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MANAGEMENT OF CHILDREN WITH AUDITORY PROCESSING DISORDER

by

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DECLARATION

I, Hooi Yin Jenny LOO, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

The pilot study was conducted with the approval by the Ethics Committee of the National Hospital for Neurology and Neurosurgery and Institute of Neurology Joint REC in the UK; whereas the main study was carried out with the National Healthcare Group Ethics Board (Domain D) approval in Singapore.

The work was done under the guidance of Dr. Doris-Eva Bamiou, at the Ear Institute, and Prof Stuart Rosen, at the Speech, Hearing & Phonetic Sciences.

Signature:

Date:

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ABSTRACT

Recent advances in auditory neuroscience have expanded our understanding of auditory processing disorder (APD) – a hearing/listening disorder that is characterized by poor perception of speech and non-speech sounds, which results from atypical neural function predominantly in the brain (BSA, 2011).

The main purpose of this thesis was to examine the effectiveness of a self-developed computer-based auditory training (CBAT) intervention for children with APD. A systematic review conducted showed that very few studies report on a well-defined APD population, and many studies do not include untrained comparison group to tease out maturational or practice effect from true treatment effect, highlighting significant limitations of the existing evidence of CBAT for children with APD.

In view of the current absence of a ‘gold standard’ test battery for the diagnosis of APD, a review of a clinical database was conducted to inform the suitability of the type of auditory processing (AP) tests to be used in the main study. While both speech and non-speech AP tests are commonly used for clinical diagnosis purposes, the findings of this retrospective study showed that the current speech-based AP tests cannot be transferred readily across cultures. Non-speech AP tests, which are less influenced by individual’s linguistic background and language competency, are therefore deemed more suitable to be used in a diverse community with multilinguals, where the main study was to be conducted.

To help inform the feasibility and suitability of the current CBAT, a pilot study was conducted on 3 neurologically abnormal (PAX6 gene mutations) children with APD.

The results showed some broad improvement among these children after 3 months of intervention. By applying the same principle with modifications to the study design, a group of neurologically normal children with APD was randomised to training (n=20) and control (n=19) groups. The AP skills of the trained group improved significantly more than that of the untrained controls; such improvement lasted for at least 3 months. The improved AP skill was also consistent with the improvement observed in the functional skill in the trained group as reported by the teachers. Finally, neither the language nor cognitive skills was predictive of the training outcome, but the initial AP skills did.

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LIST OF ABBREVIATIONS

AAA	American Academy of Audiology
ABR	Auditory brainstem response
AC	Anterior commisurre
ADHD	Attention deficits and hyperactivity disorder
AFG	Auditory figure ground
AI	Primary auditory cortex
AP	Auditory processing
APD	Auditory processing disorder
ASD	Autistic spectrum disorder
ASHA	American Speech-Language and Hearing Association
AT	Auditory training
AVCN	Anteroventral cochlear nucleus
BM	Backward masking
BSA	British Society of Audiology
CAEP	Cortical auditory evoked potentials
CANS	Central auditory nervous systems
CBAT	Computer-based auditory training
CC	Corpus callosum
CF	Characteristic frequency
CIC	Central nucleus of inferior colliculus
CN	Cochlear nucleus
COCB	Crossed olivocochlear bundle
CS	Competing sentences
DCN	Dorsal cochlear nucleus
DDT	Dichotic digits test
DPT	Duration pattern test
EEG	Electroencephalography
FD	Frequency discrimination
FFW	Fast ForWord
fMRI	Functional magnetic resonance imaging
FPT	Frequency pattern test
HG	Heschl gyrus

HRTF	Head related transfer function
IC	Inferior colliculus
IHT	Interhemispheric transfer
IIL	Interaural intensity difference
ITD	Interaural time difference
LI	Language impairment
LL	Lateral lemniscus
LPFW	Low pass filtered words
LSO	Lateral superior olivary
MEG	Magnetoencephalography
MGB	Medial geniculate body
MLD	Masking level differences
MNTB	Medial nucleus of trapezoid body
MSO	Medial superior olivary
NVIQ	Nonverbal intelligence
OCB	Olivocochlear bundle
PET	Positron emission tomography
PP	Planum polare
PT	Planum temporale
PVCN	Posteroventral cochlear nucleus
REA	Right ear advantage
RGDT	Random gap detection threshold
SLI	Specific language impairment
SNR	Signal to noise ratio
SOC	Superior olivary complex
SPD	Spatial processing disorder
SRD	Specific reading disorder
STG	Superior temporal gyrus
STS	Superior temporal sulci
UOCB	Uncrossed olicocochlear bundle

Chapter 1

Central Auditory Neuroscience

1.1 Introduction

Hearing requires not only the ability to detect sounds in the ear, but also involves complex processing of auditory signals encoded in the form of neural activities in the brain to derive meaningful information. Sound enters the external ear canal and undergoes some mechanical process in the middle ear before reaching the cochlea (inner ear). The cochlea codes the frequencies of an auditory signal by the place of maximal vibration along the basilar membrane, with the high frequencies being mapped in the basal turn and the low frequencies being located in the apex. This unique feature of frequency mapping is known as tonotopic organisation, which is preserved in the auditory nerve and along the auditory pathway to the auditory cortex (Gelfand, 1998).

The auditory nerve consists of some 30,000 nerve fibres that are responsible for signal encoding and relaying all information accurately to the Central Auditory Nervous System (CANS). The auditory signal is encoded in several ways at the auditory nerve level. In general, spectral shape is encoded as the place of neural discharge by fibres that are arranged tonotopically, reflecting the frequency specific nature of the cochlea (Stach, 1998). Frequency may be additionally coded by temporal aspects of the discharge patterns of neuronal firing (phase-locking). Intensity, on the other hand, is coded as the overall rate of neural discharge (Stach, 1998).

The peripheral system described above plays a significant part in human’s auditory system, but the main component of AP lies in the CANS. The following provides an overview of the structural and functional organisation of the CANS, and briefly review some literature about neuroplasticity that underlie auditory learning.

1.2 Central Auditory Nervous Systems (CANS)

The CANS is primarily made up of various nuclei that serve as relay stations for neural information from the cochlea and auditory nerve to the auditory cortex (Figure 1.1). The first relay station in the CANS is the cochlear nucleus (CN). Several other important nuclei such as superior olivary complex (SOC), lateral lemniscus (LL), and inferior colliculus (IC) are located along the auditory pathway in the brainstem. The medial geniculate body (MGB) in the thalamus serves as the last relay station in CANS that connects between the brainstem and the auditory cortex. These interconnected nuclear complexes that form the elaborate networks of CANS have distinct anatomical and neurophysiological profiles. The interconnecting commissures of the two hemispheres of the brain [e.g. corpus callosum (CC)] also play a role in central AP.

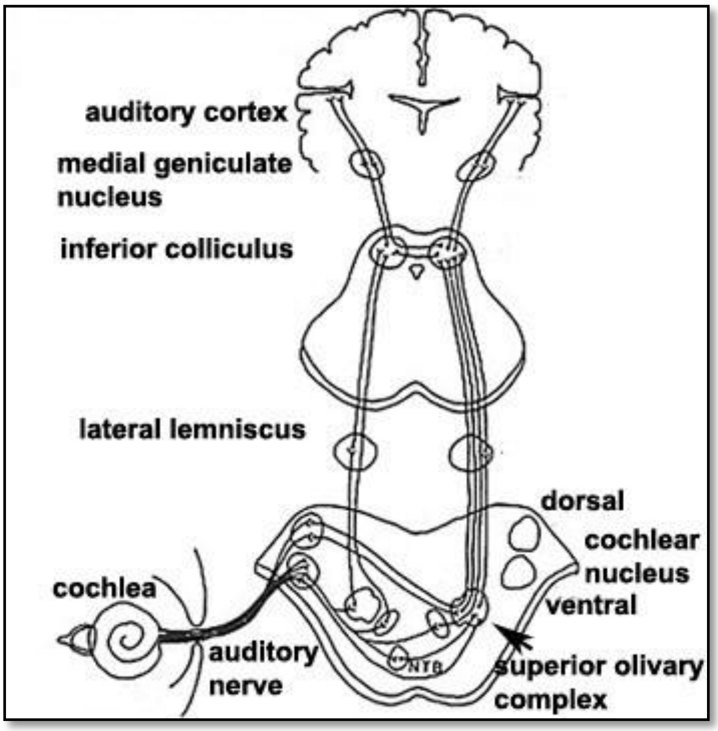


Figure 1.1: Central auditory pathway (Adapted from http://embryology.med.unsw.edu.au/notes/ear9.htm)

1.2.1 Cochlear Nucleus (CN)

The CN is located at the dorso-lateral side of the brainstem and consists of three subdivisions: anteroventral (AVCN), posteroventral (PVCN) and dorsal nucleus (DCN). Each subdivision of CN is innervated by the ipsilateral auditory nerve that bifurcates upon entering the brainstem. Three major neuron bundles project out of the CN, with the largest band from the AVCN projecting bilaterally, but primarily contralaterally to the SOC via the medial nucleus of trapezoid body (MNTB), and subsequently to the nuclei of LL and IC. Two other neuron bundles arise from the PVCN and DCN form mainly direct projections to the contralateral nuclei of LL and IC (Hackett, 2009). Physiological studies showed that the tonotopic organisation of the cochlea and auditory nerve is preserved within these CN subnuclei and their projections. Rose and colleagues (1959) demonstrated that the characteristic frequency (CF) of neurons, i.e. the frequency of tone to which they responded most briskly in AVCN changed orderly with location in the nucleus. Low frequency stimuli are generally encoded by ventrally located neurons while dorsally located neurons respond best to high-frequency stimuli.

The CN contains a plethora of morphological cell types that produce a variety of discharge patterns, and they are variously distributed within the subnuclei (Gelfand, 1998). The response patterns are progressively more inhibitory when moving from the ventral to dorsal region of the CN, and become increasingly complex. This diversity of responses makes the CN an important relay station, which pre-processes information before it reaches the central nuclei (Palmer, 1987). Classification of the CN neurons response types can be made on the basis of their response areas (as a function of frequency and intensity) and discharge patterns (as a function of time). Response areas of Type I, II, III, IV, and V units differ in terms of their relative prevalence of inhibitory regions and their response to different types of stimuli, tones or broadband noise. For instance, Type I neurons contain no inhibitory regions and respond to both tones and noise, whereas the response areas of Type IV neurons are predominantly inhibitory and respond very well to noise but weakly to tones. These neurons can additionally be classified into five basic categories according to the discharge patterns observed, i.e. primary-like, chopper, onset, build-up and pauser (Table 1.1).

Table 1.1: Firing patterns of different neuron types

Neuron types	Description of firing patterns
Primary-like	Higher discharge rate at onset, then adapting to a relatively steady rate.
Chopper	Firing pattern with preferred discharge times that are regularly spaced over time.
Onset	Discharge at the onset of the tone burst as shown by a sharply defined single peak.
Build-up	Firing rates gradually increase until they achieve a steady-state discharge rate for the remainder of the tone burst.
Pauser	The onset peak is followed by a pause in firing before the discharge gradually build-up again.

The three subdivisions of CN contain different types of cells. The AVCN encompasses the spherical bushy cells that exhibit a Type I response area and a primary-like peristimulus time histogram (PSTH). This cell type preserves the temporal organisation of the input with its phase-locking properties, which is necessary for sound localisation. In PVCN, various cell types are observed, including the chopper units, which are often associated with Type III response areas and show poor phase locking. Octopus cells, which are the only cell type found in the caudal PVCN, have type I/III response areas and exhibit onset responses that may also phase-lock. In deeper areas of the DCN, Type II units are found and which may serve as intrinsic interneurons providing inhibitory signals to the principal cells of DCN. The fusiform and giant cells, which have Types IV, V, and possibly III response areas in the output neurons of DCN, exhibit build-up and pauser patterns that phase-lock very poorly. It is believed that these neurons play a role in emphasising aspects of complex sounds and extracting phonetic information (Palmer, 1987).

In sunnary, the CN serves as an obligatory relay station in the early stage of CANS, and plays a role in selecting and redirecting information from the afferent cochlear nerve input for onward parallel processing at higher levels of the auditory pathway (Palmer, 1987).

1.2.2 Superior Olivary Complex (SOC)

The SOC is located in the region of the pons. It is the first stage in the auditory system where stimuli from both ears converge; therefore, the SOC is an important structure for encoding binaural cues necessary for sound localisation (Moore, 1991).

The SOC is made up of several subnuclei, including the medial superior olivary nuclei (MSO) and lateral superior olivary nuclei (LSO). The MSO derives its input from bilateral AVCN and from only one cell type – the spherical bushy cells (Cant & Casseday, 1986). The projections to the LSO are predominantly ipsilateral, but it receives input from at least two cell types (Cant & Casseday, 1986) – the spherical bushy cells from the ipsilateral AVCN and the globular bushy cells from the contralateral AVCN, via the ipsilateral MNTB (Irvine, 1992). The majority of MSO neurons receive excitatory inputs from either ear whereas the LSO neurons receive inhibitory input from contralateral stimulation and excitatory input from ipsilateral stimulation (Moore, 1991).

In the SOC, each of these subnuclei is organised tonotopically such that frequency representation of the AVCN is preserved (Goldberg & Brown, 1968). Although the tonotopic maps developed for the MSO and LSO show that each contains a complete frequency map, it has been suggested that there is a disproportionate frequency representation in these subnuclei, i.e. there are more neurons with low CF compared to high CF in the MSO, and the situation is reversed in LSO (Guinan, Guinan, & Norris, 1972). Osen (1969) suggested that a similar bias occurs in the parts of the AVCN projecting to the MSO and LSO, and likewise, subdivisions of the AVCN are biased towards particular CF ranges (Bourk, Mielcarz, & Norris, 1981). However, later studies found that both MSO and LSO receive inputs from parts of the AVCN that were tuned to all frequencies (Cant & Casseday, 1986).

Both subnuclei of the SOC contain different response characteristics, whereby cells concentrated at the MSO and LSO are sensitive to interaural time (ITD) and intensity differences (IID) respectively (Goldberg & Brown, 1969). ITD serves as a major cue for localisation of low frequency sounds in a horizontal plane, whereas IID provides localisation cue for high frequency sounds (Rayleigh, 1907). Goldberg and Brown (1969) noted that neurons responded to low frequency sounds behaved in a manner which, the phase of the stimulus tone was synchronised when there was a characteristics delay, or ITD, between the ears. In other words, the relative timing of the low frequency sounds that arrive at each ear determines the discharge rate. Responses were maximal when the inputs arrived in phase and were minimal when they were out of phase. For localising high frequency sounds, two groups of neurons were identified, which behaved in a different manner. The excitatory-excitatory (EE) neurons were found to respond to inputs from either ear and were sensitive to the average intensity of tones at both ears, whereas the excitatory-inhibitory (EI) neurons, which were found to receive excitation from one ear and inhibition from the other, served as detectors of intensity difference, or IID, through the balance between the excitatory and inhibitory influences from each side (Goldberg & Brown, 1969).

