 1970). Any results outside of these limits were considered to indicate a fail result on tympanometry.

5.3.3.1.3. Acoustic Reflex Testing (AR)

Acoustic reflex testing was included in the test battery of the current study because it is a reliable measure to detect middle ear dysfunction and retrocochlear pathology (Wiley & Fowler, 1997). Acoustic reflex testing was performed using the Titan Middle Ear Analyser immediately after tympanometry with the ear canal pressure maintained at TPP to maximise the possibility of obtaining a response. Pure tones of 1 and 2 kHz were delivered separately and ipsilaterally to the participant's test ear, starting at 80 dB HL and increasing in 5 dB steps up to a maximum level of 100 dB HL. Pure tone stimuli of 1 and 2 kHz were used because of their reliability and validity in eliciting stapedial reflexes (ASHA, 1979). The AR threshold was defined as the lowest level of a sound stimulus that elicits an acoustic reflex response, i.e., a measurable change in compliance of 0.02 ml (Gelfand, 2017). For the purpose of statistical analyses, no acoustic reflex response at 100 dB HL was considered a fail and assigned a value of 105 dB HL for analysis purposes.

5.3.3.1.4. Transient-Evoked Otoacoustic Emissions (OAE)

OAE testing was performed using the Quickscreen protocol of the ILO88 Otodynamics Analyser (ver. 5.6Y). Calibration of the probe was performed weekly or as necessary according to the manufacture's specifications. The adequacy of probe fit was inspected prior to the commencement of data acquisition. Non-linear clicks of 80.0 µsec duration at an average stimulus level of 83 dB peak SPL were delivered to each participant's ear. The signal-to-noise ratio (SNR) of the OAE at 1.0, 1.4, 2.0, 2.8 and 4.0 kHz was recorded. SNR values of less than 3 dB at 2 or more test frequencies in either ear was considered to indicate a fail result.

5.3.3.2. Auditory processing assessment (APA)

All participating children who passed pure tone audiometry within the CHA also underwent a limited APA. Passing pure tone audiometry with or without passing tympanometry, ARs or OAEs was deemed sufficient to progress to the limited APA on the basis these children should have adequate hearing to respond to the suprathreshold stimuli of the APA. Two tests of AP were chosen: dichotic digits (DD) and low-pass filtered speech (LPFS).

The DD test was chosen due to its measure of a child's ability to process all components of a dichotic stimulus (often referred to as *binaural integration*), its sensitivity to APD, its sensitivity and specificity to lesions of the auditory nervous system, its listing as one of two minimum tests for assessing AP, and its widespread use in AP test batteries (AAA, 2010; ASHA, 2005; J. Jerger & Musiek, 2000; Musiek et al., 2011). Furthermore, Weihing et al. (2015) reported that children with APD appeared to have greater difficulty in a dichotic test compared to those without the disorder. Moreover, higher failure rate was reported in the DD test in school-aged children with APD (Weihing et al., 2015; W. J. Wilson & Arnott, 2013).

The LPFS test was chosen due to its face validity as a measure of speech reception ability to decode degraded auditory signals (often referred to as *monaural low redundancy*), an auditory skill commonly proposed as being important in typical classroom settings, despite the LPFS test being reported as having lower sensitivity to APD and lower sensitivity and specificity to lesions of the auditory nervous system (AAA, 2010; ASHA, 2005; Bellis, 2003; Bellis & Ferre, 1999; Musiek et al., 2011). Besides, high failure rates were reported in the LPFS test in school-aged children with APD (Weihing et al., 2015; W. J. Wilson & Arnott, 2013). Not all children completed all tests within the APA due to occasions of equipment fault or children unwilling to complete parts of the assessment.

5.3.3.2.1. Dichotic Digits (DD) Test

DD testing was conducted using a personal computer installed with the R. H. Wilson and Strouse (1998) recording of the two-pair dichotic digits test. This test consisted of 25 sets of two numbers (1-10, excluding 7) spoken by a male speaker. The numbers were presented in pairs with each number within each pair presented to a different ear simultaneously via ER-3A insert earphones (Wilber, Kruger, & Killion, 1988). Children were instructed to listen to both pairs of digits and to repeat all numbers immediately after stimulus presentation (i.e., to repeat all four numbers presented). Scoring was based on the number of correctly repeated numbers regardless of the order of the presentation of the four numbers. Children were presented with the first five sets of stimuli for practice and the remaining 20 sets for scoring. All stimuli were presented at 50 dB HL as determined by the peak level produced when playing the stimuli through the earphones. The calibration of the stimulus level was performed on an artificial ear (B&K type 4153 containing a B&K type 4144 1″ pressure-field microphone) coupled to the microphone of a B&K sound level meter Type 2250 Hand-held Analyser (class 1) set to record on a fast (0.125 s) setting. Percentage correct scores less than age appropriate normative data for DD testing provided by Bellis (2003) were considered to indicate a fail on DD testing.

5.3.3.2.2. Low-Pass Filtered Speech (LPFS)

The LPFS test was performed using the same computer and earphones used for DD testing. The speech stimuli were the AUDiTEC of St Louis recording of the NU-6 Wordlist No. 1 (50 monosyllabic words) spoken by a male speaker and low-pass filtered at a cut-off frequency of 1000 Hz. Twenty-five words of this list were presented at 50 dB HL to each ear of each child (order randomised), who was instructed to repeat each word. Scoring was based on the number of words correctly repeated and a percentage correct score was calculated. If the percentage score was less than the age appropriate normative data for LPFS testing provided by (Bellis, 2003), a fail on LPFS testing was indicated.

5.3.3.3. Overall hearing assessment (OHA)

All participating children who completed both the CHA and APA assessments were considered to have completed an OHA.

5.3.3.3.1. Hearing assessment outcomes

A pass in CHA was awarded if the child passed all tests in both ears in the CHA (pure tone audiometry, tympanometry, AR and OAE). A pass in APA was awarded if the child passed all tests in both ears in the APA (DD and LPFS). A pass in overall hearing assessments (OHA) was awarded if the child was awarded a pass in both the CHA and APA assessments.

5.4. Results

Figure 1 shows the percentage of LD and TD children who failed individual tests in the CHA and APA in either ear (remembering that children who failed pure tone audiometry in the CHA did not proceed to the APA). In children with LD, 3/67 (4.5%) failed pure tone audiometry, 12/67 (18%) failed tympanometry, 14/67 (21%) failed AR, 13/63 (20.6%) failed OAE, 14/57 (24.6%) failed DD and 11/58 (19%) failed LPFS. In TD children, 4/419 (1%) failed pure tone audiometry, 26/414 (6.3%) failed tympanometry, 28/414 (6.8%) failed AR, 18/332 (5.4%) failed OAE, 36/312 (11.5%) failed DD and 25/313 (8.0%) failed LPFS.

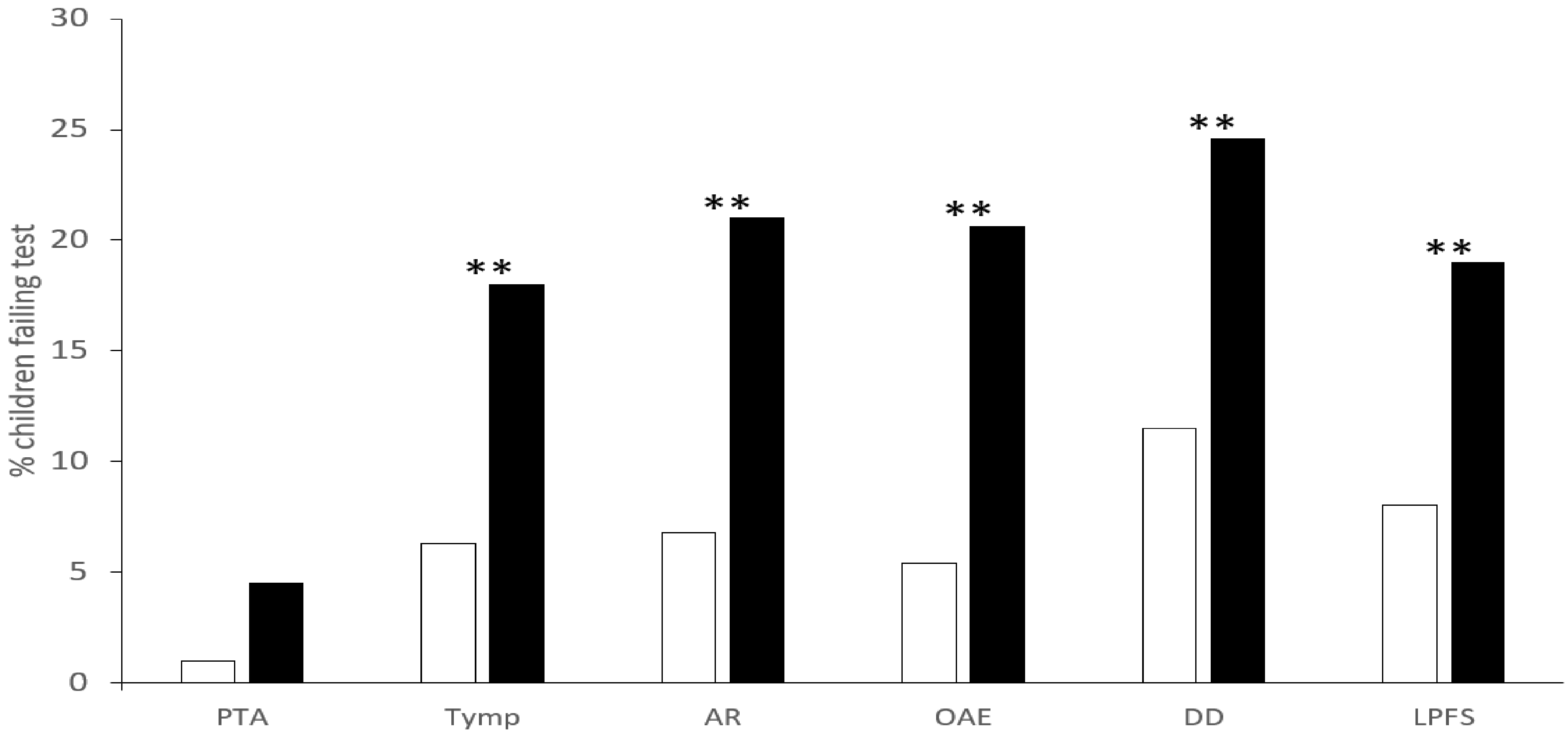

Figure 5.1. Percentages (%) of LD and TD children who failed individual tests in the CHA and AHA in either ear. LD children's results are represented by black bars.

Note: PTAAV = pure tone average, Tymp = tympanometry results, AR = acoustic reflex average results, OAE = otoacoustic emissions average results, DD = dichotic digits scores, LPFS = low-pass filtered speech scores, ** = significant $\chi 2$ test results with $p < 0.05$.

Of the seven children who failed pure tone audiometry, the three children with LD returned one mild loss at 500 Hz and 1000 Hz bilaterally; one mild, flat loss in the right ear; and one mild loss at 4000 Hz bilaterally; and the four TD children returned one mild to moderate flat loss bilaterally; one mild, flat loss in the right ear; one mild, flat loss in the right ear and mild loss at 500 Hz only in the left ear; and one mild loss at 500 Hz only in the right ear. All seven children showed evidence of middle ear dysfunction in the form of failed tympanograms and/or absent acoustics reflexes, except for one child (TD) who exhibited evidence of excessive wax build-up in his external auditory canals.