From the SOC, the projections ascend through the NLL and ultimately to the subdivisions of IC – the target of virtually all parts of the ascending (afferent) auditory pathway. There is evidence that the projections from the ipsilateral MSO and contralateral LSO to the central nucleus of the IC are excitatory, while those from the ipsilateral LSO are inhibitory (Oliver, Beckius, & Shneiderman, 1995). In addition to its ascending projections, the SOC also contributes to the efferent auditory pathway with its descending projections directed to the cochlea, namely the olivo-cochlear bundle (OCB) (Rasmussen, 1946). This efferent system constitutes two pathways: the crossed olivocochlear bundle (COCB), which primarily entails the medial system to the outer hair cells of cochlea, and the uncrossed olivocochlear bundle (UOCB), which is principally the lateral system synapsing with the afferents of the inner hair cells (Gelfand, 1998). The inhibitory function of the OCB (particularly the COCB) provides a mechanism for central feedback to, and control of activity at the auditory peripheral, which may in turn help to improve signal-to-noise ratio of signals (Dolan & Nuttall, 1988).

In summary, the function of the SOC in the auditory system is not only limited to segregating and directing cochlear signals to the higher level via the ascending i.e. afferent auditory pathway, but it may also play a role in the descending i.e. efferent auditory pathway by providing feedback control to the cochlea. The SOC is an important relay station that encodes binaural information in the form of intensity and phase differences which underpins sound localisation.

1.2.3 Inferior Colliculus (IC)

The IC is located at the level of midbrain. It can be divided into three parts: central nucleus of IC (CIC), external cortex (EC) and dorsal cortex (DC). The IC receives inputs from the ascending as well as the descending auditory pathways; and communication between the colliculi of two sides of the brainstem is achieved via the commissure of the IC (Gelfand, 1998). Therefore, the IC operates as an integrating station for monaural and binaural information processed by lower and higher auditory centres.

Of the three subdivisions of IC, the CIC is the only principal station for ascending auditory information, and is composed of neurons that are narrowly tuned and topographically arranged by CF (Merzenich & Reid, 1974; Aitkin, Webster, Veale, & Crosby, 1975). Its input connections are mainly from the LSO bilaterally, the MSO ipsilaterally and the dorsal nucleus of lateral lemniscus (DNLL) bilaterally. The crossed projections from the LSO and the ipsilateral MSO are generally excitatory, whereas the ipsilateral LSO is inhibitory (Oliver, Beckius, Shneiderman, 1995). Loftus and colleagues (2010) reported that functionally distinct zones of the CIC arising from differentially responsive ascending inputs, including low frequency ITD-sensitive projections from the ipsilateral MSO and LSO, high frequency IID-sensitive projections from the contralateral LSO and DNLL and also, monaurally responsive projections from the CN and ventral nucleus of the LL.

Neurons in the IC are therefore sensitive to ITD and IID, and thus respond to binaural stimulation in a similar way to the SOC. However, unlike the SOC, phase-locking has been found to occur in less than a third of the cells (Geisler, Rhode, & Hazelton, 1969) and also, some IC neurons are responsive to a sound source which is moved around the head (Goldberg and Brown, 1969)

1.2.4 Medial Geniculate Body (MGB)

Located in the thalamus, the MGB is the relay station for all ascending auditory pathways prior to the auditory cortex (Gelfand, 1998). Outputs from the MGB directed to the primary and non-primary auditory cortex may also be sent back to the MGB, forming a feedback loop (Hackett, 2009).

The MGB has three principal subdivisions including the ventral (MGv), dorsal (MGd) and magnocellular or medial (MGm) subdivisions. These are distinguished by their neuronal morphology, patterns of cortical and subcortical connections and physiology (Winer, 1984). Neurons in the MGv are narrowly tuned to tone frequency in contrast to the MGd and MGm, which are more broadly tuned. Cells of the MGv also have short response latencies, and show the familiar patterns of binaural input and interaction (Clarey, Barone, & Imig, 1992) whereas those of the MGd often have longer latencies and demonstrate irregular, habituating responses to input signals (Phillips, 2007).

The output projection from MGv forms the primary pathway targeting the core (primary) auditory cortex or AI (Calford & Aitkin, 1983), where neurons are arranged in laminae corresponding to the tonotopic organisation of the cochlea (Calford, 1983). The non-primary MGd and MGm project primarily to areas outside of AI, with the projection from MGd considered to be part of the non-tonotopic auditory pathway (de Ribaurpierre, 1997) due to a lack tonotopicity and broad tuning (Calford, 1983; Calford & Aitkin, 1983). The MGm is often considered to be part of a multisensory pathway (de

Ribaupierre, 1997), with some of the MGm responding to vestibular, somatic and auditory stimuli (Blum, Abraham, & Gilman, 1979).

Other than the ascending projections from the MGB to the cortex, there are some massive descending projections from the AI targeting each major MGB subdivision, in which these corticofugal projections extend beyond the thalamic nuclei further into the IC and lower brainstem (Winer, 2005). It has been suggested that these efferent pathways interact with the ascending pathways to provide a gain-control mechanism in the transmission of information from the periphery to the CANS (He, 2003).

Overall, the afferent and efferent connections of the MGB suggest that each division is primarily associated with one of several parallel pathways targeting the primary and non-primary auditory cortices, in which distinct aspects of auditory and multisensory processing appears to be mediated (Hackett, 2009). The function of the MGB therefore appears to be more complicated than just the passive transfer of information along the auditory pathway. Recent evidence has also indicated that the MGB may play a role in novelty detection (Anderson, Christianson, & Linden, 2009).

1.2.5 Auditory Cortex

In humans, the auditory cortical areas occupy an elongated region of cortex on the superior temporal plane within the Sylvian fissure (sometimes termed the lateral sulcus), which is hidden from view by the overlying parietal cortex (refer to Figure 1.2; Musiek, 1986a; Hackett, Preuss, & Kaas, 2001). The auditory cortex consists of a ‘core’ region (primary auditory cortex or AI) that is surrounded by a number of non-primary areas (Hackett, Preuss, & Kaas, 2001; Hall, Hart, & Johnsrude, 2003). For non-human primates, a model of auditory cortical organisation has been established, with the core region being subdivided into primary (AI), rostrotemporal (RT), and rostral core (R) fields, and surrounded by belt and parabelt non-primary areas (Kaas, Hackett, & Tramo, 1999; Hackett, Preuss, & Kaas, 2001). The exact number and location of subdivisions within the human primary and non-primary auditory cortex remains uncertain, however (Hall, Hart, & Johnsrude, 2003). In humans, AI corresponds to Brodmann area 41 and is largely confined to the first transverse temporal gyrus of Heschl (HG) (Hackett, 2009). The non-primary auditory regions are largely covered by Brodmann areas of 42, 52, and 22 (Galaburda & Sanides, 1980; Hackett, 2009), which include the planum temporale (PT), planum polare (PP), superior temporal gyrus (STG) and sulci (STS; Hall, Hart, & Johnsrude, 2003).

The precise cochleotopic orientation within the human auditory cortex appears to be variable across studies. Early work using a variety of techniques including magnetoencephalography (MEG), electroencephalography (EEG) and magnetic resonance imaging (MRI) showed converging evidence of low-to-high frequencies being mapped rostrolaterally to caudomedially along HG (Romani, Williamson, & Kaufman, 1982; Lauter, Jerscovitch, Fomby, & Raichle, 1985; Bilecen et al., 1998; Pantev et al., 1988). This pattern of findings was based on 500Hz and 4000Hz tone stimulation. However, more recent studies using functional magnetic resonance imaging (fMRI) with intermediate frequencies in the stimuli (Formisano et al., 2003; Talavage et al., 2004; Woods et al., 2009; Humphries, Liebenthal, & Binder, 2010) revealed tonotopic gradients with reversals along HG, which is suggestive of at least two mirror-symmetric gradients (Hackett, 2009). Humphries and colleagues (2010) also reported that low frequency regions centred on HG are bordered anteriorly and posteriorly by two high frequency areas. An additional smaller gradient was observed in the lateral posterior aspects of the STG, mainly in the left hemisphere.

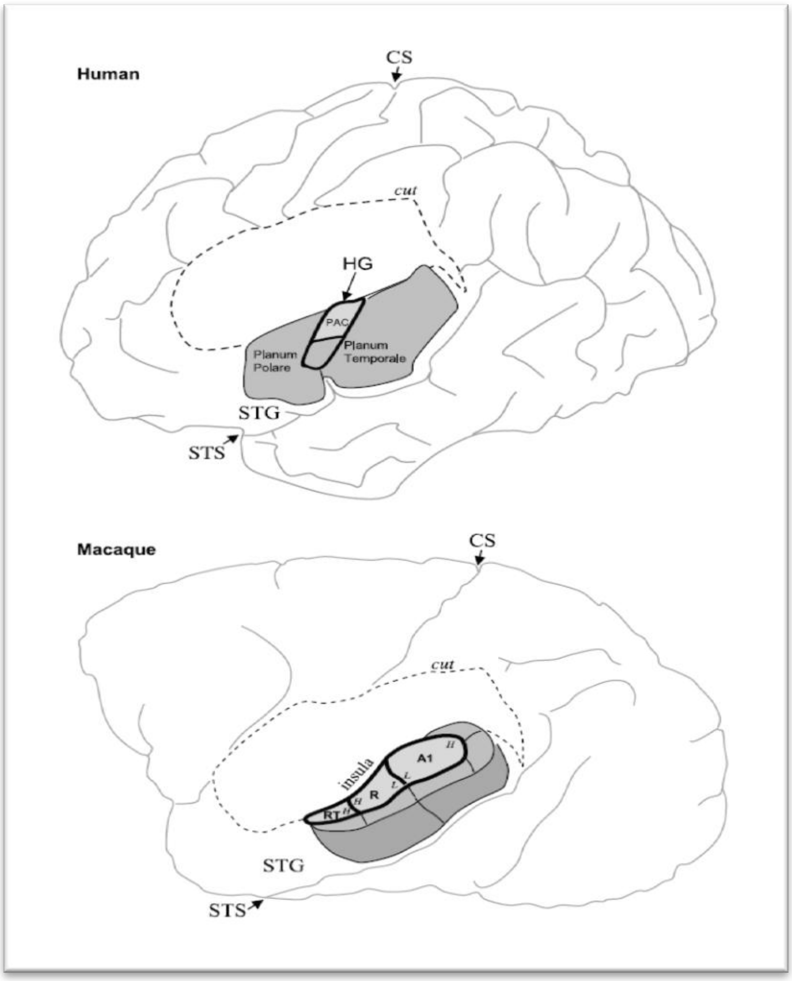


Figure 1.2: Schematic (dorsolateral) view of the human and macaque cerebral cortex after removal of the overlying parietal cortex. In the human brain, the darken line outlines the HG with primary auditory cortex (PAC) on the medial part of the gyrus. The lateral part of HG is surrounded by non-primary regions: planum polare (anterior) and planum temporale (posterior). In the macaque brain, the core region (contains three subdivisions: AI, R, RT) is outlined by the dark line and it is surrounded laterally and posteriorly by the belt region. The parabelt region occupies the most lateral part of the superior temporal gyrus (STG). CS = Central Sulcus, STS = Superior Temporal Sulcus. From Hall, Hart & Johnsrude, 2003).

The processing of sound involves activation of an extensive cortical network that is not confined only to the auditory cortex, but also to other acoustically responsive areas such as the adjacent temporal cortex, inferior portion of the frontal and parietal lobes, as well as the limbic areas (Hall, Hart & Johnsrude, 2003; Griffiths et. al, 2004; Zatorre, 2007). The interconnection between the auditory cortex and limbic system (e.g. amygdala and hippocampus) through the corticolimbic projections plays a role in the perception of emotional speech and the consolidation of auditory information to form new memories (LeDoux, Sakaguchi, & Reis, 1983).

It has been proposed that sound information is processed in a hierarchical fashion within this extensive cortical network, starting with the core auditory region proceeding through non-primary auditory areas and terminating in those acoustically responsive areas in the cortex (Hackett, 2009). This model of serial organisation of auditory cortex has been supported by anatomical and physiological evidence. In non-human primates, direct projections have been found from the core to the belt region, but not to the parabelt (Kaas & Hackett, 1998). Physiologically, evidence comes from the ablation of the core area AI that subsequently affected the responses of neurons in the adjacent belt area, in which they no longer responded to pure tone (Rauschecker, Tian, Pons, & Mishkin, 1997). In humans, studies have showed evidence of serial processing extending from HG to an area located on the posterior STG after an electrical stimulation of HG, with the latency and amplitude progressively shifted along the medial to lateral axis of the gyrus (Howard, et al., 2000; Brugge et al., 2003).

Parallel organisation within the auditory cortex has also been demonstrated in non-human primate studies. Rauschecker and colleagues (1997) reported that lesions in the AI area did not affect the neuronal responses of the adjacent core region (R), which further proved their anatomical findings of differential parallel projections from the thalamus (MGv) to the core areas AI and R. However, literature reporting similar patterns of parallel connectivity in human auditory cortex remains unclear. Wessinger and colleagues (2001) demonstrated that the human AI was primarily activated by narrow-band sounds such as pure tones; whereas greater activation in the non-primary auditory areas was via more complex, broadband stimuli, reflecting the non-sequential processing from primary to non-primary auditory areas, which is consistent with the model of parallel processing within each of those regions. In recent studies by Griffiths and colleagues (2007), however, results showed that analysis of a spectral envelope involves serial connections from HG to PT and then to STS rather than from parallel connections from HG to both PT and STS.

Some researchers (Romanski et al., 1999; Rauschecker & Tian, 2000) have proposed processing of auditory information via two separate streams: the spatial stream that originates in the posterior part of the STG and projects to the parietal cortex, and the non-spatial stream, which involves an anteriorly directed pathway of the belt region. This model has strongly influenced the description of auditory pathways as encoding ‘what’ i.e. object-related features of sound such as pitch, timbre and ‘where’ i.e. spatial related features of sound such as localisation information, respectively. To evaluate if such ‘what’ and ‘where’ pathways are present in humans, Arnott and colleagues (2004) conducted a meta-analysis of PET and fMRI studies between 1993 and 2003. Of the 10 spatial studies and 27 nonspatial studies, they revealed that activations in the temporal lobe involving spatial tasks were primarily confined to the posterior areas, whereas nonspatial activities were observed throughout the temporal lobe. Arnott and colleagues (2004) concluded that the evidence was supportive of AP segregation into two separate streams.