Results of Pearson Chi-squared tests showed significant differences in the failure rates in children with LD versus TD children for tympanometry (χ^2 (1, N = 481) = 10.72, $p < .05$), AR (χ^2 (1, N = 481) = 14.45, $p < .05$), OAE (χ^2 (1, N = 395) = 16.95, $p < .05$), DD (χ^2 (1, N = 371) = 6.98, $p < .05$) and LPFS (χ^2 (1, N = 371) = 6.73, $p < .05$). The difference in failure rates between children with LD versus TD children for pure tone audiometry did not reach statistical significance at the 0.05 level <<χ2 (1, N = 486) = 5.10, p = .06 [Fishers exact]>>. Overall, children with LD were 4.5 times more likely than TD children to fail pure tone audiometry, 2.9 times more likely to fail tympanometry, 3.1 times more likely to fail AR, 3.8 times more likely to fail OAE, 2.1 times more likely to fail DD and 2.4 times more likely to fail LPFS.

Figure 2 shows the percentage of LD and TD children who failed the CHA, APA and OHA in either ear. In children with LD, 21/67 (31.4%) failed CHA, 20/58 (34.5%) failed APA and 32/58 (55.2%) failed OHA. In comparison, in TD children, 55/413 (13.3%) failed CHA, 52/314 (16.6%) failed APA and 86/313 (27.5%) failed OHA. Pearson Chi-squared testing at a significance level of 0.05 showed significant differences in the failure rates in children with LD versus TD children for CHA (χ^2 (1, N = 480) = 14.10, $p < .05$), APA (χ^2 (1, N = 372) = 10.10, $p < .05$), OHA (χ^2 (1, N = 371) = 17.31, $p < .05$). These results indicated that children with LD were 2.4 times more likely than TD children to fail CHA, 2.1 times more likely to fail APA and 2.0 times more likely to fail OHA.

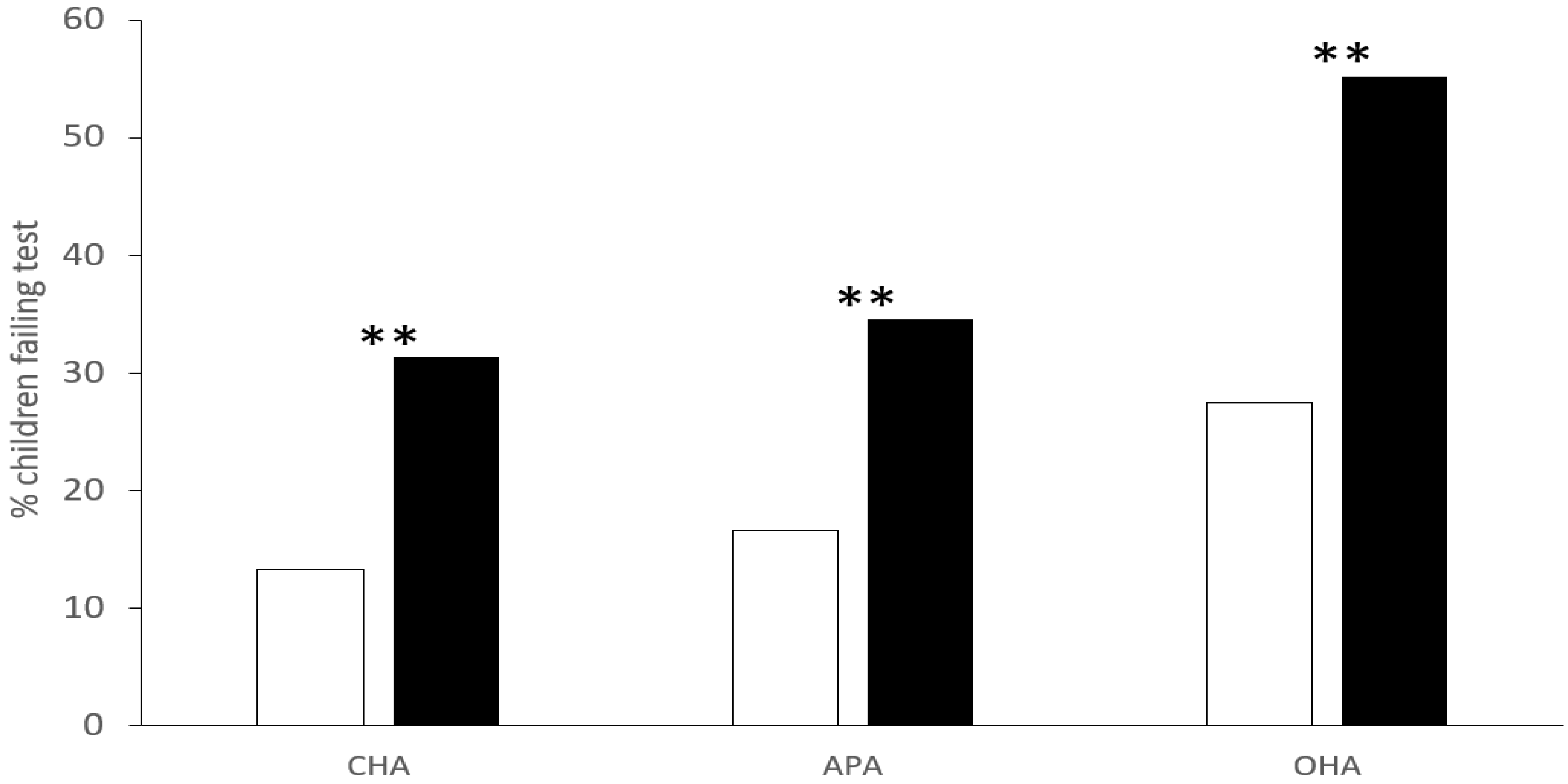

Figure 5.2. Percentages (%) of LD and TD children who failed CHA, APA and OHA in either ear. LD children's results are represented by black bars. *Note:* CHA = conventional hearing assessment, APA = auditory processing assessment, OHA = overall hearing assessment, ** = significant $\chi 2$ test results with $p < 0.05$.

Table 3 shows the descriptive results from all hearing tests for participants in the LD and TD groups. Two variables – $LPFS_R$ and $LPFS_L$ – were found to breach assumptions of normality and were transformed using a square root transformation ($LPFS_{R\text{-}SQ}$ and $LPFS_{L\text{-}SQ}$). Table 3 reports the untransformed $LPFS_R$ and $LPFS_L$ data for ease of interpretation.

Table 5.3. Descriptive statistics for the audiometric variables.

Variable	Group	Mean	SD	Min.	Max.	N
$PTA_{R\text{-}AV}$	TD	20.1	1.3	20.0	38.8	419
	LD	20.1	0.7	20.0	25.0	67
$PTA_{L\text{-}AV}$	TD	20.1	1.4	20.0	48.8	419
	LD	20.1	0.5	20.0	23.8	67
TPP_R	TD	-31.5	54.2	-0.3	47	411
	LD	-62.7	88.6	-0.3	51	66
TPP_L	TD	-32.0	62.9	-0.4	64	412
	LD	-44.6	71.5	-0.3	35	64
SC_R	TD	0.7	0.3	0.2	2.5	411
	LD	0.7	0.3	0.2	2.1	66
SC_L	TD	0.7	0.4	0.0	3.9	412
	LD	0.7	0.2	0.0	2.6	64
$AR_{R\text{-}AV}$	TD	89.7	6.3	80.0	105.0	414
	LD	92.1	7.1	80.0	105.0	67
$AR_{L\text{-}AV}$	TD	89.3	6.4	80.0	105.0	414
	LD	92.8	7.6	80.0	105.0	67

OAE_{R-AV}	TD	11.8	3.4	-2.2	22.4	334
	LD	10.1	5.0	-1.0	19.5	64
OAE_{L-AV}	TD	11.5	3.5	-0.1	24.0	332
	LD	9.3	4.8	-2.3	21.3	63
DD_R	TD	90.0	8.7	55.0	100.0	312
	LD	84.9	10.0	55.0	100.0	57
DD_L	TD	83.8	12.2	30.0	100.0	312
	LD	76.8	13.3	40.0	98.0	57
$LPFS_R$	TD	79.1	9.6	40.0	100.0	312
	LD	78.1	10.0	52.0	100.0	57
$LPFS_L$	TD	79.4	8.8	40.0	98.0	312
	LD	77.5	9.1	52.0	96.0	57

Note: PTA_{R-AV} = pure tone average for the right ear; PTA_{L-AV} = pure tone average for the left ear; TPP_R = typanometric peak pressure results for the right ear; TPP_L = typanometric peak pressure results for the left ear; SC_R = static compliance results for the right ear; SC_L = static compliance results for the left ear; AR_{R-AV} = acoustic reflex average results for the right ear, AR_{L-AV} = acoustic reflex average results for the left ear; OAE_{R-AV} = otoacoustic emissions average results for the right ear; OAE_{L-AV} = otoacoustic emissions average results for the left ear; DD_R = dichotic digits scores for the right ear; DD_L = dichotic digits scores for the left ear; $LPFS_R$ = untransformed low-pass filtered speech scores for the right ear; $LPFS_L$ = untransformed low-pass filtered speech scores for the left ear.

Before performing a multiple linear regression analysis, all variables were examined to check if there were significant correlations between the variables. When strong correlations were observed among variables within the same domain, those variables were averaged to form a new variable. The pure tone audiometry thresholds at 0.5, 1, 2, and 4 kHz were averaged to form a new variable (PTA_{AV}), the acoustic reflex thresholds at 1 and 2 kHz were averaged to form a new variable (AR_{AV}), and the OAE SNR results at 1, 1.4, 2, 2.8 and 4 kHz were averaged to form a new variable (OAE_{AV}). To avoid multicollinearity, right and left ear audiometric results were analysed separately. A multiple linear regression analysis was used to analyse the relationship between the audiometric test results (as the independent variables) and the learning score (as the dependent variable) for each ear separately. All variables except ECV were fitted into the regression model, as there was no reason to assume that ECV would affect learning score. $PTA_{R\text{-}AV}$ and $PTA_{L\text{-}AV}$ were excluded by the regression model due to their lack of variance.

Table 4 shows the results of the multiple linear regression analyses for each ear. Both regression models were significant at the 0.01 level with the model for the right ear explaining 18% of the variance in learning score and the model for the left ear explaining 13% of the variance in learning score. For each ear, AR, DD and $LPFS_{SQ}$ reached significance at the 0.05 or 0.01 level.

Table 5.4. Results of the linear regression analyses

Outcome Variable	Ear	N	Model adjusted R^2	F	P value for model	Explanatory variable (Standardized Beta coefficient)					
						TPP	SC	AR	OAE	DD	$LPFS_{SQRT}$
Learning Score	R	366	.18	14.14	<.01	.10	.00	$-.13^{*}$	.09	$.36^{**}$	$.15^{**}$
	VIF					1.27	1.02	1.08	1.21	1.02	1.10
	L	360	.13	9.79	<.01	.00	.00	$-.16^{**}$	.09	$.30^{**}$	$.12^{*}$
	VIF`					1.26	1.04	1.12	1.30	1.10	1.10

Note: VIF = variance inflation factor; TPP = tympanometric peak pressure; SC = static compliance; AR = acoustic reflex threshold (2-frequency average); OAE = average otoacoustic emissions (5-frequency average); DD = dichotic digits; $LPFS_{SQRT}$ = low-pass filtered speech (square-root transformed), * = significant at $p \leq .05$ and ** = significant at $p \leq .01$.

5.5. Discussion

This study aimed to investigate hearing and auditory processing ability in primary school children with LD. To do so, 486 school-aged children were classified into an LD or TD group by using a learning score derived from their performance on their school report (SR) and National Assessment Program – Literacy and Numeracy (NAPLAN) scores. A cut-off learning score of 17.24 was calculated by determining the learning score that would be obtained by a participant who scored values of 3 for all SR (maximum score = 5) and NAPLAN (maximum score = 6) measures, with factor loading adjustment determining the weighting of each score for the two learning measures. Children with a learning score less than 17.24 were classified as having LD, while children with a score of 17.24 or above were classified as being TD.

In general, children with LD were 2.0 times more likely to fail the overall hearing assessment (OHA) compared with TD children (55.2% vs 27.5%, respectively). This could add to the difficulties faced by children with LD, particularly in classrooms where learning occurs predominantly via the auditory modality (Berg, 1993; Heward, 2003; Rosenberg et al., 1999). While a causative link between hearing impairment and LD cannot be claimed in the present study (a single distal cause model), this finding highlights the need for educators to be alert to potential hearing impairment in children with or suspected of having LD. This is supported by reports that hearing impairment could affect not only academic achievement (Bess et al., 1998; Quigley, 1978) but interpersonal communication, psychosocial well-being, quality of life and economic independence (Bess et al., 1998; Cone et al., 2010; Kotby et al., 2008; Mason & Mason, 2007); speech, language and reading development (Bishop & Snowling, 2004; Heine et al., 2016; Ramus, 2003; Sharma et al., 2009; Wake et al., 2004); and vocational attainment (Karchmer & Allen, 1999; Venail, Vieu, Artieres, Mondain, & Uziel, 2010); and could lead to children being inappropriately labelled as having a behavioural problem (Flexer, 1994).

A closer examination of the conventional hearing assessments (pure tone audiometry, tympanometry, ARs and OAEs) showed that children with LD were 2.4 times more likely to fail one or more of these assessments compared to TD children (31.4% vs 13.3%, respectively). However, the few failures on pure-tone audiometry testing (3/67 children with LD and 4/419 TD children) showed the rate of hearing loss on pure-tone audiometry were very low in both groups. Where such failures did occur, they were most likely to indicate a slight to mild hearing loss with middle ear dysfunction in either or both ears, as reflected by tympanograms and elevated and/or absent ARs. Any mild hearing impairments resulting from a mild middle ear dysfunction could go undetected in children with LD, and/or could be misinterpreted as having a behavioural problem (Flexer, 1994). This could deprive children with LD of appropriate and timely medical and/or audiological intervention. It was also noted that children with LD in this study were more likely, and the TD children slightly more likely, to have hearing impairment compared to the 3.4 to 12.8% rates of hearing impairment reported by Choi et al. (2016) in the general Australian state school population. While this suggests higher rates of hearing impairment overall in the present study, it could also reflect the present study's use of stringent pass/fail criteria and the inclusion of ARs and OAEs in the CHA battery of tests.

The two auditory processing assessments (DD and LPFS tests) in the present study showed that children with LD were 2.1 times more likely to fail one or more of these assessments compared to TD children (34.5% vs 16.6%, respectively). The slightly higher failure rate on DD than on LPFS testing (24.6% and 19%, respectively) in children with LD suggests these children experienced greater difficulties in the skills assessed by DD than those assessed by LPFS. The exact nature of these skills remains a topic of debate, with DD thought to assess dichotic listening as well as attention and short-term memory (Hugdahl, 2000; Lawfield, McFarland, & Cacace, 2011; Moncrieff, 2006; Musiek, 1983; Parkinson, 1974) and LPFS thought to assess monaural low redundancy and auditory closure while being influenced by the person's lexicon (Arnott, Goli, Bradley, Smith, & Wilson, 2014; Bellis, 2003; Bellis & Ferre, 1999; Weihing et al., 2015). While these greater failure rates show that children with LD experienced greater difficulties with these two auditory processing skills, caution is needed before suggesting this represents a greater prevalence rate of auditory processing disorder, as diagnosis of auditory processing disorder typically requires a more comprehensive assessment than the two tests of AP used in the present study.

The multiple linear regression analyses for all children (LD and TD groups combined) who completed the OHA (i.e., both the CHA and APA, and therefore who had pure tone hearing thresholds within normal limits) showed these measures explained 18% and 13% of the variance in learning scores for the right and left ear models, respectively. Closer inspection of both regression models showed that the measures significantly related to learning score were AR, DD and LPFS (note: PTA_{AV} was not included in either model due to its lack of variance). These results are consistent with previous reports of correlations between dichotic processing and learning and reading disabilities (summarised in Weihing & Atcherson, 2014), tests of monaural low redundancy and learning disability (Iliadou et al., 2009), and ARs and auditory processing disorder (Allen, Jeng, & Levitt, 2005; Saxena, Allan, & Allen, 2015) and behavioural disturbance and language delay (Grady, Mcmurry, & Pillsbury, 1985). In particular, elevated and/or absent AR has been shown to correlate with the presence of APD as well as language and learning disabilities (Grady, Mcmurry, & Pillsbury, 1985; Saxena, Allan, & Allen, 2015). Overall, the present study's regression models showed a generally weak relationship between auditory function and learning score in children with normal hearing threshold, with this relationship being stronger between learning score and AR, DD and LPFS outcomes than between learning score and TPP, SC and OAE outcomes.

5.5.1. Practical Implications

Overall, the results from the present study suggest that one of the challenges facing children with LD could be hearing impairment, with further investigation of this possibility in children with normal hearing thresholds needing to include measures of AR, DD and LPFS. This supports previous calls for greater screening of auditory processing disorders in children with learning disabilities (Iliadou et al., 2009). While the present study showed that children with LD were at a higher risk of having a hearing deficit, the contribution of hearing impairment to LD has yet to be systematically investigated. Other potential factors that could impact learning in children with LD need to be considered, particularly in areas of cognition and language communication skills (Halliday et al., 2017; Moore et al., 2010; Tallal & Gaab, 2006; Tomlin et al., 2015).

Any further investigation of hearing impairment and LD should also target either risk factor models where hearing impairment increases the likelihood of a child developing LD, and/or association models where hearing impairment could co-occur with LD, but the likelihood of one is not dependent on the likelihood of the other. The present study's findings do not support targeting single distal cause models where hearing impairment would cause LD, or consequence models where LD would cause hearing impairment.

5.5.2. Limitations of the study

The present study had several limitations. First, since children in this study were only recruited from the greater Brisbane area of Australia, the findings may be difficult to generalise to the broader population of children with LD. Second, while all testing was conducted in quiet rooms in the participating schools, these rooms were not sound treated. While this might have had some effect on the pure tone audiometry results where testing was conducted at near threshold levels, it was not thought to have affected the AP tests as the rooms were deemed quiet enough to allow for reliable testing at these suprathreshold levels. The tester was not aware of any child being distracted by noise during the test. Third, the attention and language skills of the children were not assessed. Finally, the operational definition of LD used in the present study needs to be considered before comparing its results to studies in similar populations.

5.6. Conclusions

Children with LD had higher failure rates on the overall hearing assessment (OHA) when compared with TD children, highlighting the need for educators to be alert to potential hearing impairment in children with or suspected of having LD. Multiple linear regression analyses of children with normal hearing thresholds showed that the auditory measures considered (TPP, SC, OAE, AR, DD and LPFS) explained 18% and 13% of the variance in learning scores in right and left ear, respectively, with AR, DD and LPFS reaching significance at the 0.05 or 0.01 level. Overall, the potential for hearing impairment should be investigated in children with LD with further assessment of AR, DD and LPFS of children returning normal hearing thresholds to ensure these children receive the appropriate auditory support needed to enhance their learning.

The suggestion that hearing impairments could be related to LD warrants further investigation in the primary school-aged population. In particular, longitudinal studies that allow for greater control of confounding variables and better identification of potential cause and effect relationships are recommended. These studies should target risk factors and association models in children with LD using a wider range of auditory, cognitive and language assessments.

Chapter 6: Learning Difficulties and Auditory Processing Deficits In A Clinical Sample of Primary School-Aged Children

This chapter was submitted to the peer-reviewed journal *International Journal of Audiology* and is currently under review. The content of this chapter is inserted as published, with the exception of formatting changes to headings, tables, figures and references to maintain consistency throughout the thesis.

6.1. Abstract

The current study examined the relationship between learning and auditory processing (AP) ability in a clinical sample of children with learning difficulties (LD) and typically developing (TD) children. The participants consisted of 50 children (7.7 to 10.8 years) who had been referred for a comprehensive AP assessment based on having failed an AP screening. These children had previously been identified as having LD (n = 14) or TD (n = 36). Children with LD performed significantly worse than the TD children on frequency patterns with linguistic reports (FP_{linR} and FP_{linL}), dichotic digits (DD) and Auditory Word Memory - Forward (ANM_F) tests, with significant correlations being observed between these variables and the learning score. The multiple linear regression showed that FP_{linR}, DD_R and ANM_F scores explained 50% of the variance in the learning score. The present study's results are consistent with research linking AP to learning abilities in children. However, these results should not be generalised to non-clinical populations or to clinical populations obtained using different AP screening tests. Further investigations into the potential relationships between AP, cognition, speech and language development and learning ability in children are warranted.

6.2. Introduction

Children with LD have long been a population of interest in contemporary mainstream education systems around the world. Recently, Choi et al. (2019) suggested that LD could be related to deficits in hearing and particularly in auditory processing (AP). The present study sought to investigate this further by comprehensively assessing AP in 50 children with and without LD from the Choi et al. (2019) study who were referred for an audiological assessment of AP after failing a short AP screening program in their school settings.

Although the term *LD* has been used since 1976, its definition and potential causes are matters of debate among government agencies and researchers around the world (Ashman, 2005; Cadman, 1976; Elkins, 1983; National Health and Medical Research Council [NHMRC], 1990; Westwood, 2003). In particular, confusion regarding differences between LD and *learning disability* have resulted in imprecise estimates of the rates of LD and insufficient support for children presenting with these difficulties (Rivalland, 2002; Zammit, Meiers, & Frigo, 1999). For the purposes of the present study, LD is treated as a generic term describing children who exhibit developmental and academic problems in the absence of diagnosed intellectual impairment/s (Choi et al., 2019). Children with LD typically have difficulty in reading (van Kraayenoord, 2005; Westwood, 2003), written language and numeracy (van Kraayenoord, 2005; van Kraayenoord & Elkins, 2004). They are often seen as inactive and inefficient learners who are frequently off-task, easily distracted (Ashman & Elkins, 2002; Westwood, 2004) and unable to integrate prior knowledge into their own learning. These factors can result in reduced scholastic attainment, poor self-esteem and socio-emotional behaviour (Ashman & Elkins, 2002; Treuen et al., 2000; Westwood, 2004).

While acknowledging that many factors in varied combinations can influence a child's learning at school, Choi et al. (2019) recently suggested that LD could be related to deficits in hearing, particularly in AP. This suggestion was based on an auditory assessment of 486 children (aged 7.7 to 10.8 years) which found that those with LD (n = 67) were 2.1 times more likely than typically developing (TD) children (n=419) to have failed an auditory processing screening consisting of dichotic digits (DD) (thought to assess binaural integration) and low-pass filtered speech (LPFS) (thought to assess monaural redundancy).