This model, however, has received criticism from other researchers. For example, Hall (2003) commented that distinction based on the two isolated ‘what’ and ‘where’ pathways is unlikely to provide adequate functional account for the entire auditory cortex. Griffiths and colleagues (2004) suggested that the presence of dual processing streams may be the result of limitations in the stimuli and analytical methods used in those studies, as several single- and multi-unit recording studies in animals have failed to demonstrate distinctive patterns of spatial and non-spatial coding properties of neurons among different cortical fields. Other studies have suggested that the posterior part of the human temporal lobe is selective to particular acoustic attributes, based broadly on spectrotemporal features such as changes in frequency spectrum over time (Belin & Zatorre, 2000; Zatorre, Bouffard, Ahad, & Belin, 2002), specific correlates of spatial location e.g. acoustic spatial sequences (Warren & Griffiths, 2003), or correlates of sound-source segregation e.g. pitch height (Warren, Uppenkamp, Patterson, & Griffiths, 2003). It has also been proposed that the human posterior temporal lobe is possibly connected with speech processing areas, including Wernicke’s area (Wise et al, 2001; Blank et al., 2002).

1.2.5.1 Mapping auditory cortical function in humans

Activation of the auditory cortex is strongly influenced by changes in fundamental sound attributes such as pitch, sound level, motion and location. Compelling evidence from imaging studies (Griffiths, Buchel, Frackowiak, & Patterson, 1998; Patterson, Uppenkamp, Jonhsrude, & Griffiths, 2002; Penagos, Melcher, & Oxenham, 2004) suggests that the lateral HG plays a key role in pitch perception - a perceptual correlate of acoustic frequency which is determined by the periodicity of a sound waveform (Hall, Hart, & Johnsrude, 2003). This is further supported by cortical lesion studies that patients with bilateral HG damage are impaired on frequency and pitch discrimination tasks (Tramo, Shah, & Braida, 2002; Warrier & Zatorre, 2004). The right HG is believed to encode the direction of pitch changes (Johnsrude, Giraud, & Frackowiak, 2002) as well as discriminating the pitch of missing fundamental sounds (Zatorre, 1988). The perception of pitch may also involve a network of pitch-sensitive regions, with different areas contributing to different types of pitch judgements (Bizley & Walker, 2010). Warren and colleagues (2003) also found that cortical regions located anteriorly and posteriorly to AI are sensitive to pitch chroma (a basis for melodies) and pitch height (a basis for segregation of notes into streams to separate sound sources) respectively. Zatorre and colleagues (1994) additionally reported that the analysis of pitch patterns is associated with activity in the frontoparietal regions.

Brechmann and colleagues (2002) investigated the differential sensitivity to sound level across four different subregions of the auditory cortex and found that, the AI and the lateral part of HG (non-primary area) are the most robust areas which are responsive to sound level. The intensity of sound influences not only the magnitude of activation, but also the spatial extent of activation. Some studies reported systematic changes in activation in both amplitude and spatial distribution following an increment of sound level (Lockwood et al., 1999a; Hart, Palmer, & Hall, 2002, Brechmann, Baumgart, & Scheich, 2002), while others reported changes in either amplitude or distribution of activation (Jäncke et al., 1998; Mohr et al., 1999). Increases in amplitude have been observed around the border between HG and PT via MEG, following sound level increments (Gutschalk et al., 2002).

The auditory cortex also plays an essential role in sound localisation despite most of the subcortical nuclei being responsible for extracting interaural time and intensity differences. It has been shown that the location of sound influences activation in the PT within both hemispheres (Baumgart et al., 1999; Warren et al., 2002), with substantially larger activation observed to sounds delivered to the contralateral than the ipsilateral ear (Musiek 1986a; Woods et al., 2009). This is supported by lesion studies which showed that patients with unilateral temporal lobe damage had difficulty locating sounds that were contralateral to the damaged hemisphere (Sanchez-Longo & Foster, 1958). In addition to the auditory cortex, part of the inferior parietal lobule in the right hemisphere appears to be involved in sound localisation (Weeks et al., 1999; Alain et al., 2001). Motion discrimination was also shown to activate the PT and the inferior and superior parietal regions to a greater degree in the right rather than the left hemisphere (Baumgart et al., 1999; Ducommun et al., 2002; Hart, Palmer, & Hall, 2002).

In summary, AP involves an elaborate network within the auditory cortex as well as other acoustically responsive areas within the parietal and frontal lobes. Activations of the primary and non-primary auditory regions by sound is largely determined by fundamental features including spectral-temporal content, intensity and location. Activation can additionally be modulated by attention, as shown particularly in the non-tonotopic lateral regions (Woods & Alain, 2009; Woods et al., 2009).

1.2.5.2 Lateralisation of human brain

Hemispheric functional specialisation of the human brain is well documented (Springer & Deutsch, 1981; Zatorre 2001; Tervaniemi & Hugdahl 2003). Generally, the left hemisphere serves as the dominant site for speech and language processing (Springer & Deutsch, 1981), although lateralisation of speech processing has been suggested to be associated with hand-preference, in that left-handers have a higher prevalence of right-sided or bihemispheric representation of language compared to right-handers (Bryden, 1985). The left hemisphere is also crucial for recognising and processing detailed information (Springer & Deutsch, 1981; Scott & Johnsrude, 2003) compared to the right hemisphere, which is important for recognising contours of acoustical information within tones and music (Zatorre, 2001; Tervaniemi & Hugdahl, 2003). Consistent with this functional asymmetry, a dynamic dual processing pathway model for auditory language comprehension was proposed by Friederici and Alter (2004). In this model, the syntactic, i.e. grammatical and sentence formation rules, and semantic, i.e. meaning of a sentence/word, of speech are primarily processed in the left hemisphere in a temporo-frontal pathway, whereas the sentence level prosody is processed in the right hemisphere. A list of other functions related to each hemisphere is summarised in Table 1.2.

Table 1.2: Types of functions attributed to the cerebral hemispheres (Adapted from Musiek, 1986a)

Left hemisphere	Right Hemisphere
Language/speech (grammar, vocabulary, literal)	Language/speech (intonation, prosody, pragmatic) and music
Detailed	General
Analytic	Gestalt
Reading, writing	Figure and facial recognition
Controlled	Emotional
Concrete	Abstract

In summary, the human brain has a strong predisposition to process speech in the left hemisphere and tonal-related or music sounds in the right hemisphere. However, this cortical functional lateralisation, as reviewed by Tervaniemi and Hugdahl (2003), is not bound to informational sound content but to rapid temporal information, i.e. speech is characterised by rapidly changing broad-band sounds and is better processed in the left hemisphere, while music is more of slower narrow-band stimulus type and is therefore optimally processed in the right hemisphere.

1.2.6 Corpus Callosum (CC) - Interhemispheric Pathways

As mentioned above, the human brain is characterised by hemispheric lateralization. However, even though both hemispheres have been noted to have selective and distinctive functional network, they are able to exchange information via reciprocal inter-hemispheric pathways.

The CC is the largest myelinated fibre tract that connects the two cerebral hemispheres and is located at the base of the longitudinal fissure (Figure 1.3). The superior portion of CC is primarily covered by the cingulate gyri, whereas the inferior portion forms most of the roof of the lateral ventricles. The most anterior and posterior aspect of CC is known as genu and splenium, respectively. The middle portion of the CC is made up of the trunk, and the rostrum connects postero-inferiorly to the genu. The anterior commissure (AC) is a separate structure that is located inferior to the anterior segment of the CC and has been noted for form connections with each hemisphere (Musiek. 1986b).

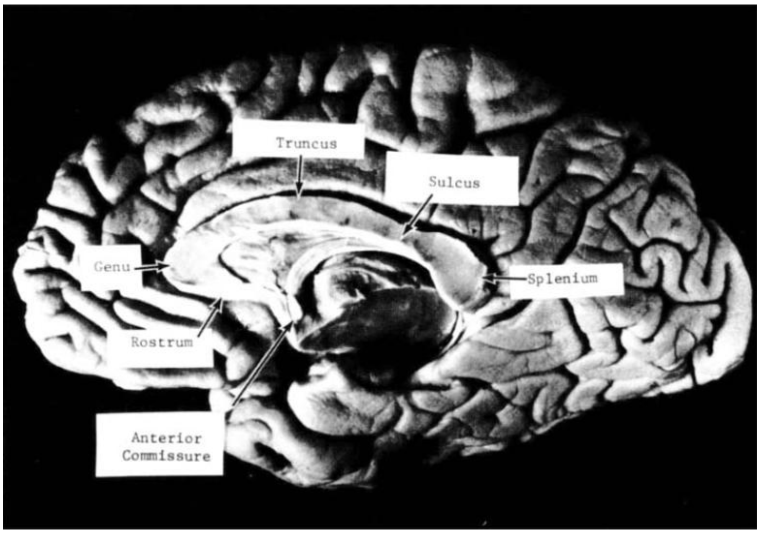


Figure 1.3: A midsagittal section of the corpus callosum showing the main anatomical areas. From Musiek, 1986b.

The CC fibres form two types of connection between the hemispheres: homolateral and heterolateral connections. The homolateral fibres, which form the primary connections of the CC, originate at certain loci in one hemisphere and connect to the corresponding contralateral loci, whereas the heterolateral fibres connect different loci in the two hemispheres (Pandya & Seltzer, 1986). Different parts of the CC contain commissural projections from other cortical areas. The anterior two thirds of the genu contain fibres originating from the prefrontal lobe and the central portion of the trunk contains primary motor and somatosensory fibres. The fibres from auditory areas in the inferior part of the parietal and temporal lobes, and also the posterior part of the insular, connect with the opposite hemisphere through the posterior part of the CC, i.e. around the posterior segment of trunk as well as the splenium and the AC (Musiek, 1986b). Fibres transmitting the visual representation from the occipital lobe, are confined to the splenium (Pandya & Seltzer, 1986).

As noted in cortical areas, the CC is topographically mapped (Pandya & Seltzer, 1986). Evidence also suggests that its fibre composition differs regionally in terms of the specific conduction properties associated with different functional pathways (Aboitiz, Scheibel, Fisher, Zaidel, 1992). For example, callosal regions that connect to primary and secondary sensory and motor areas have fast-conducting, large diameter myelinated fibres, whereas callosal regions connecting to association areas have a high density of slow-conducting, small diameter, lightly myelinated fibres (Aboitiz, 1992). The auditory segment, which is confined to the posterior half of the CC, is also found to have large diameter fast conduction fibres that enable fast interaction between the hemispheres. This may subserve some important AP skills such as dichotic listening and sound localisation (further discussion in section 1.2.6.1; Aboitiz, Scheibel, Fisher, & Zaidel, 1992).

An association between the size of the CC and hand-preference has been shown, with callosal areas found to be larger in consistent right-handers than in non-consistent right-handers (Witelson, 1985 & 1989; Habib et al., 1991). Sex-related differences in the size of the posterior segment of the CC (isthmus) have also been reported, but these findings remain controversial. In some studies, females were found to have a proportionally larger isthmus compared to males (Witelson, 1989; Steinmetz et al., 1992; Clarke & Zaidel, 1994). However, other researchers have reported that a smaller isthmus is only observed in males that have a significant asymmetry in the size of Sylvian fissure (Aboitiz, Scheibel, & Zaidel, 1992).

1.2.6.1 The role of corpus callosum in auditory processing

The CC plays an important role in the interhemispheric transfer of information and therefore may contribute to integrating and optimising perception of the different modalities. Abnormalities of the CC may significantly affect the functional laterality and the speed of information transfer between the hemispheres (Hannay et al., 2008). The structural and functional importance of the CC in AP has become evident from a number of studies. The following paragraphs will attempt to summarise and discuss some of these findings, including results obtained from patients with a split- brain i.e. where the CC was surgically sectioned, and from those where the CC was congenitally absent.

(A) Dichotic Listening Tests

One of the most powerful but non-sophisticated psychoacoustic tests for assessing interhemispheric transfer of auditory information is dichotic listening. This involves simultaneous presentation of similar but non-identical acoustic stimuli to both ears, with the listener then repeating the stimuli heard from either one or both ears. Commonly-used stimuli include consonant-vowel (CV) syllables, digits, words, spondees, and sentences (Keith & Anderson, 2007); however nonverbal stimuli such as humming, coughing, and laughing have also been employed for research purposes (Kimura, 2011). Historically, the dichotic listening technique was introduced by Broadbent (1954) to investigate certain aspects of attention and memory. It was subsequently expanded to become an important auditory assessment after Kimura (1961) reported its effectiveness in measuring brain dysfunction and hemispheric asymmetries.

In dichotic speech testing, right ear advantage (REA) is observed in right-handed normal subjects (Jäncke, 2002). This phenomenon has been interpreted as reflecting the dominance of the left hemisphere in speech perception, and the supremacy of the contralateral auditory pathways in signal transmission when the two ears are in competition. This hypothesis was first described by Kimura (1967) and subsequently led to the proposal of the "callosal relay model" by Zaidel (1986). According to this model, dichotic speech stimuli presented to the left ear are thought to be first sent to the right hemisphere and then, via the corpus callosum, being transferred to the dominant left hemisphere for processing. Therefore, the extra callosal transfer time from the right to the left hemisphere results in the delayed processing of stimuli presented to the left ear (Hugdahl, Carlsson, Uvebrant, & Lundervold, 1997). Another model that has been proposed to explain the REA is the "direct access model", which assumes that speech stimuli from the left ear are directed to the less efficient right auditory cortex, which requires a longer processing time (Zaidel, 1986).

The critical role of the CC in accordance with the callosal relay model has been supported by several split-brain studies that have employed dichotic listening experiments (Milner, Taylor, & Sperry, 1968; Musiek, Reeves, & Baran 1985; Musiek et al., 1989; Mohr, Pulvermuller, Rayman, & Zaidel, 1994; Sugishita et al., 1995). The pattern of dichotic speech test results obtained from split-brain patients is fairly consistent among these studies, indicating significant suppression or near extinction of speech stimuli presented to the left ear while the right ear performance is preserved and therefore, REA is enhanced. The improvement in the performance of the right ear after commissurotomy is believed to be due to a release from central auditory competition (Musiek, Reeves, & Baran, 1985). Normal results were obtained with monaural speech tests (Milner, Taylor, & Sperry, 1968; Musiek & Reeves, 1986).