While lacking a universally accepted definition (W. J. Wilson & Arnott, 2013), the most cited definition of AP is that shared by the American Speech-Language-Hearing Association (ASHA, 2005) and the American Academy of Audiology (AAA, 2010). ASHA (2005) defines AP as "the auditory system mechanisms and processes responsible for the following behavioural phenomena (the domains of AP): sound localization and lateralization; auditory discrimination; auditory pattern recognition; temporal aspects of audition including temporal resolution, temporal masking, temporal integration, and temporal ordering; auditory performance with competing acoustic signals; and auditory performance with degraded signals." AP difficulties are considered to be heterogeneous and often comorbid with deficits in language (Medwetsky & Musiek, 2011) and/or attention (Moore et al., 2010), making its potential relationship with LD complex and multifaceted (Heine, Joffe, & Greaves, 2003).

Suggestions that LD and AP could be related are not new. Children showing poor academic performance are often suspected of having poor AP abilities because of their substandard listening skills and auditory behaviour (e.g., Smoski et al., 1992). Adding to this are reports of potential relationships among AP and reading deficits (e.g., Bishop & Snowling, 2004; Purdy et al., 2009; Ramus, 2003; Sharma et al., 2009), cognitive deficits (e.g., Moore et al., 2010), literacy and language deficits (e.g., Halliday et al., 2017; Tallal & Gaab, 2006) and poorer academic achievement (e.g., Heine et al., 2016). Such findings form part of the psychoeducational approach to APD, which J. Jerger (2009) describes as being built on the premise that primary auditory abilities exist that are likely to affect auditory behaviour and are important for learning.

The present study aimed to investigate AP in the LD and TD children who were granted referrals by Choi et al. (2019) after failing an AP screening program in their school settings. Two research questions were asked with respect to these children: (1) Do the LD and TD children perform differently on tests of AP?; and (2) To what degree is variance in learning explained by AP? It was hypothesised that the children with LD would perform worse on tests of AP.

6.3. Materials and Methods

6.3.1. Research design

A non-randomised, cross-sectional, single measure research design was used for the present study. Ethical clearance was given by Education Queensland and the Medical Research and Ethics Committee of The University of Queensland. Written consent was received from parents or caregivers and the participating children.

6.3.2. Participants

All participants had to have the following results from their participation in school-based testing by Choi et al. (2019): (1) a learning score classifying them as having LD or being TD; (2) a pass result from pure tone audiometry (pure tone thresholds ≤20 dB HL at octave frequencies from 0.5 to 4 kHz), tympanometry (SC of 0.3 – 1.6 ml (J. Jerger et al., 1972), an ECV of 0.9 – 2.0 ml (Wiley et al., 1996) and TPP between +50 and -100 daPa (J. Jerger, 1970)), ipsilateral acoustic reflex (a measurable change in compliance of 0.02 ml (Gelfand, 2017)) and transient evoked otoacoustic emission (TEOAE; SNR values of more than 3 dB at 2 or more test frequencies in either ear); and (3) a refer result from a short AP assessment consisting of dichotic digits (DD) and low pass filtered speech (LPFS) testing in the schools, with the refer triggered by scores being below age-appropriate normative data (Bellis, 2003) on at least one of the tests in at least one ear.

Justification for choosing these AP tests is provided by Choi et al. (2019). In brief, DD was chosen for its reported sensitivity to AP disorder and its listing as one of two minimum tests for assessing AP, while LPFS was chosen for its face validity as a measure of children’s ability to process degraded auditory signals, an auditory skill commonly proposed as being important in typical classroom settings (AAA, 2010; ASHA, 2005; Bellis, 2003; Bellis & Ferre, 1999; Musiek et al., 2011). The limitation of including only DD and LPFS in this AP screening program is noted with a different group of children likely to have been sampled had a different pair of AP tests been used in the AP screening. Following their referral, the children also had to have attended a diagnostic hearing and AP assessment at a hearing research clinic at The University of Queensland, Australia. The mean time between the screening and follow-up assessments was five weeks (range = 0 to 23 weeks), although one participant had a follow-up time of 57 weeks.

Out of the 72 children (TD and LD combined) who failed the AP screening in Choi et al. (2019), 50 children met all inclusion criteria and were conveniently recruited into the present study. The demographics of these participants are shown in Table 1. The participants in this study had no diagnoses of intellectual impairment, as confirmed by the parental report and school records. Children with other diagnoses such as attention deficit hyperactivity disorder (ADHD), dyslexia, high functioning autism spectrum disorder (ASD) were included as these conditions are known to exist in the general school population and are not exclusive to children with LD. They were also included because of this study's definition of LD as a generic term, describing children who exhibit developmental and academic problems in the absence of diagnosed intellectual impairments.

Table 6.1. Demographic characteristics of the participants (n = 50).

	N (%)
Male/Female	31 (62)/19 (38)
Age Range (in years; mean, min, max)	9.19 (8.17, 10.75)
Learning Difficulty/Typically Developing	36 (72.0)/14 (28.0)
Caucasian/Non-Caucasian	35 (70.0)/ 6 (30.0)
Speaking other languages in addition to English	6 (30.0)
Other history factors	
Otitis media	2 (4.0)
ADHD	3 (6.0)
Dyslexia	1 (2.0)
High functioning ASD	1 (2.0)
Receiving speech/language therapy	2 (4.0)
Other	4 (8.0)
Parental concern in reading/writing/numeracy	23 (46.0)/23 (46.0)/16 (32.0)
Parental concern in hearing	17 (34.0)

Note: ADHD = Attention Deficit Hyperactivity Disorder; ASD = Autism Spectrum Disorder.

6.3.3. Learning measures

The learning measures of the children in the present study had been previously completed by Choi et al. (2019).

6.3.3.1. Learning Ability

A measure of the child's learning ability was obtained using a combination of their school report and scores on the National Assessment Program – Literacy and Numeracy (NAPLAN) assessment. The use of both school report and NAPLAN scores was thought to mitigate potential bias of using school reports alone.

6.3.3.2. School Report

Written school reports (SR) obtained from grades three and four from either semester one or two (depending on when the child was tested) in the areas of English (SE) and Mathematics (SM) were collected (if available). In Queensland, a school report is issued to parents/caregivers biannually at the end of each semester. The school report shows a student's achievement for each learning area/subject studied in the reporting period, as well as the student's effort and behaviour. In years three and four students, the reporting scale ranges from A to E, where 'A' is the highest achieving grade (Education Queensland, 2017). For further analysis of learning ability in the present study, this scale has been converted to a numerical scale ranging from 1 to 5, with '1' being the lowest grade E and the '5' being the highest grade A.

6.3.3.3. NAPLAN

NAPLAN results for grade three were collected from the participating schools. The NAPLAN was introduced into Australian primary schools in 2008. Every year, all primary school students in grades three and five are assessed in four domains: Reading (NR), Writing (NW), Language Conventions [Spelling (NS), Grammar & Punctuation (NGP)] and Numeracy (NN). The NAPLAN assessment scale is divided into bands of 1 to 10, with band '1' being the lowest. The National Minimum Standards recommends, for each year level, a minimum standard (band) out of a range of bands representing a wide range of the typical skills demonstrated by the students. For instance, the assessment scale for year three students ranges from band 1 to 6, with '3' being the minimum standard recommended by the National Minimum Standards. Group statistics for the comparison of performance are also available from the Australian Curriculum Reporting Authority (ACARA, 2017), allowing results to be converted into z-scores. The child's score is expressed as a number between 1 and 10 (to one decimal place), which demonstrates within which band the child's score fell, and the decimal point indicates the child's position within the band.

6.3.3.4. Missing School Report and NAPLAN Scores

Thirteen (26%) of the 50 children returned some missing NAPLAN reading (NR), writing (NW), spelling (NS), grammar and punctuation (NGP), and/or numeracy (NN) scores. Two children missed one NAPLAN score, two children missed two NAPLAN scores, four children missed four NAPLAN scores, and five children missed five NAPLAN scores. A Pearson's product-moment correlation analysis returned strong correlations among all SR and NAPLAN scores (r values ranging from 0.55 to 0.75, $p \leq 0.01$). To rectify the issue of incomplete data, missing NAPLAN scores were estimated by scores generated from other SR or NAPLAN scores.

6.3.3.5. Factor Analysis to Generate a Learning Score

To assess the learning capability of each student, a learning score was derived from the SR and NAPLAN data. A maximum likelihood factor analysis using varimax rotation was carried out on the SR and NAPLAN results of all participating children. This analysis returned a one-factor model with an Eigenvalue of 4.72 that explained 67% of the model variance. No further factors with an Eigenvalue >1.0 were identified. The learning score for each child was calculated by multiplying their SR and NAPLAN scores by the matching factor loading scores and summing these products.

6.3.3.6. Learning Difficulty Classification

To classify children as having an LD or not having an LD (the latter group being typically developing (TD)), it is necessary to assess children's learning ability by their learning score A cut-off learning score was calculated by determining the learning score that would be obtained by a child who scored values of 3 for all SR and NAPLAN measures. Each value for SR and NAPLAN measures was multiplied with its corresponding factor loading, and these valued were summed up to produce the cut-off learning score of 17.24. This is consistent with the decision to use LD as a generic term to describe children who are significantly lagging behind their peers in scholastic attainment (Ashman, 2005; AUSPELD, 2014; Australian Government, 2017; Choi et al., 2019; Elkins, 1983; NHMRC, 1990; Westwood, 2003).

6.3.3.7. Auditory processing and memory measures

The measures of AP and memory completed on the children in the present study are described below.

On the recommendations of ASHA (2005) and Bellis (2003), each participant completed four tests of AP: DD, LPFS, frequency patterns with linguistic report (FP_{lin}), and competing sentences (CS); as well as two tests of memory: the Auditory Number Memory – Forward (ANM_F) and Auditory Word Memory (AWM) subsets from the Test of Auditory Processing Skills – version 3 (Martin & Brownell, 2005). For the AP measures, percentage correct scores lower than age-appropriate normative data for DD, LPFS, FP_{lin} and CS tests provided by Bellis (2003) were considered to be failing scores. For the memory tests, age equivalent scaled scores lower than the normative data provided by Martin and Brownell (2005) were considered to be failing scores.

6.3.3.7.1. Dichotic Digits (DD) Test

The DD test stimuli were two-pair dichotic digit stimuli (R. H. Wilson & Strouse, 1998) consisting of 25 sets of two numbers (1-10, excluding 7) spoken by a male speaker. These numbers were presented at 50 dB HL (J. L. Clark & Rosser, 1988) in pairs with each number within each pair presented to a different ear simultaneously. Each child was instructed to repeat all four numbers presented.

6.3.3.7.2. Low-Pass Filtered Speech (LPFS)

The LPFS stimuli were the AUDiTEC of St Louis recording of the NU-6 Wordlist No. 1 (50 monosyllabic words) spoken by a male speaker and low-pass filtered at a cut-off frequency of 1000 Hz. Twenty-five words of this list were presented at 50 dB HL to each ear of each child (order randomised) who was instructed to repeat each word.

6.3.3.7.3. FP Test

The FP test stimuli were from R. H. Wilson and Strouse (1998). Three different tones, designated as 'low' (880 Hz) or 'high' (1122 Hz), were presented at 50 dB HL to each ear of each child who was instructed to verbally report the frequency pattern (e.g., 'low,' 'low,' 'high').

6.3.3.7.4. CS Test

CS testing was conducted using the AUDiTEC of St Louis recording of the NU-6 Wordlist No. 1. This test consisted of 30 pairs of simple sentences (six to seven words in length) spoken by a male speaker. During the test, two separate sentences were played to a child's ears simultaneously, and the child was instructed to repeat the sentence played to the test ear while ignoring the sentence played to the non-test ear.