Individuals with congenital absence or agenesis of the CC, however, yielded mixed findings in dichotic speech tests (Chiarello, 1980) and their performance is markedly different from that of the split-brain patients (Musiek, 1986b). It has been postulated that redundant cerebral lateralisation established in each hemisphere (Lassonde, Bryden, & Demers, 1990) and the development of alternative interhemispheric routes resulting from brain plasticity (Lessard, Leporé, Villemagne, & Lassonde, 2002; Santhouse et al., 2002) probably account for the functional compensation of the congenital absence of the CC. For example, Geffen (1980) reported equal left and right ear performance in a single case of total CC agenesis, suggestive of bilateral language representation, whereas other researchers (e.g. Bryden & Zurif, 1970; Lassonde, Lortie, Ptito & Geoffroy, 1981) reported clear lateral asymmetries in total CC agenesis patients. These studies also indicated a superior left ear performance, in contrast to the finding of an enhanced REA seen in commissurotomy cases. It should be noted that the number of subjects in these studies was small, i.e. n = 1 (Bryden & Zurif, 1970) and n = 2 (Lassonde Lortie, Ptito & Geoffroy, 1981), however, possible corroboration of this work came from a later study that investigated auditory interhemispheric transfer (IHT) in patients with congenital CC anomalies associated with spina bifida meningomyelocele (SBM; Hannay et al., 2008). It was found that the performance of SBM children (n = 90) varied with splenium status, i.e. right-handed SBM children that had either a normal splenium (n = 12) or hypoplasia (n=49) showed a REA comparable to that of normal children (n = 27), whereas those with splenial agenesis (n = 31) indicated a slight left-ear advantage (LEA).

Bamiou and colleagues (2004) conducted a study to investigate the auditory IHT of adults with PAX6 genes mutations (n=8) associated with AC agenesis/hypoplasia and CC hypoplasia. It was found that all PAX6 adults showed abnormal results in at least two of the auditory tests that required IHT, which included dichotic digits, dichotic CV, dichotic rhyme tests, frequency and duration pattern tests. The left ear performance in dichotic speech tests was significantly poorer in the PAX6 adults compared to the age-matched normal controls. Similar left ear deficits in dichotic speech tests were also reported in children with PAX6 genes mutations (Bamiou et al., 2007a). However, subtle differences in performance were noted between the adults and children when they performed dichotic listening using different speech material. For example, adults with PAX6 mutations showed a significantly reduced left ear score on the dichotic CV test but no significant difference between the right and left ear scores with the dichotic rhyme test (Bamiou et al., 2004), whereas the opposite was found in the studies that tested children (Bamiou et al., 2007a). The authors commented that a few possibilities could account for these differences, including a limited sample size, as well as age-related or developmental changes of the auditory interhemispheric pathways.

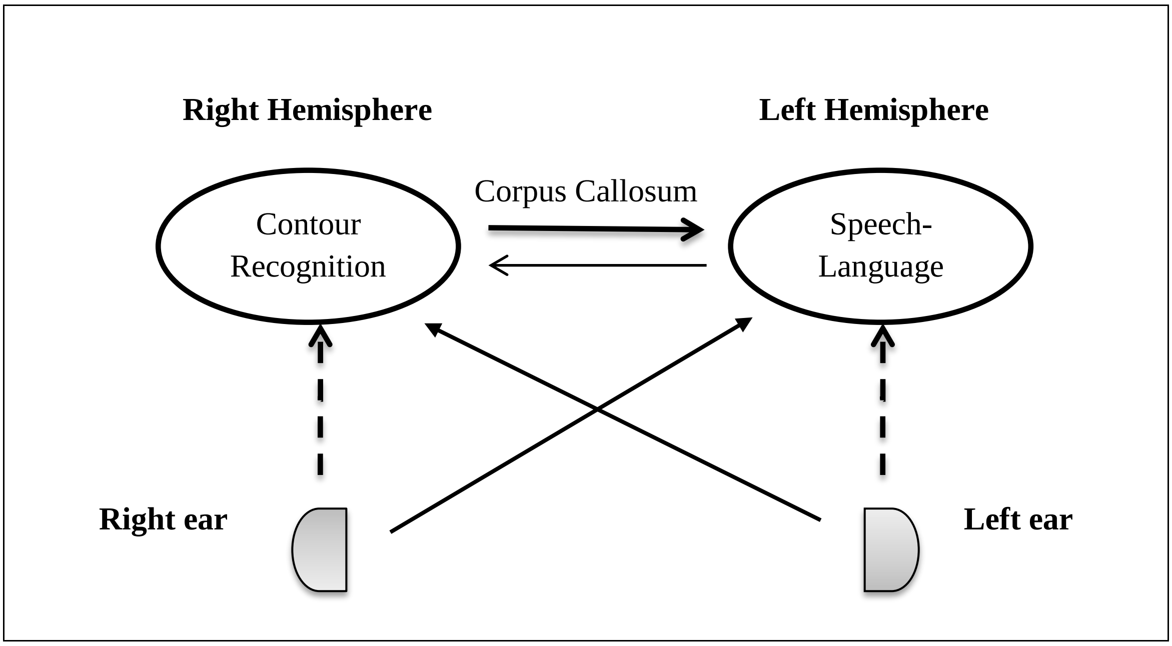
(B) Auditory Patterning Test

The auditory pattern test is another psychoacoustic method that has been used to assess patients with hemispheric lesions and interhemispheric dysfunction. It was originally introduced by Pinheiro and Ptacek (1971) to assess the pattern perception of normal hearing subjects, and was subsequently extended to patients with hemispheric lesions (Pinheiro, 1976) and AP dysfunction related to dyslexia (Pinheiro, 1977).

The involvement of the CC in the auditory pattern test was first demonstrated in the split-brain patients reported by Musiek and colleagues (1980). Bilateral deficits on monaural auditory pattern tasks (such as frequency pattern and duration pattern), with an inability to verbalise/label the tone patterns being reported in patients after commissurotomy (Musiek, Pinheiro, & Wilson, 1980). It was postulated that the recognition of tone contour is processed in the right hemisphere, and then sent to the left hemisphere for linguistic labelling via the CC (see Figure 1.4). In cases where the CC is compromised, the dysfunction of IHT impedes the information from the right hemisphere being sent to the left for labelling (Pinheiro & Musiek, 1985). However, in cases with intact auditory cortex in the right hemisphere, the ability to identify and hum the tone patterns is typically preserved.

In studies performed by Bamiou and colleagues (2004 & 2007a), similar results to the split-brain studies were observed in more than half of the PAX6 subjects (both adults and children), i.e. bilateral labelling response deficits were observed in frequency pattern and/or duration pattern tests. Normal results on auditory pattern tests were also reported in a few adults with PAX6 mutations (Bamiou et al., 2004). Since the structural anomalies of the CC and AC in PAX6 patients is more variable than the split-brain patients where the CC is completely sectioned, the results obtained from this group of patients on tests that require IHT is also expected to be less homogenous.

Figure 1.4: Pathways involved in temporal patterning (Adapted from Shinn, 2007)



(C) Localisation Test

As mentioned earlier in section 1.2.5.1, the auditory cortex in both hemispheres is involved with sound localisation. The two cortices are interconnected by the CC, and thus it is believed that the CC facilitates sound localisation by integrating inputs from the two hemispheres.

Poirier and colleagues (1993) conducted a study to examine the response accuracy of acallosal patients (n=4) to stationary and simulated moving sound stimuli in the horizontal plane. They found that acallosal patients performed significantly poorer than normal controls in localising the fixed sound source; however, no significant differences were reported between the two groups in localising moving sound stimuli, with the same pattern of localisation accuracy being found with no apparent hemispheric asymmetry. This observation was not in line with the notion of a right hemispheric specialisation for spatial processing (Sanchez-Longo & Foster, 1958; Ruff, Hersh, & Pribram, 1981), thus the authors concluded that sound localisation in humans may be determined by higher order cognitive functions.

Conversely, Lessard and colleagues (2002) reported that acallosal (n=5) and early callosotomised (n=1) patients performed equally well with neurologically intact controls in localising fixed sound sources in the horizontal plane, but were less accurate in localising moving sound targets in binaural conditions. However, in monaural listening conditions (with one ear blocked), acallosal patients outperformed normal controls in sound localisation, indicating a more efficient use of monaural cues, which presumably developed over time in order to compensate for impaired IHT. Subsequently, the assumption of functional reorganisation of the auditory interhemispheric pathway in sound localisation was tested and confirmed in some, but not all acallosal patients, by Paiement and colleagues (2010).

Hausmann and colleagues (2005) assessed the lateralisation skills of callotomised (n=2) and CC agenesis (n=1) patients using tasks with variable interaural time differences. They found that patients with a congenitally absent CC had a marginal reduction in response accuracy whereas the callosotomised patients showed significant deficits with a leftward bias of sound lateralization compared to normal controls. As compared to patients with a hemispherectomy, who had total loss of sound-lateralisation ability, this ability is still preserved in patients with an absent CC. Therefore, the authors commented that the role of the CC in auditory IHT is important for spatial hearing based on binaural cues; however, it is not indispensable. From combining their findings with those of Lessard and colleagues (2002), the team also postulated that the age at which the CC was surgically sectioned had an impact on the extent of functional reorganisation of the auditory interhemispheric pathways i.e. compensatory plasticity may have occurred to a lesser degree in callosotomised adults compared to children.

In summary, the functional role of the CC is undoubtedly crucial in the human auditory system. However, the effects of an absent CC in audition are different in individuals who had an insult to the CC structurally via complete or partial callosotomy later in life compared to those with agenesis of the CC or a congenitally absent CC, where less severe deficits have been observed.

1.3 Neuroplasticity

There is a substantial body of literature demonstrating that the CANS has the capacity to change, which enables neurons in the auditory domain to better conform to the immediate environmental listening demands (Musiek, Shinn, & Hare, 2002). The mechanisms underlying cortical reorganisation or “plasticity”, induced by experience or stimulation, may involve the activation of inactive neuronal connections and/or the formation of more efficient synaptic connections within the brain (Chermak, Bellis, & Musiek, 2007). Three types of neural plasticity (Musiek, Shinn, & Hare, 2002; Musiek, Chermak, & Weihing, 2007) have been described in the literature:

1. *Developmental* plasticity – this is the result of increased myelination and connectivity of neurons that lead to neural maturation of the brain.
2. *Compensatory* plasticity – this occurs after an insult to the brain, where the intact part of the nervous system assumes the function of the damaged areas.
3. *Learning-related (activity-dependant)* plasticity – the brain changes in response to the needs and experience of the individual.

The following paragraphs will attempt to give examples of studies that have provided evidence of plasticity in the auditory system.

1.3.1 Developmental Plasticity

Even though the cochlea is fully mature at birth, there is mounting evidence showing that the development of auditory pathways in the subcortical and cortical areas have different maturational time courses.

The human auditory brainstem is thought to be fully mature by the age of 2 years because the auditory brainstem response (ABR) to tones and clicks resembles that of an adult at this time (Moore & Guan, 2001). However, Johnson and colleagues (2008) recently found that children aged 3-4 showed differences in speech-evoked ABRs i.e. delayed and less synchronous onset and sustained activity, compared to older children (aged 5-12 years-old), despite showing identical responses to click stimuli. This suggests that developmental plasticity in the auditory brainstem extends beyond the age of 2 years and that development of speech encoding in subcortical regions may be underpinned by experience-dependent plasticity. Johnson and colleagues highlighted that this is consistent with the observation that children learn how to read and develop a strong sense of phonological awareness at around 5 years old, after starting school.

In contrast to subcortical areas, the auditory cortex has a more protracted developmental time course (Moore & Guan, 2001). Cytoarchitectonic evidence shows that early axonal maturation of the auditory cortex is limited to superficial layer 1 at birth. Between the ages of 1 and 5 years, maturation increases to the deeper layers (II-VI) with the auditory cortex reaching full maturity at around 12 years of age (Moore & Guan, 2001). In parallel to the axonal maturation of the auditory cortex, age-related changes in electrophysiological measures were also reported, which appear to correlate with maturation in behavioural measures such as speech perception (Eggermont & Ponton, 2003).

Ponton and colleagues (2000) evaluated CANS maturation by recording cortical auditory evoked potentials (CAEP), elicited by clicks and tones in 118 subjects aged between 5 and 20. It was noted that the latency and amplitude of P1 and N1b decreased as a function of age, and became essentially adult-like in subjects aged 15-16 years. There appeared to be a longer maturational time course for the development of P1 amplitude, which appeared to extend up to 18-20 years. Maturational changes in P2 amplitudes were very similar to that of P1 and little change in P2 latency was noted during middle childhood. However, the amplitude of N2 was found to increase as a function of age. These maturation patterns appear to reflect the distinct time courses of development of the different auditory pathways and generators underlying the CAEP. The prolonged maturational time course of the auditory cortex is also evident through the observed development of AP skills. For example, it has been found that younger children have poorer speech recognition ability in noise compared to adolescents (Elliot, 1979).

An MRI study investigating the progression of myelination in seven human cortical regions related to auditory and language processing revealed that despite reaching maturity by 1.5 years, myelination continued to progress into adulthood (Su et al., 2008). It was also reported that myelination in motor, auditory and visual cortex takes place earlier than in Broca’s area (speech production area), Wernicke’s area (speech reception area), the angular gyrus and the arcuate fasciculus, which took the longest time to mature. The observations obtained in this study suggest that the higher cortical areas matured later than the primary areas and that myelination progresses most rapidly from birth to age 5 years. This may explain the observed acceleration of language acquisition in children during this age range, which became known as the critical period.

Behavioural studies such as those by Johnson and Newport (1989) and Werker and Tees (1983) appeared to support the critical period hypothesis, which may explain why capacity for language acquisition is greatest in early life, but then gradually disappears or declines with maturation. Johnson and Newport (1989) reported that adults who learnt a second language in early childhood mastered that language more proficiently than those who acquired it much later in life i.e. after puberty. Werker and Tees (1983) showed that the ability to discriminate non-native speech contrasts declined by 4 years of age. These studies therefore suggest that development in linguistic perceptual abilities occurs primarily in early childhood. An fMRI study by Kim and colleagues (1997) provides further evidence of early developmental organisation of language representation in the brain being dependent on the time of language acquisition. It was shown that in subjects who acquired a second languages in adulthood, representation of the second and native languages was spatially separated in Broca’s area, while in subjects who acquired native and second languages together during the critical period, a common spatial pattern of representation for both languages was present.

1.3.2 Compensatory Plasticity

Evidence from event-related potential (ERP) and neuroimaging studies has shown that cortical reorganisation occurs after auditory deprivation, either by cross-modal reorganisation or expansion of adjacent (perilesion) frequency representations. Using a PET scan method, Nishimura and colleagues (1999), showed that the STG in both hemispheres can be activated by sign language in congenitally deaf subjects, even though this brain region is usually reserved for hearing. Similar findings were also reported by Petitto and colleagues (2000), who showed that the planum temporalis and inferior frontal cortex, which are widely assumed to be unimodal speech or sound processing areas, were activated when signers viewed signs. In blind subjects, auditory activation has been found in the occipital cortex using ERP techniques (Kujala et al., 1995). Cross-modal plasticity has also been demonstrated in adult deafened cats, where enhancement of the peripheral visual field was found which lead to localisation skill that was superior to that of hearing cats (Lomber, Meridith, & Kral, 2010). A longitudinal PET study conducted by Park and colleagues (2010) has highlighted significant metabolic changes in AI following deafness, with significant declines in metabolic activity at 24 months and subsequently, a disappearance of activity after 33 months. In parallel to changes in AI, a significant metabolic upsurge was observed in occipital areas bilaterally at 33 months, suggesting that cross-modal and compensatory plasticity was occurring.

Auditory deprivation due to partial hearing loss resulting from cochlear lesions has been shown to result in the reorganisation of frequency representation in the auditory cortex (Irvine, 2000). In animal experiments, mechanical damage to the basilar membrane in high-frequency cochlea regions resulted in an enlarged neural representation of the lesion-edge frequencies (Rajan, Irvine, Wise, & Heil, 1993; Irvine, Rajan, & Brown, 2001). MEG studies in patients with high-frequency cochlear hearing losses have also shown reorganisation in the auditory cortex (Dietrich et al., 2001). This was attributable to neurons representing the lesioned frequencies developing low threshold responses to adjacent i.e. ‘cut-off’ frequencies, leading to an over-representation of the lesion-edge. The same mechanism has been hypothesised to cause tinnitus associated with sensorineural hearing loss (Lockwood et al., 1999b; Mühlnickel, Elbert, Taub, & Flor, 1998). Some psychoacoustic studies have also shown an enhancement of difference limen frequencies (DLF) for ‘cut-off’ frequencies in patients with steep hearing losses and therefore provide further evidence for an enlargement in the cortical representation of lesion-edge frequencies (McDermott, Lech, Kornblum, & Irvine, 1998; Thai-Van et al., 2010).

1.3.3 Learning-Related Plasticity

There is plethora of evidence showing that auditory training using tonal, musical or even simple speech stimuli induces functional and structural changes in the auditory system.

Over the past decade, there has been growing interest amongst researchers in investigating the effects of musical training on the anatomical and functional organisation of the brain (Pantev et al., 2003; Trainor, Shahin, & Roberts, 2003; Shahin, Roberts, & Trainor, 2004; Koelsch et al., 2005; Schlaug, Norton, Overy, & Winner, 2005; Moreno et al., 2009; Hyde et al., 2009; Kraus & Chandrasekaran, 2010). CAEP studies in children have consistently revealed an enhancement in the amplitude of P1, N1, and P2 (Shahin, Roberts, & Trainor, 2004); and N300 (Moreno et al., 2009) following a period of musical training. Such changes were not observed in age-matched controls who had no training (Shahin, Roberts, & Trainor, 2004) or in subjects who received other forms of training (Moreno et al., 2009). In the latter study, transfer effects were also reported since it was found that musical training lead to significant improvements in reading and pitch discrimination abilities with speech.

Neuroimaging techniques such as PET, MEG, fMRI have also been widely used to elucidate learning-induced plasticity resulting from musical training. In the study by Pantev and colleagues (2003) which used MEG, an enlarged cortical representation of tones within the musical scale was observed in skilled musicians. Sensitivity to different timbre was also evident, with responses appearing to be highly specific to the instrument the musician had trained with. Musical training has also been demonstrated to increase activation of the inferior fronto-lateral cortex (Koelsch et al., 2005), the right STG (Koelsch et al., 2005; Schlaug et al., 2005) and the sensorimotor cortex (Schlaug et al., 2005) relative to non-musically trained subjects. In addition, one longitudinal MRI study that followed up children after 15 months of musical training reported relatively greater changes in voxel size for AI of the right hemisphere (Heschl’s gyrus) and the CC in (Hyde et al., 2009). The structural changes were also correlated with improvements in performing a motor task and a melody/rhythmic task.

Evidence of learning-induced plasticity has also been demonstrated in studies employing short-term discrimination training with tones or simple speech sounds. For example, in the study by the team of Menning (2000), subjects were trained with an oddball procedure to detect small differences in spectral frequency between a standard tone and a deviant tone. Enhancement of the mismatch negativity (MMN) was shown during and after three weeks of training but decreased three weeks thereafter. Similar results were reported in adults who received five days of training with unfamiliar prevoiced-labial (/mba/) stimuli (Tremblay, Kraus, Carrell, & McGee, 1997), with an enhancement of MMN responses observed for trained, but not untrained subjects. In an fMRI study by Jäncke and colleagues (2001), hemodynamic responses for auditory cortical regions were found to decrease significantly in subjects who showed performance gain in frequency discrimination training. The researchers postulated that this was attributable to an increased proficiency of perceptual processing acquired during short-term learning and that a smaller and more focused amount of neuronal activation was required for the same task.

In summary, the brain has the ability to change structurally and functionally over a life time. In cases where auditory deprivation occurred as a result of a cochlear lesion, the auditory cortex will reorganise in a way such that areas representing a lesioned site will subsequently represent adjacent sites or even a different modality. Short-term auditory training has also been demonstrated to induce cortical plasticity; however, the long-term effects of such training on neuroplasticity are less well understood.

Chapter 2

Auditory Processing Disorder: Diagnostic Principle and Procedure

2.1 Introduction

Hearing plays a pivotal role for communication and learning. Some individuals present with complaints of listening difficulties in background noise, or in environments with degraded or competing speech sounds, despite having normal peripheral hearing sensitivity and cochlear function. Such symptoms are amongst the more common, but diverse presenting complaints of individuals with disordered auditory processing (Bamiou, Musiek, & Luxon, 2001).

This introductory section will first discuss the current definitions of auditory processing disorder (APD) with an overview of related presenting symptoms. A brief review of literature regarding the prevalence of APD and its comorbidity with other language related disorders will be provided. Then, the diagnostic criteria and controversial issues in APD diagnosis will be discussed. Finally, an overview of AP tests that are currently used for clinical diagnostic purposes will be provided, with emphasis given on the tests used in this thesis.

2.2 Definition of Auditory Processing Disorder (APD)

According to the technical report of the American Speech-Language-Hearing Association (ASHA) Working Group (2005), APD is defined as deficits in the perceptual processing of auditory information in the Central Nervous System (CNS) and the neurobiological activity that underlies that processing and gives rise to electro-physiological auditory potentials. APD can be demonstrated by poor performance in one or more of the following skills: sound localisation and lateralisation, auditory discrimination, auditory pattern recognition, temporal aspects of audition (including temporal integration, temporal ordering and temporal masking), auditory performance in competing acoustic signals and auditory performance with degraded acoustic signals. APD may be associated with, but not consequent upon, difficulties in higher order language, cognitive, or related communicative functions.

The broad definition of APD given by the ASHA Working Group (2005) is in general agreement with the UK definition. The recently published British Society of Audiology (BSA) position statement on APD (2011) states that, APD is characterised by poor perception of both speech and non-speech sounds, which results from impaired neural function (both afferent and efferent pathways in the auditory system) that is closely associated with impaired top-down, cognitive function. Specifically, the BSA position statement on APD (2011) categorises APD into three subtypes:

1. *Developmental* APD: Cases presenting in childhood with normal peripheral hearing sensitivity and in the absence of other known aetiology or potential risk factors.
2. *Acquired* APD: Cases associated with a known post-natal event (e.g. neurological trauma, infection) that could plausibly contribute to APD.

3. *Secondary* APD: Cases where APD occurs in the presence, or as a result, of peripheral hearing impairment, which may include transient hearing impairment after its resolution (e.g. glue ear or surgically corrected middle ear diseases).

Of the three subtypes, *developmental* APD has attracted interest from the majority of experts and researchers in this practice area, at both national and international level, and will also be the primary focus of this thesis.

2.2.1 Risk Factors for APD

There is little evidence of a clear aetiology of APD, but some risk factors have been reported to be associated with this disorder. The risk factors for APD can broadly be classified into three categories: (a) neurological conditions, (b) delayed maturation of the central nervous system, and (c) other developmental disorders (Bamiou, Musiek, & Luxon, 2001).

The occurrence of APD in the presence of a cerebral lesion due to space occupying mass, epilepsy, cerebrovascular disorders, or trauma has been reported in the literature. Musiek, Baran and Pinheiro (1990) reported that subjects with cerebral lesions (n = 21) performed significantly more poorly in an auditory patterning test than either the normal subjects (n = 50) or those with cochlear hearing loss (n = 24). Individuals with the absence of CC congenitally (Chiarello, 1980, Geffen, 1980), those suffered from split-brain (Musiek, 1986b), or PAX6 gene mutations (Bamiou et al., 2004, 2007a) have also been shown to have deficits in the AP. Other neurological related conditions that have been reported as the risk factors for APD are closed head injury, *Lyme* disease (a tick borne infection), and low level heavy metal exposure (Bamiou, Musiek, & Luxon, 2001).

Another potential risk factor for APD is the effect of otitis media (glue ear). It is believed that otitis media can cause temporary auditory deprivation, which if recurrent may lead to delayed maturation of the central auditory pathways. As compared to children without a known history of ear disease, Hall and Grose (1993) found that children with a history of otitis media had significantly reduced Masking Level Differences (MLDs) - one of the behavioural AP tests, as well as prolonged waves III and V absolute latencies in the ABR. Nonetheless, a retrospective review of a clinical database by the team of Dawes (2008) revealed no significant difference between the APD and non-APD children with a known history of otitis media, even though there appeared a higher proportion of children with APD (5/17 = 29%) than the non-APD (4/38 = 10%) had a history of otitis media (Dawes, Bishop, Sirimanna, & Bamiou, 2008).

APD is also commonly found in association with other developmental disorders such as specific language impairment (SLI) (Bamiou, Musiek, & Luxon, 2001; Sharma, Purdy, & Kelly, 2009), specific reading disorder (SRD) (Dawes, Bishop, Sirimanna, & Bamiou, 2008; King, Lombardina, Crandell, & Leonard, 2003; Iliadou et al., 2009), and attention deficits and hyperactivity disorders (ADHD) (Riccio et al., 1994). However, it should be caution that the presence of APD with coexisting developmental disorders does not imply a causal link between the two. A review by Rosen (2003) in fact revealed that only a minority of SLI/SRD listeners had any auditory deficits. There was also no significant relationship between the severity of the auditory and language deficits in the SLI/SRD group (Rosen, 2003).

In conclusion, while there are many risk factors that could potentially contribute to APD, the aetiology of APD remains unclear. This is because the nature of this disorder is still poorly understood (see section 2.3).

2.2.2 Behavioural Symptoms of APD

Individuals with APD are a heterogeneous group with various presenting symptoms. Some of the commonly reported or observed behavioural symptoms of individuals with APD [American Academy of Audiology (AAA, 2010)] are:

a. Difficulty understanding speech in the presence of competing background noise or in reverberant acoustic environments
b. Difficulty following directions
c. Difficulty hearing on the phone
d. Difficulty following rapid speech
e. Difficulty learning a foreign language or novel speech materials, especially technical language
f. Inconsistent or inappropriate responses to requests for information
g. Frequent requests for repetition and/or rephrasing of information
h. Difficulty maintaining attention
i. A tendency to be easily distracted
j. Academic difficulties, including reading, spelling and/or learning problems
k. Problems with the ability to localize the source of a signal
l. Poor singing, musical ability, and/or appreciation of music
m. Difficulty or inability to detect the subtle changes in prosody that underlie humour and sarcasm
n. Tinnitus, especially when localised in the head

The majority of the above outlined symptoms are not specific to individuals with APD but often overlap with those that are related to linguistic (e.g. SLI, SRD), cognitive (e.g. memory and attention deficits), or behavioural [e.g. autistics spectrum disorder (ASD)] disorders (ASHA, 2005; Bamiou, Musiek, & Luxon, 2001; Dawes, Bishop, Sirimanna, & Bamiou, 2008). Therefore, the presence of one or more of these behavioural symptoms does not warrant a diagnosis of APD; rather, it indicates a potential auditory-related disorder that needs a multidisciplinary team approach to assessment.

2.2.3 Prevalence of APD

The true prevalence of APD is unknown, as it varies across different studies depending on the diagnostic criteria as well as the test battery used. Domitz and Schow (2000) identified 21% of 81 third grade children from three multilingual elementary schools as having APD, using the criterion of performance falling 2s.d.'s below the mean on at least one of the Multiple Auditory Processing Assessments (MAPA). The MAPA included the frequency pattern test (FPT), dichotic digits test (DDT), competing sentences (CS), and monaural selective auditory attention test (mSAAT). In a Greek population, Iliadou and colleagues (2009) reported a higher prevalence of APD (43.3%) in the group of children suspected of learning disabilities (n=127) on the basis of deficits on at least 2 AP tests. The AP test battery used in this study included the DDT, FPT, duration pattern test (DPT), random gap detection test (RGDT), and Speech-in-Babble test.

Based on a retrospective review of a clinical database of children referred to a UK specialist APD clinic, Dawes and colleagues (2008) reported that 36% of the 89 children fulfilled the clinical criterion for a diagnosis of APD. These children performed below 1s.d from the mean of US-referenced norms in a speech test, i.e. SCAN-C, and had a deficit in at least one of the AP test battery [FPT or DPT, RGDT, and Gap-In-Noise (GiN)]. In a New Zealand population, Sharma and colleagues (2009) identified a higher percentage (72% of 68) of APD in their sample group on the basis of scores falling 2s.d.'s below the mean on two AP tests (DDT, FPT, RGDT, MLD, and compressed and reverberant CVC words), or 3s.d.'s below the mean on any one test.. It is noteworthy though their children were from a more selected group who were suspected of, or already had a diagnosis of APD.

In summary, different populations reported different percentage of children being identified with APD, which varies from 21% to 72%. The considerable variation in these reports may be due to the different types of populations assessed (in terms of ethnicity and referral route), but to a large extent was due to the different diagnostic criteria used in different studies, which highlight the lack of universal agreement on how APD should be diagnosed.