6.3.3.7.5. TAPS-3

Each child was tested on two subtests only: (1) Auditory Number Memory – Forward (ANM_F), which requires the child to repeat back increasing numbers of single digits; and (2) Auditory Word Memory (AWM), which requires the child to repeat back increasing numbers of words. The subtests were applied using live voice without any visual cues at a distance of approximately 1m from the child.

6.3.4. Data collection and analysis

Descriptive statistics were calculated for the raw percentage scores on DD, LPFS, FP_{lin}, CS, ANM_F , and AWM. These scores were inspected for parametric assumptions using histograms, Q-Q plots, box and whisker plots, and Kolmogorov-Smirnov and Shapiro-Wilcoxon tests of normality. T-tests were used to examine differences between the LD and TD groups on each test of AP and memory. Pearson's Product Moment correlation analysis was used to examine correlations between all AP and memory measures for the LD and TD groups combined. Finally, a multiple linear regression analysis was used to examine the ability of the measures of AP and memory to concurrently predict learning ability.

6.4. Results

It was observed that 30% of children on DD_R test, 34% of children on DD_L test, 15% of children on $LPFS_R$ test, and 18% of children on $LPFS_L$ test obtained different result during the screening versus the diagnostic AP assessment (e.g., failing LPFS at the screening assessment but passing it at the diagnostic assessment). This could be related to the different test environments present in the screening versus diagnostic conditions and/or to test-retest reliability factors within the LPFS and DD tests themselves. These possibilities are topics for further investigation by the present study's authors and will not be discussed here.

Table 2 shows the AP and memory results for LD and TD children. T-tests were applied to the test scores. All statistical analyses were considered at the 1% level. The results showed that the LD children performed significantly worse than the TD children on FP_{linR} and FP_{linL}, with both DD_R and ANM_F being near significance. It was noted that the children's results from the previously completed DD and LPFS testing in the school setting did not always match their subsequent DD and LPFS results in the clinical setting. This discrepancy could be due to differences between school and clinical environments, such as increased noise and distraction in the school setting, and the matter is currently being investigated by the present study's authors for possible future publication.

Table 6.2. Descriptive statistics for each auditory processing measure for the clinical sample of children LD (N = 14) or TD group (N = 36) and the corresponding t-test statistics.

Variable	**Clinical sample of Children**	**Mean**	**Median**	**Min.**	**Max.**	**p**
DD_R	*TD*	90.8	92.8	60.0	100.0	<.01*
	LD	83.4	83.8	72.5	92.5	
DD_L	*TD*	84.0	88.8	55.0	100.0	.08
	LD	77.3	77.5	60.0	90.0	
$LPFS_R$	*TD*	76.1	76.0	40.0	96.0	.29
	LD	73.4	74.0	64.0	80.0	
$LPFS_L$	*TD*	76.0	76.0	44.0	92.0	.57
	LD	74.0	76.0	44.0	88.0	
FP_{linR}	*TD*	61.8	66.0	8.0	100.00	<.01*
	LD	40.0	42.0	12.0	80.0	
FP_{linL}	*TD*	61.4	66.0	16.0	100.0	<.01*
	LD	36.0	34.0	4.0	80.0	
CS_R	*TD*	82.2	90.0	25.0	100.0	.78
	LD	80.4	85.0	32.5	100.0	

CS_L	*TD*	51.3	51.2	7.5	97.5	.93
	LD	52.0	42.5	30.0	90.0	
ANM_F	*TD*	16.4	16.0	10.0	24.0	.01*
	LD	13.8	13.5	10.0	18.0	
AWM	*TD*	17.0	17.5	12.0	26.0	.31
	LD	15.9	15.5	12.0	24.0	

NOTE: DD_R = dichotic digits right ear scores; DD_L = dichotic digits left ear scores; $LPFS_R$ = low-pass filtered speech right ear scores; $LPFS_L$ = low-pass filtered speech left ear scores; FP_{linR} = frequency patterns with linguist report right ear scores; FP_{linL} = frequency patterns with linguist report left ear scores; CS_R = competing sentences right ear scores; CS_L = competing sentences left ear scores; ANM_F = auditory number memory - forward scores; AWM = auditory word memory; *$p < .01$

Table 3 shows Pearson's product-moment correlation results between learning score, AP and memory test scores. All statistical analyses were considered at the 1% level. Significant correlations were observed between LS and DD_R, FP_{linR}, FP_{linL} and NMF. A range of correlations were observed within the AP and memory measures.

Table 6.3. Pearson's product-moment correlation between learning score (LS) and AP test scores, showing the R coefficients and the levels of significance.

Variable	LS	DD_R	DD_L	$LPFS_R$	$LPFS_L$	FP_{linR}	FP_{linL}	CS_R	CS_L	ANM_F	AWM
LS		.38**	.21	.19	-.03	.5**	.56**	.16	.12	.48**	.26
DD_R	.38**		.26†	.18	-.02	.14	.14	.41**	.27†	.22	.10
DD_L	.21	.26†		-.02	.10	.27†	.39**	.18	.43**	.13	.10
$LPFS_R$	.19	.18	-.02		.46**	.00	.18	.34*	.22	.18	.03
$LPFS_L$	-.03	-.02	.10	.46**		-.08	.15	.08	.10	-.05	.15
FP_{linR}	.5**	.14	.27†	.00	-.08		.88**	-.02	.10	.42**	.41**
FP_{linL}	.56**	.14	.39**	18	.15	.88**		.78	.26	.39**	.35*
CS_R	.16	.41**	.18	.34*	.08	-.02	.78		.37**	.09	.08
CS_L	.12	.27†	.43**	.22	.10	.10	.26	.37**		.35**	.30*
ANM_F	.48**	22	.13	.18	-.05	.42**	.39**	.09	.35**		.68**
AWM	.26	.10	.10	.03	.15	.41**	.35**	.08	.30*	.68**	

†$p \leq .10$. *$p \leq .05$. **$p \leq .01$.

Table 4 shows the results of the multiple linear regression analysis with learning scores as the dependent variable and the AP and memory scores as the independent variables. To avoid multicollinearity, FP_{linR} and AWM were excluded from this analysis. All statistical analyses were considered at the 1% level. The regression model returned three significant AP and memory predictors explaining 50% of the variance in learning score ($R^2 = .50$, F (8, 41) = 5.1, $p < .01$). These three predictors were FP_{linL} ($\beta = .44$, $p < .01$), ANM_F ($\beta = .29$, $p < .05$) and DD_R ($\beta = .27$, $p < .05$).

Table 6.4. Results of the linear regression analyses.

Outcome Variable		N	Model adjusted R^2	F	P value for model	Explanatory variable (Standardized Beta coefficient)							
						DD_R	DD_L	$LPFS_R$	$LPFS_L$	FP_{linL}	CS_R	CS_L	ANM_F
Learning Score		50	.50	5.05	<.01	.27*	.03	.10	-.11	.44**	.04	-.21	.29*
	VIF					1.31	1.52	1.60	1.38	1.41	1.44	1.57	1.39

Note: VIF = variance inflation factor; : DD_R = dichotic digits scores for the right ear; DD_L = dichotic digits scores for the left ear; $LPFS_R$ = low-pass filtered speech scores for the right ear; $LPFS_L$ = low-pass filtered speech scores for the left ear; FP_{linL} = frequency patterns with linguist report scores for the left ear; CS_R = competing sentences scores for the right ear; CS_L = competing sentences scores for the left ear; ANM_F = auditory number memory - forward scores. * = significant at $p < .05$ and ** = significant at $p < .01$.

6.5. Discussion

The results of the study showed that the LD children performed worse than the TD children on FP_{linR} and FP_{linL}, DD_R, and ANM_F, with these measures concurrently predicting 50% of the variance in their learning scores. These findings were consistent with our hypothesis that children with LD would perform worse on tests of AP.

The poorer FP_{lin}, DD and ANM_F scores observed in the children with LD were consistent with reports linking these processes to learning abilities in children. This includes reports linking frequency patterning to reading and language (Sharma et al., 2009) and early indications of LD in children (Clay, 1997; Louden et al., 2000; van Kraayenoord, Elkins, Palmer, Rickards, & Colbert, 2000); reports linking dichotic listening to cognition (Tomlin et al., 2015), learning (Ferre & Wilber, 1986; Kushner, Johnson, & Steven, 1982), and language; and reports linking memory to arithmetic (e.g., Bull, Espy, & Wiebe, 2008; Siegel & Linder, 1984), reading (e.g., Archibald & Gathercole, 2006; Swanson, Zheng, & Jerman, 2009), learning (e.g., Alloway et al., 2005; Ashman & Elkins, 2002; Westwood, 2004), and attention (e.g., Mayes, Calhoun, & Crowell, 1998). The present study's results add to these ongoing suggestions that auditory processes contribute, at least in part, to learning in school-age children.

The finding that FP_{linL}, DD_R, and ANM_F concurrently predicted 50% of the variance of learning scores in this cohort of children was surprising given the many factors expected to contribute to learning in the classroom. We offer three possible explanations for this finding.

The first possible explanation is that the auditory processes measured by FP_{lin}, DD and the memory processes measured by ANM_F contribute significantly to children's learning. This would suggest a risk factor model whereby poor AP abilities place children at a greater risk of developing LD. In such a model, the presence of AP difficulties early in a child's development could, in some cases, interfere with the development of other skills needed for efficient and effective learning (such as language skills) (Halliday et al., 2017).

The second possible explanation for this variance is the presence of a deficit in a separate skill (or set of skills) that affects both AP and learning in children with LD. This would suggest an association model whereby poor abilities in this separate skill (or set of skills) lead to deficits in both AP and learning. In such a model, a deficit in a separate skill such as attention could explain poor scores on the measures of AP, memory and learning used in the present study. An alternative to a separate skill argument is the possibility that the tests of AP were testing more than just AP skills. This can be seen in some research that suggests both temporal patterning and dichotic listening tests are associated at least partly with cognitive skills such as memory and attention (Keller, Tillery, & McFadden, 2006; Riccio et al., 2005; Tomlin et al., 2015; W. J. Wilson et al., 2011).

The final explanation for this variance is the presence of a neurodevelopmental syndrome (NDS) as proposed by Moore and Hunter (2013). These authors conceptualise NDS as an associated core of auditory, speech, language, attention, memory and behavioural difficulties in children that are each expressed along a continuum of severity. These difficulties vary from child to child depending on their unique genetic endowment and developmental environment. The developmental trajectory, combined with the demands of the academic and social environment, can result in unfolding skill deficits within the syndrome over time, making NDS a complex and highly dynamic condition (Witton, 2010).

6.5.1. Limitations of the study

A key limitation of the present study is the method used to classify children as having LD. The use of different methods may have resulted in some children being classified differently (the challenges of defining LD are noted). A second key limitation was the need for each child to have failed an AP screening (DD and LPFS) in the school settings to be included in the study. This prevented the results from being generalised to non-clinical populations or to clinical populations that would have been obtained using different AP screening tests. Further limitations of the present study include the lack of measures of attention and language skills in the sampled children and the study's relatively small sample size.

6.6. Conclusions

Children with LD performed worse than TD children on FP_{linR} and FP_{linL}, DD_R, and ANM_F, with these measures concurrently predicting 50% of the variance in their learning scores. These results are consistent with reports linking AP to learning abilities in children. The finding that FP_{linR} and FP_{linL}, DD_R, and ANM_F concurrently predict 50% of the variance of learning scores was surprising and could be explained as follows: (1) auditory processes contributing to learning; (2) auditory processes and learning being affected by a separate variable (such as attention); or (3) LD being part of a larger NDS. However, caution is needed when generalising the present study's results to non-clinical populations or to clinical populations that would have been obtained using different AP screening tests.