2.2.4 Comorbidity of APD and Other Language-Related Disorders

In many cases diagnosed with APD, APD co-exists with SLI (Ferguson, Hall, Riley, & Moore, 2011; Sharma, Purdy & Kelly, 2009; Miller & Wagstaff, 2011) and SRD (King, Lombardina, Crandell, & Leonard, 2003; Dawes, Bishop, Sirimanna, & Bamiou, 2008; Iliadou et al., 2009). However, the percentage of overlap varies considerably in the literature. For examples, Iliadou and colleagues (2009) reported that 51% of children with APD (n = 55) had SRD, whereas only 14% and 25% were reported in the studies by the team of Sharma (2009) and Dawes (2008) respectively. About 13% of children with APD were reported to present with language problems (Dawes, Bishop, Sirimanna, & Bamiou, 2008; Sharma, Purdy & Kelly, 2009), and a considerably high percentage of children with APD (65%) had a combination of SLI and SRD in Sharma's study (2009).

Several reasons could account for this variation in the overlap between APD and these language-related disorders. Different subject characteristics and inclusion criteria (e.g. general population referred for APD assessment, or specific group with learning difficulties), and study design (e.g. clinical versus laboratory based study thus lesser inter-tester differences) could explain some of these differences. Again, it is more likely to be attributable to the varying AP test batteries and diagnostic criteria used in different studies, especially when some AP tests have clear linguistic components. It is also felt that the current behavioural AP tests may not be specific enough to distinguish between auditory, language, and reading impairments. Hence, a child with a mixture of auditory and learning difficulties that originate from a single higher function disorder may be inappropriately diagnosed with multiple conditions when he/she fails the multidisciplinary assessments (Sharma, Purdy, & Kelly, 2009).

2.3 Diagnostic Criteria and Controversies in APD

The clinical diagnosis of APD remains a challenge. There has been a long standing debate on the nature of APD and its diagnostic criteria (Keith, 2007; Rosen, 2005). A few consensus statements of APD had evolved over the years (ASHA, 1996, ASHA 2005; BSA 2007); despite a clearer definition now, it remains an area of controversy both amongst different professional groups and internationally. The controversial issues surrounding clinical diagnosis of APD revolve around:

(1) The modular-specificity nature of APD and its differential diagnosis

In early definition of APD that was indeterminate, APD was diagnosed in any cases with overlapping symptoms such as other learning and language-related disorders (e.g. SLI, SRD), thus making differential diagnosis very difficult (Bellis, 2007). This led to criticism by McFarland and Cacace (1995), and subsequently Cacace and McFarland (1998), who argued that APD should be considered distinct from other attention, language and more generalised higher order dysfunctions; therefore, the definition of APD should be more concise as a perceptual dysfunction that is auditory modality-specific. Cacace and McFarland (2005) further contended that, in order to achieve a clear conceptualisation of APD as a useful clinical construct, a multimodality testing approach was necessary, as such testing could demonstrate poor performance on a battery of auditory tasks in the presence of age-appropriate normal performance on comparable tasks in other sensory domain (e.g. vision). Cases with deficits in both auditory and visual comparable tasks (e.g. auditory frequency pattern tasks versus visual colour pattern tasks) would indicate a more global disorder or an influence of attention/cognition.

The auditory modality-specificity concept of APD and the diagnostic criteria proposed by Cacace and McFarland (2005) were criticised by others (Katz & Tillery, 2005; Musiek, Bellis, & Chermak, 2005; Rosen, 2005). Some questioned the practicality of a multimodal testing approach since it might not be possible to have a close match between two tasks in the two modalities (Rosen, 2005), and some argued that the use of intra- and inter-test comparison in an auditory test battery (unimodal approach) is as good in disassociating APD from other supramodal factors (i.e. attentional influence) (Katz & Tillery, 2005). The ASHA Working Group (2005), while recognising the auditory nature of the disorder, concluded that complete modality-specificity as a diagnostic criterion for APD is neurophysiologically untenable because the interactive nature of brain function is nonmodular. The nonmodularity of the brain can be demonstrated from the complex shared neuroanatomic substrates, multisensory neural interfaces, the convergence and divergence of sensory “tracts”, and the interdependence of bottom-up and top-down factors (ASHA, 2005; Bellis, 2007).

Another major criticism is the extent to which AP deficits are causally linked to language and reading disorders. The ‘rapid auditory processing deficit’ theory of Tallal (1976, 1980) explicitly claims that an auditory temporal processing deficit is the underlying cause of SLI and SRD. This view posits that the inability to perceive rapidly changing or transient sound leads to poor phonological representation and processing, which consequently hinders the development of typical language and reading abilities. Even though this theory has received support from some studies (e.g. Merzenich et al., 1996; Tallal et al., 1996; Wright et al., 1997), it is not universally accepted. There is a growing body of evidence showing that auditory temporal processing deficit does not necessarily underpin SLI or SRD in all individuals (Bishop, Carlyon, Deeks, & Bishops, 1999; Griffiths, Hill, Bailey, & Snowling, 2003; McArthur & Hogben, 2001; Rosen, Adlard, & van der Lely, 2009; see Rosen, 2003 for a review).

A more recent issue has been raised relative to the validity of APD as a distinct clinical construct. The APD consensus statement by the ASHA Working Group (2005) clearly states that APD may be associated with, but not consequent upon, difficulties in higher order language, cognitive, or related communicative functions. In other words, APD is regarded as a distinctive clinical disorder. A substantial body of literature (e.g. Hugdahl et al., 2003; Moncrieff, McColl, & Black, 2008; Musiek & Lee, 1998), as cited in AAA (2010, pp.3), also supports the existence of APD. However, the question of APD as a distinct clinical entity surfaced when some recent studies reported that the clinical diagnosis of APD and SLI are indistinguishable based on laboratory test-based classifications of APD and SLI. For examples, Ferguson, Hall, Riley and Moore (2011) found that children in the UK who had received a clinical diagnosis of APD or SLI had very similar behavioural and parental report profiles, thus suggesting that these children were differentially diagnosed on the basis of their referral route rather than on actual differences.

Miller and Wagstaff (2011) also reported that the behavioural profiles of a group of American children with a priori diagnosis of APD or SLI were very similar, while the laboratory test-based classifications of APD and SLI did not correspond closely to the clinical diagnoses. Miller and Wagstaff (2011) further suggested that in order to prove that APD and SLI are distinct constructs, behavioural measures that target a specific cognitive process with minimal influence of other factors should be devised. In the speech-language pathologists' community, some strongly oppose treating APD as a distinct clinical entity, as there is lack of evidence showing auditory interventions provide unique benefit to auditory, language, or academic outcomes in contrast to language interventions (Fey et al., 2011; Kamhi, 2011). Therefore, it has been suggested that APD may be more appropriately viewed as a processing deficit that commonly occurs with other developmental disorders (e.g. SLI, SRD). The recently published BSA Position Statement on APD states that APD may be one symptom of a broader neurodevelopmental problem that has a close link with other language-related disorders (BSA, 2011).

(2) The auditory processing test batteries

To date, there is no 'gold standard' test battery for the diagnosis of APD; neither is there a minimal set of AP tests that are universally agreed upon. While both speech and non-speech tests are currently used for the diagnosis of APD, as recommended by the ASHA working group (2005), some have advocated for the need to utilise only non-speech tests in the identification of APD (Moore, 2006; Hall & Johnston, 2007). The position statement on APD published by the British Society of Audiology (BSA, 2007) explicitly stated that APD should only be diagnosed using non-speech tasks to minimize the confounding influence of language and other cognitive factors.

However, there is a contrasting view resulting from the belief that the CANS has different processing mechanisms for speech and non-speech signals (AAA, 2010). This view is supported by some neurophysiologic studies showing atypical neural responses and/or hemispheric asymmetries in CANS function when tested with speech stimuli as opposed to non-speech stimuli (e.g. Jerger et al., 2000; Song, Banai, Wible, Nicol, & Kraus, 2005; Russo, & Kraus, 2006, in AAA, 2010, p.14). Nonetheless, the American Academy of Audiology (AAA, 2010) recognizes the need to develop non-speech tests that can be applied internationally to facilitate consistency and uniformity in the diagnosis of APD.

In summary, there are two contrasting views regarding the type of tests used for AP assessment. One view limits APD to a disorder that is strictly related to the processing of low-level acoustic-phonetic features of speech and therefore, non-speech AP tests should be used. Another view holds that speech tasks remain an important component in APD assessment because CANS dysfunction is likely to impact more on speech than non-speech signal processing.

2.4 Auditory Processing (AP) Tests

In the absence of a clear ‘gold standard’ test battery for APD, most audiologists refer to the guidelines published by professional organisations in diagnosing APD (e.g. ASHA, 2005; AAA, 2010; BSA, 2007; 2011). Based on the guidelines published by the ASHA (2005, p.12-13) and AAA (2010, p.16-22), five auditory processes (as seen in Table 2.1) have been identified as appropriate to assess for APD, and a variety of test options are recommended to assess each auditory process. It is recommended though, that an individualised test battery approach should be adopted (ASHA 2005; AAA, 2010). This means that the selection of AP tests should be based on the individual’s case history and relevant information provided to the audiologist. A survey conducted by Emanuel, Ficca, and Korczak (2011), however, revealed that a majority of US audiologists (n=155/199; 81%) are still driven by a minimum test battery approach of four to six different AP tests for all patients, with additions based on individual case history and age. At this point in time, there is no minimal set of AP tests that are universally agreed upon. Hind (2006) reported that different types of direct and indirect AP tests (e.g. language, cognitive, memory, and questionnaire) were being used in different clinics in the UK. These studies reflect a lack of consistency and uniformity in the APD diagnosis among audiology professionals, both on a national and international level.

Table 2.1: Categorization of central auditory tests and the types of measures (Adapted from ASHA – Technical Report, 2005)

Auditory domains	Test function	Types of test measures
Auditory discrimination tests	Assess the ability to differentiate similar acoustic stimuli that differ in frequency, intensity, and duration	• Difference limen for frequency • Difference limen for intensity • Phoneme discrimination
Auditory temporal processing and patterning tests	Assess the ability to analyse acoustic events over time	• Frequency patterns • Duration patterns • Gap detection thresholds • Fusion discrimination • Forward and backward masking
Dichotic listening (speech) tests	Assess the ability to separate (i.e. binaural separation) or integrate (i.e. binaural integration) disparate acoustic stimuli presented to each ear simultaneously	• Dichotic digits • Dichotic CVs • Competing sentences • Competing words
Monaural low redundancy speech tests	Assess recognition of degraded speech stimuli presented to one ear at a time	• Speech in noise • Speech-in-competition • Filtered speech • Compressed speech
Binaural interaction tests	Assess binaural (i.e., dichotic) processes dependent on intensity or time differences across ears of acoustic stimuli	• Masking level difference • Localisation and lateralisation • Interaural intensity difference

2.4.1 An Introduction to the Clinically Used AP Tests

The following section describes some of the common AP tests used in a clinical setting. They can be divided into:

1. Non-speech tests – random gap detection test (RGDT), frequency pattern test (FPT), duration pattern test (DPT), and masking level differences test (MLD).
2. Speech-based tests – dichotic digits test (DDT), competing sentences test (CS), and monaural low redundancy speech tests.

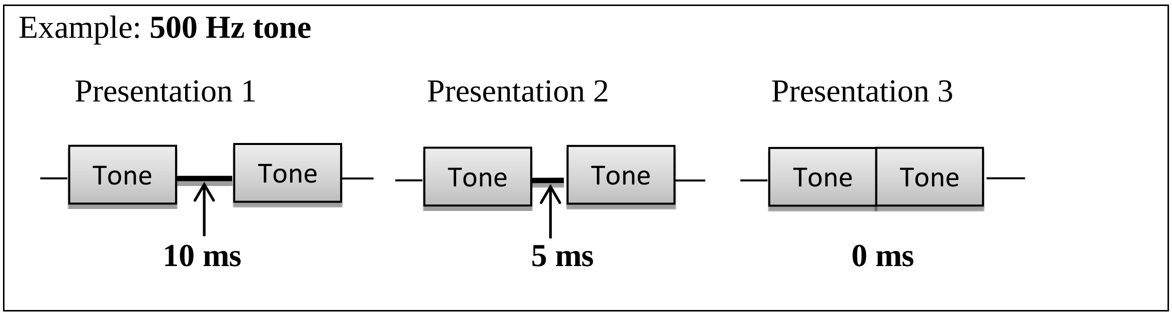
These AP tests were selected because they have been widely used in populations with confirmed CANS lesions, and have adequate sensitivity and specificity documented for detecting AP deficits. Besides, they can be easily administered in paediatric populations. The combination of non-speech and speech-based tests assesses different auditory processes, as per the recommendations of ASHA (2005), and also provides information about the functional deficits of a child.

2.4.1.1 Random Gap Detection Test (RGDT)

The RGDT is a test of temporal resolution. Temporal resolution skill refers to the ability to resolve acoustic events evolving over time (Shinn, 2007).

RGDT was developed by Keith (2000). It comprises a set of paired-tonal stimuli that vary in intertone interval (gap between the two tones): 0, 2, 5, 10, 15, 20, 25, 30, and 40 ms (see Figure 2.1). For each presentation, the listener is asked to indicate whether one or two tones were heard. There are all together 4 sets of frequency-specific stimuli: 500, 1000, 2000, and 4000 Hz. The test is presented binaurally at 55 dBHL. The average of the smallest gap (shortest duration of time) that can be detected in the 4 sets of stimuli is the threshold for temporal resolution. Normative values for the RGDT tonal stimuli range from 6.0 to 7.8 msec for individuals aged 7 and above (Shinn, 2007).

Figure 2.1: An example of gap detection



2.4.1.2 Frequency Pattern Test (FPT)

The FPT is a test of temporal ordering or sequencing. Temporal ordering skill refers to the ability to process two or more auditory stimuli in their correct sequence over time (Pinheiro & Musiek, 1985).

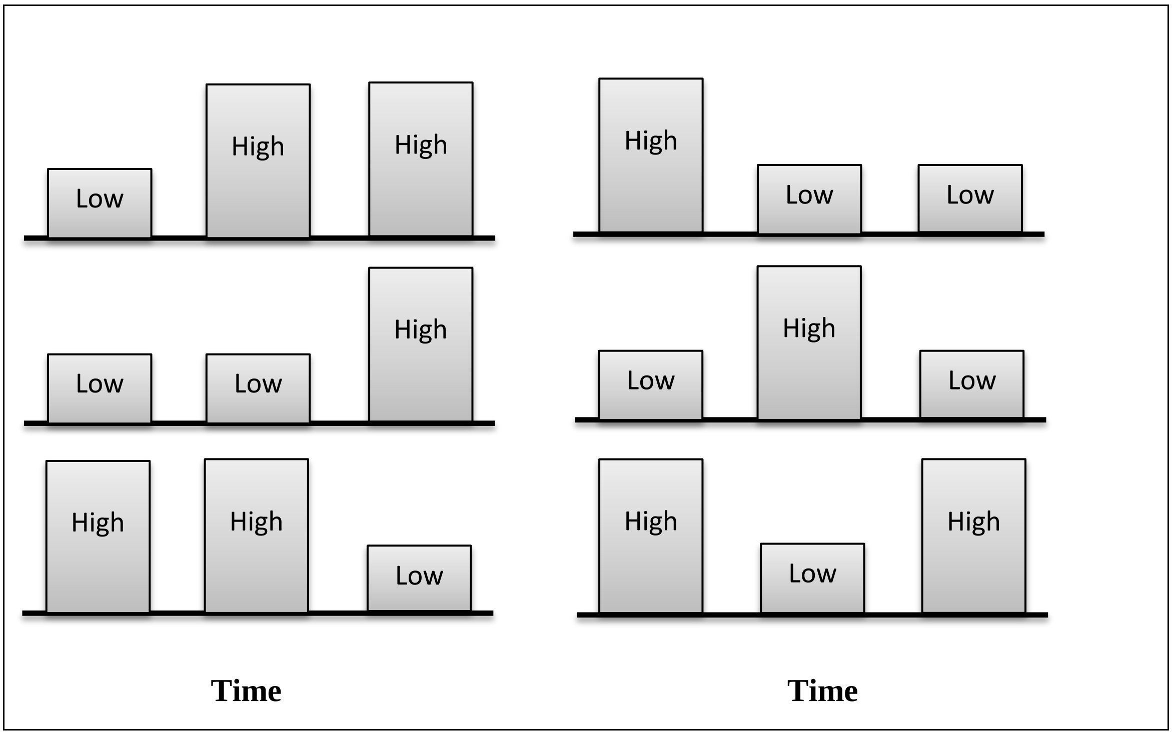
The FPT was first introduced by Pinheiro and Ptacek (1971). It was widely used in split-brain patients (i.e. patients with surgically sectioned corpus callosum) as well as patients with cerebral lesions (refer to section 1.2.6.1, chapter 1), but subsequently extended to neurologically normal individuals with an auditory complaint or disordered AP. The FPT was reported to have high sensitivity and specificity to hemispheric lesion and interhemispheric dysfunction (Musiek & Pinheiro, 1987), and it is easy to administer on young children (Musiek, 1994).

The FPT (Musiek, 1994) comprises a set of three tones with a combination of high (1122Hz) and low frequency (880Hz) tones presented in random sequences (as seen in Figure 2.2). Each tone lasts for 150 ms with a 200 ms intertone interval. The FPT of a different recording by AUDITEC ® has a slightly different parameter, in which a

1430Hz tone is used for high frequency while the low frequency remains the same (880Hz). The duration of tone also varies from 200 ms (for adult version) to 500 ms (for child-version). The intertone interval is set at 300 ms (Auditec).

The test is presented monaurally at 50 dBSL, with 30 items in each ear. The listener is required to verbally label the sequence of tones as ‘high’ or ‘low’. The number of correct responses is compared to age-specific normative values. It is noteworthy that the inability to label, but preserved ability to hum the tones, may imply an interhemispheric dysfunction.

Figure 2.2: The six frequency patterns with time represented on the x-axis and amplitude on the y-axis

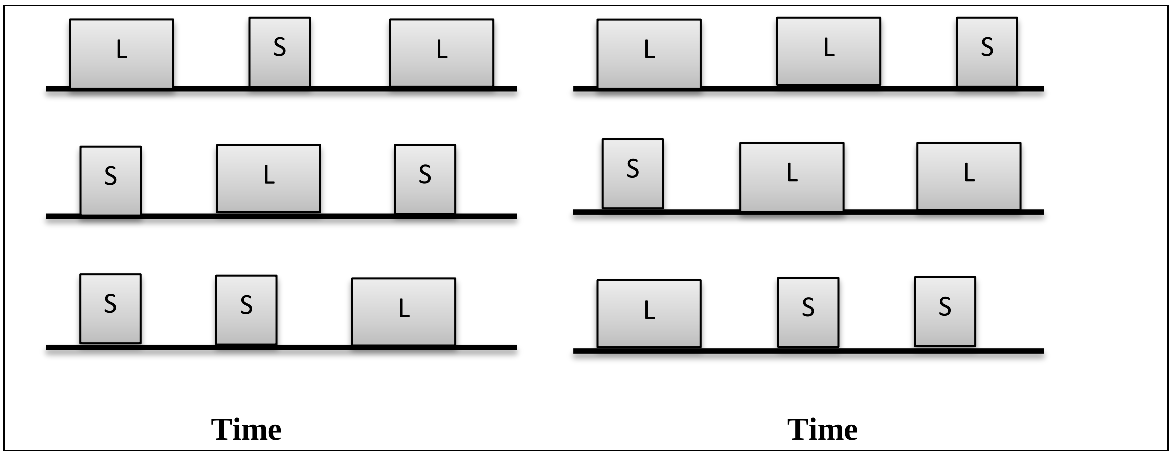


2.4.1.3 Duration Pattern Test (DPT)

The DPT is another test of temporal patterning developed by Musiek (1994). It has been shown to be highly resistant to peripheral hearing loss (Musiek, Baran, & Pinheiro, 1990).

The DPT is made up of three consecutive 1000 Hz tones, one of which is either of longer or shorter duration than the other two (Musiek, 1994). The durations are either 250 ms (short) or 500 ms (long). There are six different combinations of short and long sequences (as seen in Figure 2.3) and an intertone interval of 300 ms is used. The test is presented monaurally at 50 dBSL, with 30 items in each ear. The listener is instructed to report the pattern perceived by saying the appropriate ‘short’ and ‘long’ perceptions. The number of correct responses is again compared to age-specific normative values.

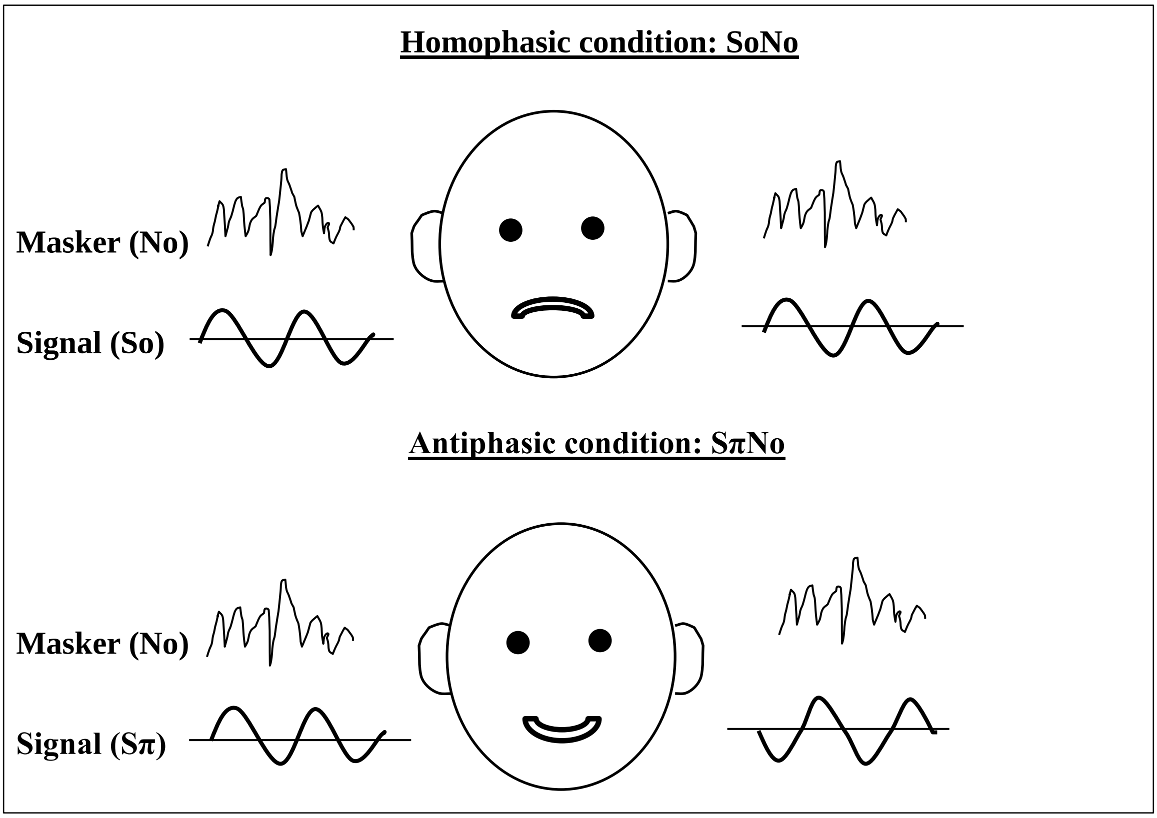
Figure 2.3: The six duration patterns with time represented on the x-axis and amplitude on the y-axis (L = long; S = short)



2.4.1.4 Masking Level Differences (MLD)

The MLD is a test of binaural interaction that measures the ability to identify an acoustic signal in the presence of a background noise (masker) when listening with two ears. The MLD is derived by measuring the difference between two listening conditions. In one condition, the signal and the noise are in-phase (SoNo); in the other, either the signal (SπNo) or the noise (SoNπ) is 180° out-of-phase. When the tones are out of phase relative to the ears and the noise in phase (SπNo), the tones are typically easier to perceive (see Figure 2.4). The MLD has been shown to be sensitive to lower-level brainstem dysfunction (Lynn, Gilroy, Taylor, & Leiser, 1981), but may also be affected by cortical pathology (Bamiou, 2007).

Figure 2.4: Illustration of the masking level difference paradigm (Adapted from Bamiou, 2007)



The MLDs can be measured using speech or tone (normally 500-Hz). The binaural MLD phenomenon was first described by Hirsch (1948) for tones and Licklider (1948) for speech. The tonal MLD (500 Hz) is much more commonly used in clinical setting as reported in the literature (e.g. Olsen, Noffsinger, & Carhart, 1976; Sweetow & Reddell, 1978; Roush & Tait, 1984).The reasons for the preference of tonal MLD over a speech MLD could be that, (1) 500 Hz MLD protocol developed for clinical implementation is simple and easy to administer on children, (2) it is not easily affected by language factor, and (3) some evidence showing that tonal MLDs are more effective than speech MLDs in discriminating children with auditory perceptual dysfunction from normal children (Sweetow & Reddell, 1978). The tonal MLD thresholds ranged from 10 to 14 dB (mean = 12.2 dB, SD = 1.1) have been reported on normal hearing children (Roush & Tait, 1984), while 90% of the adult listeners in the study by Wilson and colleagues had MLD thresholds ≥ 10dB (Wilson, Moncrieff, Townsend & Pillion, 2003).

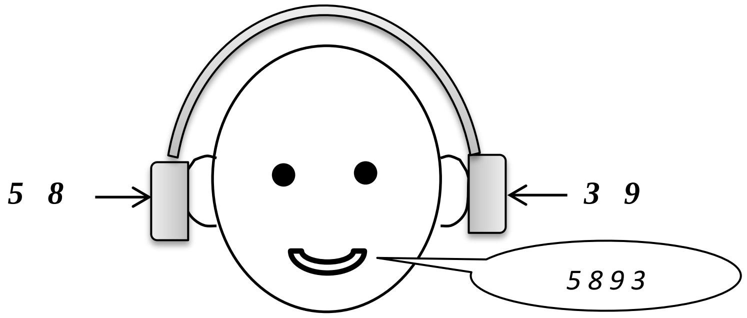
Clinically, the Auditec version of the tonal MLD (500 Hz) test consists of 10 sets of SoNo condition, 12 sets of SπNo condition, and 11 sets of no-tone condition. The masker noise is a narrowband noise. The presentation levels of SoNo and SπNo conditions are manipulated in terms of signal to noise ratios that vary from 1 to -17dB, and -7 to -29dB, respectively. The test is presented binaurally at 50dBHL. The listener is asked to indicate whether the tone pulses were heard or not.

2.4.1.5 Dichotic Digits Test (DDT)

The DDT was developed by Musiek (1983), and is one of the tests of dichotic listening. Tests of dichotic listening can measure the ability to either integrate or separate similar but non-identical information presented to both ears at the same time. This test is sensitive to interhemispheric dysfunction but can be affected by peripheral hearing loss.

The DDT consists of 25 pairs of double digits containing all single numbers from 1 to 9 (except 7). The test is presented simultaneously to both ears at 50dBSL, with the digits being different in each ear (see Figure 2.5). The listener is required to repeat all the numbers heard. If the listener only reports from one ear, it is called the divided attention technique. Of note, it is normal to obtain a higher percentage of correct responses in the right than the left ear for younger listeners but this ear difference becomes smaller in magnitude for adults. This effect is known as the right ear advantage (REA). Two models have been proposed to explain this perceptual asymmetry as explained in Chapter 1 (section 1.2.6.1). It is worth mentioning that a left ear advantage (LEA) is considered abnormal in subjects of any age, and this is often observed in children with phonologic, reading, and language disorders (Keith & Anderson, 2007), but is presumably more common in left handers.

Figure 2.5: Illustration of a dichotic digits test



2.4.1.6 Competing Sentences (CS) Test

The CS test is another test of dichotic listening but the mode of administration differs from that of the DDT. Two sentences are presented simultaneously, and one to each ear. The listener is required to focus attention and repeat what is heard in the pre-cued ear, and to disregard what is heard in the non-cued ear. Sometimes this mode is called the ‘directed attention’ mode (Keith & Anderson, 2007).

Typically, the CS test is made up of pairs of sentences that are similar in theme, which begin and end simultaneously. Some examples of the CS tests are of the Willeford battery (Willeford & Burleigh, 1994) and the subtest of SCAN (Keith, 2000). The version of the CS test used in the studies discussed in chapter 5 of this thesis is from the Auditec recording.