Further investigations into the potential relationships between AP, cognition, speech and language development and learning ability in children are warranted. Such investigations would benefit from the inclusion of a wider range of cognitive and learning measures (Halliday et al., 2017; Moore et al., 2010; Tomlin et al., 2015) in larger clinical and non-clinical paediatric populations.

Chapter 7: General Discussion & Conclusions

7.1. Introduction

Children who experience poor academic performance at school have been described as having learning difficulties (LD). These children are thought to show reduced performance in reading, written language and numeracy, and to be inactive and inefficient learners who are often off-task, easily distracted and unable to integrate prior knowledge and their own experiences into learning. Hearing is one of several factors thought to influence a child's learning at school, with students spending at least 45% of their time in the classroom engaged in activities that require listening and 45 to 75% of their time comprehending their teachers' and classmates' speech. Hearing impairment can include loss of hearing sensitivity and/or impaired auditory processing (AP). Rates of periperal hearing loss (loss of hearing sensitivity) in the Australian primary school-aged population are estimated to be between 3.4 and 12.8%. Rates of impaired AP in this population are not available, although USA data suggests rates of between 2 and 3% might be expected.

Children with loss of hearing sensitivity and/or impaired AP often show behaviours similar to those reported in children with LD, such as increased requests for repetition of information, misunderstanding messages, and delays in responding, and inconsistent or inappropriate responses to oral instructions). These similarities suggest LD and hearing impairment could be related in primary school child populations.

7.2. Restate of the Rationale and Aim of the Thesis

The current thesis investigated LD and hearing impairment in school-aged children in the greater Brisbane region of Queensland, Australia. Two main research questions were considered: (1) Do children with LD have higher rates of impaired hearing and/or impaired AP compared with typically developing children?; and (2) What models might best explain any relationships between LD and hearing impairment?

The thesis was conducted in three phases. The first study systematically reviewed the audiology literature in an attempt to estimate the rate of peripheral hearing loss in the general child population in Australia (Chapter 4). The second study investigated the rates of hearing impairment and AP in a large, non-clinical sample of LD and TD children (Chapter 5). The third study investigated the performance of the clinical sample of children with and without LD referred for AP assessment on six tests of AP (Chapter 6). The findings of these three studies are summarised below and followed by the overall conclusions of the thesis presented in order of importance, limitations and areas for further research.

7.3. Summary of the Main Findings

The first study (chapter four) systematically reviewed the audiology literature in an attempt to estimate the rate of peripheral hearing loss in the general child population in Australia. A search of five electronic databases yielded three A search of five electronic databases yielded three studies – Driscoll, Kei, and McPherson (2000), Cone et al. (2010) and Keogh et al. (2010) – that had quantitatively reported the peripheral hearing results of screening and follow-up assessment of hearing in primary school children in Australia. The review concluded that the overall rate estimate of PHL in primary school child population in Australia was between 3.4% and 12.8%. The highest rate was reported for mild, conductive hearing loss (Cone et al., 2010; Driscoll et al., 2001; Keogh et al., 2010), while the lowest rates were reported for mixed and sensorineural hearing losses (Cone et al., 2010; Keogh et al., 2010). The review also compared these rates to those of other high-income countries and concluded that primary school children in Australia had higher rates of hearing loss primarily due to higher rates of conductive hearing loss. The review highlighted difficulties in estimating rates of hearing loss due to disparities in definitions of normal hearing thresholds in children as well as use of population distributions of hearing thresholds in adults to define normal hearing thresholds in children. The review also highlighted the need to base any reporting of rates of hearing loss on the results of follow-up diagnostic hearing assessments and not on hearing screenings.

The second study (chapter five) used a non-randomized, cross-sectional single measure research design to investigate the rates of impaired hearing and AP in a large, non-clinical sample of children with LD and typically developing (TD) children. A total of 486 children aged 7.7 to 10.8 years and attending years three and four in six primary schools in Brisbane, Australia, were classified as having an LD (n = 67) or being TD (n = 419). This classification was based on a Learning Score generated from their school report results and National Assessment Program – Literacy and Numeracy (NAPLAN) scores. All children attempted a conventional hearing assessment (CHA) involving pure-tone audiometry, tympanometry, acoustic reflexes (AR), and otoacoustic emissions (OAEs). Children returning pure-tone audiometry results within normal limits also attempted an auditory processing assessment (APA) including dichotic digits (DD) and low-pass filtered speech (LPFS) tests. The results showed that, compared to TD children, children with LD were 2.0 times more likely to fail the overall hearing assessment (OHA) if they failed either or both CHA and APA, 2.4 times more likely to fail CHA, and 2.1 times more likely to fail APA. In children who completed the OHA, multiple linear regressions revealed that average AR thresholds, DD scores and LPFS scores explained 13 to 18% of the variance in the Learning Score. The study proposed that the nature of the relationship between AP and learning abilities appears to be better explained by risk factor or association models than by consequence models, and not explained by single distal cause models. It concluded that the potential for hearing impairment should be investigated in children with LD, with these investigations beginning with CHA; and for children returning normal-hearing thresholds, continuing with measures of AR, DD, and LPFS, to ensure they receive the appropriate auditory support needed to enhance their learning.

The third study (chapter six) used a non-randomised, cross-sectional, single measure research design to investigate the performance of children with and without LD referred for AP assessment on six tests of AP. Fifty children (aged 7.67 to 10.75 years) referred for AP assessment on the basis of having failed the school-based APD screening tests were classified as having an LD (n = 14) or not having an LD (n = 36) based on a factor score generated from their school report results and NAPLAN scores. All children completed basic audiometry and an AP assessment consisting of DD, LPFS, FP-lin, CS and two subtest from TAPS-R: ANM_F and AWM. All participants had normal hearing thresholds (≤ 15 dB HL from 0.5-4 kHz). Children with LD performed significantly worse than the TD children on FP_{lin}, DD and ANM_F, with significant correlations being observed between these variables and the learning score. The multiple linear regression showed FP_{linR}, DD_R and ANM_F scores explained 50% of the variance in the learning score. The study expanded on the previous study's models and proposed that the nature of the relationship between temporal patterning, dichotic listening, short-term memory and learning abilities appears to be better explained by risk factor models than by association models, and not explained by consequence and single distal cause models. These findings supported the suggestion that AP is linked to learning, and they demonstrate that further investigations into the potential relationships between AP, cognition, speech and language development and learning ability in children are warranted.

7.4. Discussion of the Main Findings

7.4.1. Learning Difficulties

On considering hearing loss (HL) and its broader implications in children with LD, the challenges around defining LD and subsequently identifying children with LD warrant consideration. The group of children the thesis targeted were those who were underachieving academically for a range of reasons other than a diagnosed neurodevelopmental and/or medical disorder that might have seen them classified as having a learning disability. Identifying children with LD in this thesis proved to be challenging given the ambiguity surrounding LD and its definition and diagnosis. An operational definition of LD was established to address this issue for the purposes of this thesis. This defined children with LD as being children who underachieve academically for a wide range of reasons including sensory impairment (weaknesses in vision or hearing); severe behavioural, psychological or emotional issues; English as a second language or dialect (ESL or ESD); high absenteeism; ineffective instruction; or, inadequate curricula, but excluding intellectual impairment (IQ less than 75) (Schalock, 2012). These students have the potential to achieve at age-appropriate levels once provided with programs that incorporate appropriate support and evidence-based instruction.

Using the operational definition of LD, a factor analysis using NAPLAN and SR scores was employed to identify children with LD for inclusion in this thesis. The NAPLAN scores were thought to be a reasonable representation of a child's learning ability as, despite its challenges, NAPLAN remains the benchmark used to inform policy development, resource allocation and curriculum planning for schools in Australia (Gannon, 2013; Hardy & Boyle, 2011; Mockler, 2013). The challenges facing NAPLAN include growing research evidence showing unintentional consequences of its use that mirror many experiences of similar tools used in the US and UK (Thompson, 2013). These include teaching to the test, narrowing the curriculum focus, increased student and teacher anxiety, promoting direct teaching methods, and the creation of classroom environments that are less inclusive (Comber, 2012; Comber & Nixon, 2009; Lingard, 2010; Polesel, Dulfer, & Turnbull, 2012; Thompson, 2013; Thompson & Harbaugh, 2013). The publication on a public website of NAPLAN results by school is thought to contribute to reports of up to 5% of children, many of whom have disabilities or LD, being withdrawn on the days of NAPLAN testing (Davies, 2012). This latter threat appear to be partly present in the studies included in this thesis with 16 children (3%) having to be excluded from data analysis due to missing NAPLAN scores.

It is noted that the operational definition of LD used in this thesis may not agree with definitions of LD used in other research. For example, Abu-Hamour and Al-Hmouz (2016) discusses the prevalence children with LD and defines the term LD as low achievers not due to any disability (but subsequently included children with learning disability in their sample). Gillies and Ashman (2000) discussed children with LD but did not define the term. Instead, these authors argued that children with LD should be identified using professional judgement and assessed needs.

In the audiology literature, children with learning disabilities are often discussed but not children with LD. The lack of agreed definitions and terminology for describing children with LD continues to have many consequences. It has created doubt over the appropriate level of concern for these children and the identification methods, criteria, and labels best suited to helping them. It has hindered effective communication amongst stakeholders about these children. It continues to confuse decisions over who is resourced for intervention, and it has prevented cumulative research as the population being studied needs to be explained and re-explained to teachers, government sectors, and funding bodies. At best, this lack of agreed terminology is unsustainable; at its worst, it is as bad as having no terminology at all.

The lack of real or conceptual definitions of LD continues to be a challenge, as formal definitions fail to provide significant insight into the nature of the condition. While ongoing efforts in identifying children with LD is paramount in providing appropriate intervention and support, future research investigating hearing in children with LD needs to re-examine the construct of LD. This could involve drawing upon an existing conceptual model that outlines the purpose and scope of various terms, parameters that define LD, and a common language for various stakeholders. An amended construct of LD will improve the identification pathway, as well as outcomes for children with LD.

7.4.2. Peripheral Hearing Loss (PHL)

Overall, PHL was not a major concern in children with LD. While one-third of children with LD failed CHA, most of these failures were due to middle ear dysfunction that was not causing a PHL, with only 3 out of 67 children with LD (4.5%) failing the pure-tone screening. Compared to the rate of failure in pure-tone screening in the general primary school child population reported in Chapter 4 (the Choi et al., 2016) of between 7.1 to 12.8%, the rate of failure in pure-tone screening in children with LD appears to be lower. Similarly, when the rates of failure in pure-tone screening of children with LD and TD children were combined, the rate was 1.4%, which was substantially lower than that reported by Choi et al. (2016). In fact, the combined rate failure in pure-tone screening in the combined population is comparable to that of other high-income countries such as the US and Sweden (Choi et al., 2016). This could be due to a number of reasons. First, the mean age of children in this research was at least one to two years older compared to those included in Chapter 4 (the Choi et al., 2016). The mean age of children in this research was 8.87 years, while the mean age of children in Driscoll et al.'s (2001), Cone et al. 's (2010) and Keogh et al.'s (2010) studies were 6.2 years, 7.1 and 11.1 years, and 7.7 years, respectively. Younger children are more likely to have higher failure rates of pure-tone screening due to middle ear dysfunction such as otitis media (Keogh et al., 2015), which may partially explain lower failure rates of pure-tone screening in the current study. Second, the use of different criteria to define the presence of PHL also needs to be considered. Currently, the ASHA (1997), the AAA (2011) and the BSA (2011) recommend using hearing threshold of ≤20 dB HL as normal hearing in screening audiometry in children, as any hearing loss greater than 20 dB HL could have an adverse effect on communication skills, cognitive development, and academic achievement (Skarzynski & Piotrowska, 2012). While the criteria employed in this thesis followed this recommendation, not all studies in reviewed in Chapter 4 (Choi et al., 2016) used ≤20 dB HL as normal hearing thresholds, making it difficult to accurately compare the difference in rates. In future, a more consistent approach to the assessment of hearing in school-aged children with HL is needed.

The failure rates of tympanometry in children with LD were comparable with rates reported in Chapter 4 (Choi et al., 2016), 18% vs 15.5% - 20.8%, respectively. However, when the failure rates of tympanometry for children with LD were combined with those of TD children, it fell to 8%. These results suggest that despite the lower rates of failure in pure-tone screening, children with LD may be more susceptible to transient conductive loss due to middle ear conditions, such as otitis media (OM). Conductive hearing loss resulting from middle ear dysfunction may have a subtle effect on speech and language development in children (Friel-Patti, 1999; Luotonen et al., 1996; Teele et al., 1989), although no consensus has been reached regarding any causative effects of having a significant history of OM and delayed speech and language. Some studies have shown that children with a history of OM have significantly poorer phonological and communication skills than their normally hearing peers (e.g., Miccio, Gallagher, Grossman, Yont, & Vernon-Feagans, 2001; Petinou, Schwartz, Gravel, & Raphael, 2001; Ruben, Wallace, & Gravel, 1997). Other studies failed to detect any causal relationship between the number of episodes of OM and later speech and language development (e.g., Keogh et al., 2005; Roberts, Burchinal, Davis, Collier, & Henderson, 1991). However, conductive hearing loss could still result in negative educational consequences, and behavioural problems in the affected children (Bess, 1985; Bess et al., 1998; J. E. C. Lieu, 2004; Tharpe, 2008; Wake et al., 2006), and therefore should be managed with early identification and intervention.

7.4.3. Central Hearing Loss – Auditory Processing

7.4.3.1. Overall AP

Overall, AP deficit was a major concern in children with LD. The AP deficits observed were varied and will now be discussed in turn.

7.4.3.2. Temporal Patterning

While the FP_{lin} test was not used in the large school-based study reported in chapter four (Choi et al., 2018), children with LD performed significantly worse on this test than their counterparts in the smaller, clinic-based study reported in chapter five. FP_{lin} test results have been associated with reading ability, as reading requires frequency discrimination, temporal sequencing and sustained attention (Hämäläinen, Salminen, & Leppänen, 2013; Sharma, Cupples, & Purdy, 2019). In particular, children with dyslexia have been shown to have frequency discrimination deficits (Banai & Ahissar, 2004; Halliday & Bishop, 2006). Although the reading ability of children with LD was not explored in depth in this thesis, the poor temporal patterning abilities in this group could be a reflection on their reading difficulty, rather than numeracy difficulty. This was consistent with similar reports of poor temporal patterning abilities in children identified as poor readers (Barker, Kuruvilla-Mathew, & Purdy, 2017; Cacace, McFarland, Ouimet, Schrieber, & Marro, 2000; Purdy et al., 2009; Sharma et al., 2006; Talcott et al., 2003) and children with dyslexia (Billiet & Bellis, 2011). It is thought that children with poor reading skills are unable to establish the necessary detailed speech sound patterns, retrieve, and/or maintain those patterns (Sharma et al., 2018). Temporal patterning has been reported to be a significant contributor to nonword spelling, however its exact mechanism is still unclear (Sharma et al., 2018). However, FP_{lin} test also relies on some nonauditory factors such as sustained attention and memory (Sharma et al., 2006). While sustained attention does not appear to show significant contribution to word reading, further research is required to investigate the various auditory and cognitive factors that contribute to FP_{lin} test. Reading difficulty is often the first indicator of LD and has been used as a common criterion in schools to detect LD in children (Clay, 1997; Louden et al., 2000; van Kraayenoord et al., 2000). In future, the reading ability of children with LD in relation to their temporal patterning ability should be explored in depth.

7.4.3.3. Dichotic Listening

In both the large school-based study reported in Chapter 5 (Choi et al., 2018) and the smaller, clinic-based study reported in Chapter 6, children with LD performed significantly worse on DD than TD children. The poorer dichotic listening ability in children with LD could be due in part to their language ability (Hugdahl, Carlsson, Uvebrant, & Lundervold, 1997; R. Zatorre, 1989) as shown by their poorer reading ability compared to TD children on NAPLAN testing and their school reports. Sharma et al. (2019) found a significant correlation between word reading, phoneme manipulation and passage reading in 90 children aged seven to 12 years with listening and reading concerns based on reports by parents and professionals. Similarly, poor performance on dichotic tests has been seen in children with a range of listening difficulties based on parent, teacher and/or speech pathologist reports, and in children with diagnosed language impairment (de Wit et al., 2016; Vermiglio, 2016).

It is also possible that children with LD could have a maturation delay of the CNS that could affect their auditory integration skills (Bakker, 1973; Bakker, Smink, & Reitsma, 1973; Bakker, Teunissen, & Bosch, 1976; Satz & Van Nostrand, 1973; Sparrow & Satz, 1970), although this is a topic of ongoing debate. As such, children with LD could have a global developmental delay that does not only affect auditory processing, but other areas that are important for learning such as speech/language and memory.

Finally, it is possible that children with LD have poor attention. Hugdahl, Thomsen, Ersland, Rimol and Niemi (2003) used fMRI to examine dichotic listening ability and showed that when a focused attention dichotic task was performed on thirteen healthy adults, brain areas associated with attention were activated more than areas associated with AP. While attention was not measured in this thesis, poorer attention could be impacting on children's learning ability, as well as dichotic listening ability. Further research that examines the relationship between attention, learning and dichotic listening in children with LD should be considered.

7.4.3.4. Memory and Attention

In the smaller, clinic-based study reported in Chapter 6, children with LD performed significantly worse in auditory working memory tasks compared to their counterparts. This is not surprising as general cognitive ability has been shown to correlate with, and even dependant on, performance in a range of behavioural tasks (Ahissar et al., 2000). As such, memory is often linked to arithmetic (e.g., Bull et al., 2008; Siegel & Linder, 1984), reading (e.g., Archibald & Gathercole, 2006; Swanson et al., 2009), learning (e.g., Alloway et al., 2005; Ashman & Elkins, 2002; Westwood, 2004), and attention (e.g., Mayes et al., 1998). The results from this thesis suggest that children with LD may have poor memory, which could affect other aspects of learning and auditory processing abilities. Indeed, a weak correlation between FP_{lin} and AWM and ANM_F was seen in the smaller, clinic-based study reported in Chapter 6. This is consistent with reports of FP_{lin} and DD being weakly correlated with auditory memory scores (Sharma et al., 2009; Tomlin et al., 2015; W.

J. Wilson et al., 2011), and reduced cognitive ability in children referred for APD assessment compared to those without APD (Rosen et al., 2010). While no relationship between scores from DD test and auditory working memory was seen in the results from clinic-based study reported in Chapter 6 could be a reflection of the small sample size of the study.

One of the skills that can influence behavioural AP tests and test scores is attention. In this thesis, the attention rates of children with LD was neither measured nor controlled for in the thesis. Attention is thought to play an important part in learning. Children with learning disabilities are reported to be highly distractible, and showed inability to filter out extraneous stimuli and focus selectively on the task (Tarver & Hallahan, 1974). Similar to children with learning disabilities, children with LD are reported to be frequently off-task, and are easily distracted (Ashman & Elkins, 2002; Treuen, van Kraayenood & Gallaher, 2000; van Kraayenood & Farrell, 1998). Given these factors, poor attention could have played a part in AP scores. Recently, Sharma et al. (2019) found that the scores of FP and DD tests were weakly correlated with sustained attention in 30 out of 49 children with APD. However, Tomlin et al. (2015) found that while memory and IQ significantly predicted the scores of FP and DD tests in a sample of school-aged children, attention did not. Although attention and AP overlap, they are thought to be separate processes that do not necessary occur together (Keller & Tillery, 2002). However, the relationship between attention and its effect on AP in children with LD should be investigated in future studies as the comorbidity of AP and attention deficits has been reported previously (Moore et al., 2010; Riccio et al., 2005).

7.5. Models to Explain the Relationship between PHL, AP Deficits and LD

The potential relationship between peripheral hearing loss (PHL) and/or AP deficit and learning is extremely complex and poorly understood, due in no small part to the complexities surrounding each of these areas. This section will attempt to explain models that might best explain relationships between LD and hearing impairment.

The regression models in the larger school-based study reported in Chapter 5 (Choi et al., 2018) and the smaller, clinic-based study reported in Chapter 6 showed that one peripheral hearing measure (AR), three AP hearing measures (FP_{lin}, DD and LPFS), and one cognitive measure (ANM_F) contributed significantly to regression models of children's learning. These findings could be explained by a risk factor model, whereby the presence of PHL or AP difficulties early in a child's development could, in some cases, interfere with the development of other skills needed for efficient and effective learning (such as language skills). For example, a subtle middle ear dysfunction that results in elevated AR thresholds could interfere with the development of language and social skills. Bennett, Ruuska, and Sherman (1980) showed that learning disabled children had more middle ear dysfunctions than non-learning disabled children. The authors speculated that chronic, undetected middle ear dysfunction could play a role in a child developing learning disabilities. As children with LD had significantly higher failure rates in tympanometry and AR tests, PHL could play a role in a child's LD. Similarly, as children with LD had significantly higher failure rate in temporal patterning and dichotic listening, AP difficulties could also play a role in a child's LD. However, neither PHL nor AP difficulties would be necessarily for LD in children.

Another model that could explain the relationships between hearing impairment and LD observed in this thesis is an association model where the presence of a deficit in a separate skill (or set of skills) that affects both AP and learning in children with LD. For example, a deficit in attention could explain poor scores on the measures of AP, memory and learning used. An alternative to the separate skill argument of an association model is the possibility that the tests of AP were testing more than just AP skills. This can be seen in some researchers suggesting both temporal patterning and dichotic listening tests associated at least partly with cognitive skills such as memory and attention (Keller et al., 2006; Riccio et al., 2005; Tomlin et al., 2015; W. J. Wilson et al., 2011).

The possibility of an association model explaining the relationship between hearing impairment and LD would be consistent with Moore and Hunter's (2013) proposed neurodevelopmental syndrome (NDS). The authors conceptualise NDS as an associated core of auditory, speech, language, attention, memory and behavioural difficulties in children that are each expressed along a continuum of severity. These difficulties vary from child to child depending on their unique genetic endowment and developmental environment. The developmental trajectory, combined with the demands of the academic and social environment, can result in unfolding skill deficits within the syndrome over time, making NDS a complex and highly dynamic condition (Witton, 2010).

Two other models that have less initial appeal for explaining the relationship between hearing impairment and LD observed in this thesis are the consequence model (where poor PH and/or AP are a consequence of LD) and the single distal cause model (where poor PH and/or AP causes LD). These two models were not well supported by the present study's findings as not every child with LD had poor PH and/or AP (as per the consequence model) and not every child with poor PH and/or AP had LD (as per the single distal cause model).

7.6. Implications for Practice: Is There a Need to Expand Hearing Screenings in Schools?

One of the practical implications of this thesis is that school-based hearing screenings should continue to ensure that PHL is detected as early as possible. Currently, most children in Australia participate in school-based hearing screenings upon entry to primary school. In most developed countries and in some developing countries, school-based hearing screenings have been widely implemented (Bamford et al., 2007; Theunissen & Swanepoel, 2008). Universal school-based hearing screenings have long been recognised as effective in detecting hearing loss that cannot be identified via newborn hearing screenings (Bamford et al., 2007). For instance, cases of PHL that are progressive, late-onset, or acquired through known (e.g., infection, chemotherapy, ototoxicity) or unknown causes (Fortnum, 2003).

The results from this thesis indicate that the rates of permanent PHL in children with LD are low. Instead, these children are more likely to experience transient PHL throughout their schooling. This poses a question of whether continuation of a universal hearing screening program is appropriate, or whether a targeted approach that relies on parental and teacher referral should be taken. A report by Bamford et al. (2007) suggested that despite higher costs, universal school-based hearing screening programs resulted in slightly higher quality-adjusted life-years when compared with a no screening or targeted hearing screening approaches. Similarly, the European consensus statement on school-aged hearing screenings indicated that universal school-based hearing screenings were highly effective when implemented correctly, and recommended that such screenings be an integral part of the school health program (Skarzynski & Piotrowska, 2012). Given such benefits, and despite relatively low rates of permanent PHL in children with LD, universal school-based hearing screenings at entry to school should continue to be implemented in primary schools in Australia. This approach could be strengthened to include newer, more sensitive methods of testing the middle and inner ear, such as wideband tympanometry and TEOAEs. For children who are already in the middle of their primary schooling, e.g., in years three and four, a more targeted school-based hearing screening approach could be implemented, one that would require teachers and parents to be more vigilant of the hearing health of the children in their classrooms and homes.

Another practical implication of the thesis is whether current school-based hearing screenings should be expanded to include AP screening. Considering children with LD showed high failure rates in AP tests, universal school-based AP screenings appears to be warrented. Currently, AP is not usually evaluated in children with LD except for cases when there is a suspected deficit in their listening abilities in noisy environments, despite having normal hearing sensitivity. Universal school-based AP screening has long been recommended by Iliadou et al. (2009) who suggest that auditory training in children with AP difficulties can improve phonological awareness, reading and speech discrimination ability, as well as enhance learning and academic achievement. In particular, the results from this thesis indicate that children with LD are more likely to have temporal patterning deficits as compared to their TD counterparts. Temporal patterning deficits have been related to reading deficits that are common in children with LD. As such, universal school-based screening that includes FP_{lin} as one of its tests could identify not only AP deficits in children, but also identify those who are at risk of LD. Currently, the identification process of LD at school involves standardised tests of reading, writing, spelling and mathematics, as well as memory and IQ screening (van Kraayenoord & Elkins, 2004). If the results from this thesis were true for all children with LD, the implementation of a universal school-based AP screening could streamline the identification process for children with LD. However, further research examining the relationship between AP tests and LD is warranted before implementing universal school-based AP screening as the findings from this thesis may not generalise to the broader population of children with LD.

Any introduction or expansion of universal hearing screening programs in schools would need to be supported by adequate resources, an effective referral pathway and rehabilitative options. The effective implementation of a school-based hearing screening can face several significant challenges. The cost can be prohibitive due to the expense of audiometric equipment and the requirement for trained personnel to conduct the screening and quiet, enclosed, unoccupied, furnished rooms in which to conduct the screening (Bamford et al., 2007; FitzZaland & Zink, 1984; Lo & McPherson, 2013). Poorly implemented school-based hearing screening also risk producing over-referrals for unnecessary and costly diagnostic assessments (Lo & McPherson, 2013). At present, effective referral pathways for those who fail AP screening are not widely available and would need to be considered before implementing universal school-based hearing screenings that include AP screening. Similarly, while several rehabilitative options are in place for each AP process (such as auditory training apps, personal FM systems), AP deficit is often linked with other deficits such as in reading, attention, and memory, and treatment and rehabilitative options for these co-morbid conditions would need to be considered. This would require multi- and preferable trans-disciplinary teams to ensure that the child is receiving appropriate and effective treatment.

Another barrier for including AP screening in current universal school-based hearing screening is the lack of a gold standard for the AP test battery. This makes evaluating test efficacy difficult and the selecting appropriate screening test battery complex (Iliadou et al., 2009). For this reason, a targeted AP screening approach may be more appropriate in children with LD. Heine et al. (2016) showed that school teachers were often the most common referrers for AP evaluation, with the reason for referral in most cases being due to concerns regarding literacy, speech and language, and academic underperformance. A targeted AP screening that sees teachers identify children at risk on this basis could be more cost-effective and minimise over-referrals for an AP screening program.

7.7. Limitations

Several limitations were identified in this thesis. First, the method used to classify children as having LD may differ from those used in other studies (although the challenges of defining the term are noted). As a possible consequence of this, some children with LD may not have been identified as such using this study's criteria for LD.

Second, the children included in this thesis were only recruited from the greater Brisbane area of Australia. The sample size of the smaller, clinic-based study reported in Chapter 6 was therefore small, and the findings of this research are difficult to generalise to the broader population of children with LD.

Third, in the school-based study, while all testing was conducted in quiet rooms in the participating schools, these rooms were not sound treated. While this might have had some effect on the pure tone audiometry results where testing was conducted at near-threshold levels, it was not thought to have affected the AP tests as the rooms were deemed quiet enough to allow for reliable testing at these suprathreshold levels. The tester was not aware of any child being distracted by noise during the test.

Fourth, the children in the smaller, clinic-based study reported in Chapter 6 were a clinical population only. These children had been recruited from the children in the larger school-based study reported in chapter 5 (Choi et al., 2018) on the basis of having failed one or both of the two AP tests used in that study (DD and LPFS). Children who would have failed other tests of AP would not have been identified through the school-based study and would not have been recruited into the clinic-based study. The specific nature of this clinical population prevents the results of the smaller, clinic-based study from being generalised to other clinical populations or to the general school-aged child population.

Finally, attention and language skills of the children were not assessed in any studies in this thesis. This prevented any direct considerations of the effects of attention and language on the AP and learning test outcomes.

7.8. Direction for Future Research

Future research investigating hearing in children with LD will first need to re-examine the construct of LD. The lack of real, conceptual or nominal (stipulative) definitions of LD continues to be a challenge as the remaining operational definitions fail to provide significant insight into the nature of the condition. This re-examination could draw upon existing conceptual models of LD that outline the purpose and scope of various terms and parameters that define LD, but this would need to occur using a language suitable for all stakeholders. An improved definition of LD will improve the identification pathway as well as outcomes for children with LD.

Future research would also need to reconsider our approaches to identifying children with LD in school. At present, universal hearing screening is limited to detecting the presence or absence of PHL. The results from the present thesis suggest that it is worth considering expanding the hearing screening to include screening for APD as a possible indicator of risk for LD. If the present study's findings hold true, simple measures such as a FP_{lin} test could serve this purpose. Given that deficits in language and cognition are co-morbid factors that can accompany deficits in AP and/or LD, a hierarchical assessment approach should be used to follow-up results from expanded school-based hearing screening.

Any re-examination of the construct of LD and/or reconsideration of approaches to identifying L in children would benefit from trans-disciplinary approaches involving teams of professionals. This would see audiologists working with other professionals from various disciplines such as classroom teachers, speech pathologists and psychologists to ensure that ultimately children with LD receiving adequate support and intervention. These activities will need to be supported by adequate resources, funding and support structure to ensure their viability.

7.9. Conclusions

This thesis investigated LD and hearing impairment in the school-aged child population in the greater Brisbane region of Queensland, Australia. In summary, children with LD had higher rates of transient PHL and AP difficulties compared to their typically developing peers. Any relationships between LD and hearing impairment might best be explained by risk factor models (where the presence of hearing impairment places a child at risk of LD, and vice versa), association models (where hearing impairment and LD can co-occur as a result of a common, underlying factor but the presence of hearing impairment does not guarantee the presence of LD and vice versa), and not explained by single distal cause models (where hearing impairment causes LD). The practical implications of these findings for personnel in the health and education sectors are continued screening for peripheral hearing loss, and a possible expansion of current school-based hearing screening to include AP tests. Future research will need to examine the feasibility of such a screening program, along with the possibility of a trans-disciplinary approach to subsequent referral and rehabilitative pathways.

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Appendicies

Appendix A. The University of Queensland Medical Research Ethics Committee Ethical Approval Letter

THE UNIVERSITY OF QUEENSLAND

Institutional Human Research Ethics Approval

Project Title:	Evaluating Auditory Function in Children with Learning Difficulties
Chief Investigator:	Ms Robyn Choi
Supervisor:	Dr Wayne Wilson, A/Prof Joseph Kei
Co-Investigator(s):	Dr Wayne Wilson
School(s):	SHRS, Division of Audiology
Approval Number:	2015000218
Granting Agency/Degree:	PhD
Duration:	31st March 2018

Comments/Conditions:

Note: if this approval is for amendments to an already approved protocol for which a UQ Clinical Trials Protection/Insurance Form was originally submitted, then the researchers must directly notify the UQ Insurance Office of any changes to that Form and Participant Information Sheets & Consent Forms as a result of the amendments, before action.

Name of responsible Committee:
Medical Research Ethics Committee
This project complies with the provisions contained in the *National Statement on Ethical Conduct in Human Research* and complies with the regulations governing experimentation on humans.

Name of Ethics Committee representative:
Professor Bill Vicenzino
Chairperson
Medical Research Ethics Committee

Signature ____________ Date 27.3.15

Appendix B. Education Queensland Medical Research Ethics Committee Ethical Approval Letter

Queensland Government

Department of
Education and Training

26 June 2015

School Principal(s)
Queensland State School(s)

Dear Colleague,

Ms Robyn Choi of the University of Queensland has the Department's approval to approach your school inviting participation in *Evaluating Auditory Function in Children with Learning Difficulties*. The acceptance of the invitation to participate is entirely voluntary and at your discretion.

This letter provides you with information about the Department's terms and conditions for research conducted on state school sites to inform your decision as to whether or not your school will participate in this research. The Department supports the conduct of quality research in State schools and values the potential contribution of good research in informing educational policy and professional practice. Participation in research, however, may impact on the daily operations of schools, and it is therefore imperative that discretion is used when deciding whether to agree to research involving your school.

As a minimum, the researcher should provide you with the following documentation to inform your decision regarding school research participation:

- an information statement which describes the research, identifies who will be involved (e.g. students, teachers, parents/caregivers) and explains what will be required of these participants
- the informed consent form for you to sign to indicate your agreement that school staff, students and/or parents/caregivers can be invited to participate in the research
- a copy of the approval to approach letter from central office or regional office (where applicable)
- a copy of the final ethical clearance from their institution's Human Research Ethics Committee
- full copies of any data collection instruments such as surveys, questionnaires, and interview schedules to be used in the study
- a copy of all current Blue Cards and/or exemption notices from Blue Card Services at www.bluecard.qld.gov.au for any researcher(s) seeking access to children on school sites.

Most importantly, participation in any research is voluntary, and you have the right to decline your school's participation in a research project, even if approval to approach your school has been granted at central office or regional level. It is also recommended that you monitor any research activities conducted in your school and you may, if you wish, withdraw your support for the research study at any time without penalty.

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ABN 76 337 613 647

At the conclusion of research involving your school, the researchers are required to provide you and participants with a written report summarising the main findings of the study.

Should you require further information on the research application process, please feel free to contact Tanya Murray, Senior Research Officer, Strategic Policy and Intergovernmental Relations on (07) 3034 6945. Please quote the file number 550/27/1566 in future correspondence.

Yours sincerely

Dr Angela Ferguson
A/Director
Research Services
Strategic Policy and Intergovernmental Relations