2.4.1.7 Monaural Low Redundancy Speech Test

Monaural low redundancy speech tests make use of stimuli that have been degraded in the frequency, time or intensity domain (Krisnamurti, 2007) to assess CANS pathology. Patients with temporal lobe lesions had been found to show abnormal scores on monaural low redundancy speech tests in the ear contralateral to the affected hemisphere (Bocca, Calearo, Cassinari, & Migliavacca, 1955; Kurdziel, Noffsinger, & Olsen, 1976; Sinha, 1959). Some examples of monaural low redundancy speech tests are: low-pass filtered speech tests, speech-in-noise tests, and time-compressed speech tests. Despite only yielding moderate sensitivity to CANS lesions (Musiek & Baran, 2002), these tests continue to be used in APD assessment because they provide information about functional deficits as well as practical information for intervention (Krisnamurti, 2007). Of note, performance on monaural low redundancy speech tests is easily affected by language and cognitive factors, as well as peripheral hearing status of an individual.

a) Low-Pass Filtered Speech (LPFS) Tests

Two different versions of LPFS tests were used in the studies described in Chapter 4 and 5. One is the Filtered Word (FW) subtest of the SCAN-C designed for children between 3.0 to 11.11 years developed by Keith (2000). Another version is the Auditec recording of the 1000Hz filtered NU-6 words (Wilson & Mueller, 1984) with paediatric norms reported by Bellis (2003) for children aged 7 to 12 years. The monosyllabic words are presented at 50dBHL.

b) Speech-in-Noise (SIN) Test

There are many different versions of SIN tests such as the Auditory Figure Ground (AFG) subtest of SCAN-C (Keith, 2000), the Synthetic Sentence Identification with Ipsilateral Competing Message (SSI-ICM), and the Pediatric Speech Intelligibility Test with Ipsilateral Competing Message (PSI-ICM). The version used in the studies described in Chapter 4 is the AFG subtest of the SCAN-C. The AFG subtest is made up of monosyllabic words embedded in multitalker speech babble. Words are presented at 50 dBHL, with a message competition ratio of +8 dB. The listener is instructed to repeat the words heard with his/her best guess.

2.4.2 Computerised Auditory Processing Test Batteries

Two different types of computer-based AP test batteries have recently been developed for the clinical testing of APD: (1) the IMAP test battery, and (2) the Listening in Spatialised Noise – Sentences Test (LiSN-S). These computerised AP test batteries were developed to supplement the AP tests currently used for APD investigation as described in 2.4.

2.4.2.1 IMAP test battery

The IMAP test battery is a standardised testing tool that was developed at the MRC Institute of Hearing Research in Nottingham, UK. The IMAP battery provides comprehensive auditory and cognitive assessment, which comprises the following tests:

- 5 non-linguistic AP tests (backward masking with 0ms gap and 50 ms gap, simultaneous masking with and without notch, and frequency discrimination)
- Speech-in-noise test
- Sustained attention test
- Auditory working memory test (digit span forward and backward tasks)
- Verbal short-term memory test (nonword repetition task)
- Nonverbal intelligence test (the Matrices task)
- Reading test (Test of Word Reading Efficiency – TOWRE)

The IMAP battery uses a child-friendly approach based on a game-format. During the non-linguistic AP testing, the child listens to auditory stimuli delivered through a headphone and responds via a colourful three button box (as shown in Figure 2.6).

Figure 2.6: A child being tested on the IMAP test battery with the child-friendly images on the computer screen and a three-colour response button box (From Barry, Ferguson, & Moore 2010).

The AP tests are designed using an ‘adaptive’ staircase method, where the relevant parameters for the ‘target’ are varied according to the child’s previous response (Barry, Ferguson, & Moore, 2010). For each AP test run, there are 2 adaptive tracks, each of which comprises 20 trials. Each trial is made up of a sequence of three stimuli (inter-stimulus interval 400 ms). Two of the stimuli are identical or ‘standard’ while the other one is different, or the ‘target’ stimulus. The child is required to identify the ‘odd-one-out’. Normative values are available for children aged 6 to 11 years old.

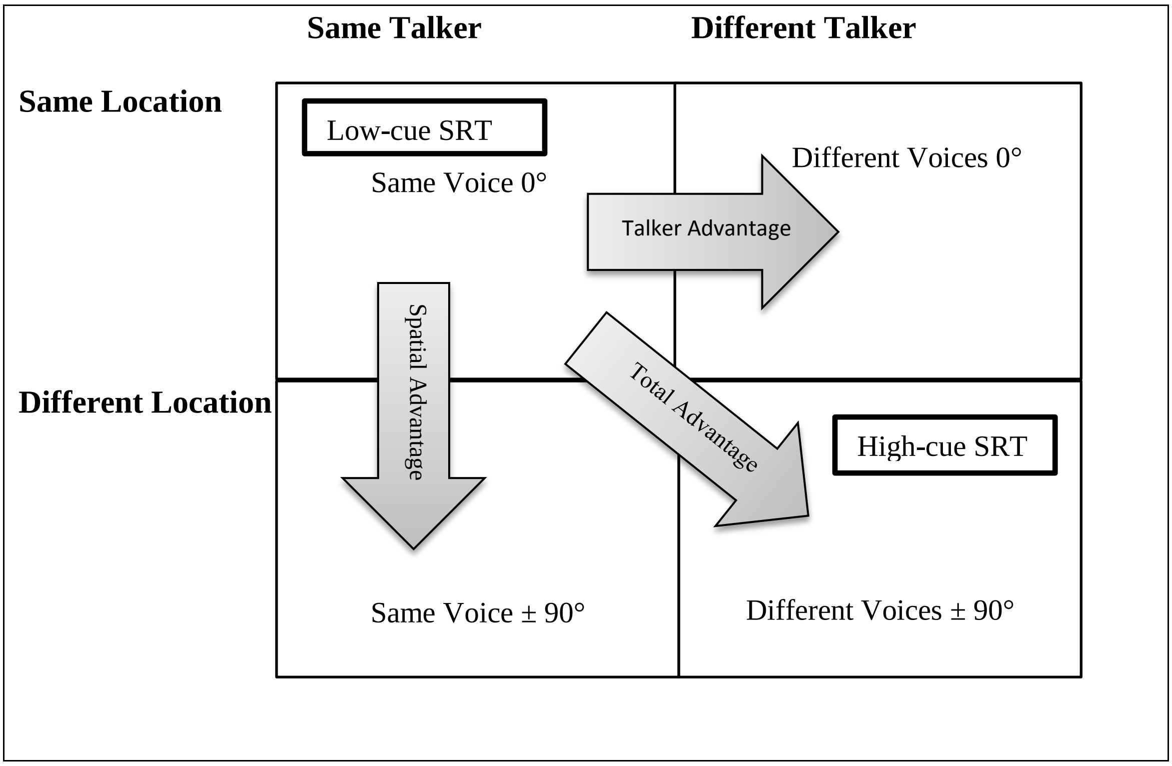
2.4.2.2 Listening in Spatialised Noise – Sentences Test (LiSN-S)

The LiSN-S was developed by Cameron and Dillon (2007) in Australia to assess the ability of children aged 5.0 to 11.11 years to understand speech in background noise. The LiSN-S is a test of binaural hearing, which is thought to be measuring the auditory stream segregation skills – a process by which an individual is able to extract meaningful incoming acoustic signals from the different auditory signals that arrive simultaneously at the ears, by making use of various auditory cues (e.g. spatial location or speakers' voices) (Cameron & Dillon, 2008).

The LiSN-S is presented via a personal computer and the software produces a three-dimensional auditory environment under headphones. This is done by processing the speech stimuli with head-related transfer functions (HRTFs). Using HRTFs, the target sentences are perceived as coming directly in front of the listener (0° azimuth), whereas the competing speech (children's stories) is manipulated in respect to its location (0° versus ± 90° azimuth) and the vocal quality of the speaker(s) (same as, or different to, the speaker of the target sentences). Four listening conditions are created: same voice at 0° azimuth (SV0), same voice at ± 90° azimuth (SV90), different voices at 0° azimuth (DV0), and different voices at ± 90° azimuth (DV90). The listener's performance in each of the listening conditions is measured in dB (signal-to-noise-ratio; SNR) or known as the speech reception threshold.

The LiSN-S performance can also be evaluated in three derived 'advantage' measures: talker advantage, spatial advantage, and total advantage (see Figure 2.7). The advantage measures represent the benefit in dB gained when either vocal (DV0), spatial (SV90), or both vocal and spatial cues (DV90) are incorporated in the maskers, compared to the baseline (SV0) condition where fewer cues are present in the maskers (Cameron & Dillon, 2007).

Figure 2.7: The LiSN-S test speech reception threshold (SRT) and advantage measures



The difference scores derived for the advantage measures are supposed to minimise the influence of higher-order language, learning, and communication skills on test performance (Cameron & Dillon, 2007). Cameron & Dillon (2008) reported that a high proportion of children presenting with listening difficulties (suspected APD) were found to have a deficit in the spatial processing skill, which was not found in children with language disorder. Therefore, the LiSN-S test has the potential to differentiate an auditory-based disorder from a language-based one.

2.4.3 Recommendations for Test Interpretation

The ASHA Technical Report (2005) proposes two ways of interpreting AP test results: (1) norm-based and (2) patient-based. A norm-based interpretation involves comparison of an individual’s performance to normative data, in which a performance score that falls below two standard deviations from the mean on two or more tests in the battery are considered as indicative of deficits in the relevant process. A patient-based interpretation, on the other hand, involves comparison of an individual’s test scores to his or her own baseline, by comparing the performance scores between the two ears within a given test (intratest analysis) or comparing the overall results across the diagnostic test battery (intertest analysis). Another approach for patient-based interpretation is cross-discipline, in which AP test results are compared with language, psycho-educational and related cognitive test findings.

It is worth highlighting that in some circumstances, a diagnosis of APD may not be warranted even though a child’s performance meets the criteria. For instance, if a child performed poorly or inconsistently across all tests, it may be indicative of other non-auditory factors such as higher order cognitive, memory or motivational issues confounding the results. A diagnosis of APD should also be considered carefully in cases where poor performance is found only on one test, unless the performance was at least three standard deviations below the mean and there is a manifestation of functional auditory difficulty related to the demonstrable auditory deficit. So, in order to confirm the initial findings, re-administration of the same test or similar test that assesses the same process is required (ASHA Technical Report, 2005).

Chapter 3

Auditory Processing Disorder: Management & Interventions

3.1 Introduction

As for any other developmental disorder, the goal for APD rehabilitation is to improve the functional deficits of individuals with specific impairments that are impacting on social, educational and communicative development. Given the heterogeneous nature of APD, an individualised management programme with a deficit-specific approach is recommended. The close association of APD with language and learning difficulties also suggests that, in order to achieve maximum functional benefit, the management of APD should be based on a multidisciplinary team approach (Bamiou, Campbell, & Sirimanna, 2006). Generally, a comprehensive management programme for APD should focus on the following three areas (Bamiou, Campbell, & Sirimanna, 2006, Bellis, 2003):

1. Remediate the disorder by means of techniques designed to enhance discrimination and associated neuroauditory function (e.g. auditory training).
2. Improve the accessibility of auditory information by changing the environment (e.g. signal enhancement strategies and teacher/speaker based adaptations).
3. Improve learning and listening skills by teaching children compensatory strategies to overcome their residual functional difficulties (e.g. metacognitive and metalinguistic training).

In this chapter, each aspect of intervention will be discussed, with particular focus placed on auditory training, as this part of APD rehabilitation contributes to the main theme of this thesis. As part of the process to inform the design of the study described in Chapter 6, a systematic review was undertaken by Loo and colleagues (2010) to examine the efficacy of various computer-based auditory training (CBAT) programmes for children with language-related and AP difficulties. Some of the findings and conclusions drawn from that review are presented in 3.2.1.2.

3.2 Auditory Training

Auditory training (AT) is regarded as one of the pivotal components in APD rehabilitation. AT involves listening exercises that are designed to improve the function of the auditory system by capitalising on the brain's neural plasticity. Changes in the neural substrates are often associated with behavioural changes (Musiek, Shinn, & Hare, 2002). These changes can be measured in terms of listening performance, auditory and language processing assessments, and possibly, neuroimaging and neurophysiological tests (refer to Chapter 1, section 1.3.3 for more details).

AT can be categorised as *formal* or *informal.* Formal AT is typically conducted in a controlled setting, like a clinic or a lab by audiological professionals, using acoustically controlled training paradigms with the ability to specify and precisely alter the stimuli (Chermak & Musiek, 2002). Formal AT employs a variety of auditory tasks including tonal (e.g frequency or intensity discrimination training) and simple speech stimuli (e.g. dichotic digit listening), which may require some instrumentation headphones.

Informal AT, on the other hand, can be a school- or home-based programme, as well as therapy conducted by a speech language therapist or audiologist in the clinic. The training tasks are predominantly language-based and tap into multiple processes concurrently. For example, discrimination and recognition of degraded speech stimuli can be used to improve auditory closure skills as well as building vocabulary (Chermak & Musiek, 2002). Some other examples of informal AT are discriminating similar sounding notes on a keyboard for training temporal patterning skills, phoneme discrimination exercises for training auditory discrimination skills, and listening to lyrics of songs for training speech-in-noise ability (Musiek, Shinn, & Hare, 2002; Bamiou, Campbell, & Sirimanna, 2006).

Prior to the implementation of an AT programme, a full APD diagnostic evaluation is necessary. However, a clinical decision on the type of AT programme is not governed by the results of specific auditory tests alone. Rather, input from multidisciplinary professionals that help to reveal a child's full range of functional deficits should be considered in the planning of an appropriate AT programme. Regardless of the type of AT approach – *formal* or *informal*, the principles summarised in Table 3.1 should be applied in order to maximise the chance of a successful training outcome.

Table 3.1: Summary of auditory training principles (Adapted from Musiek, Chermak, & Weihing, 2007)

Auditory training principles	Description
Training material	The training material should be age appropriate and within the means of the child's language, cognitive and communicative skills.
Motivation	Both parents and child should be motivated and engaged to do the tasks; understanding the rationale underlying AT is essential.
Varying AT tasks	Various tasks and stimuli should be used to heighten a child's motivation and to prevent boredom; topics of interest to the child can be included in the therapy.
Progression of AT tasks	The tasks should be presented systematically, progressively but appropriately made more challenging, dependent on the child's performance.
A balanced success-failure rate	Chermak and Musiek (2002) suggested a success/failure criterion ratio of 7:3 before changing the level of task difficulty. A task that is too easy will not be sufficiently challenging to elicit optimal change to the auditory system, but excessive difficulty will jeopardise behavioural change.
Sufficient therapy time	Sufficient therapy time with realistic goals should be allocated in order to successfully induce change or improvement in functional abilities.
Monitoring and feedback	Careful monitoring of the child's progress is vital and there should be provision of feedback and reinforcement that will allow the child to gauge his/her own performance. The clinician will also have better insight into the appropriateness of the AT programme with close monitoring and periodic evaluation of the child's progress.

3.2.1 Efficacy of Auditory Training Interventions

There is a paucity of evidence regarding the efficacy of AT approaches to APD. The majority of the outcome studies have reported on populations with language-based learning difficulties like SLI and/or SRD. Among these studies, only a few included auditory tasks as one of the outcome measures. In the following section, the reviewed outcome studies are categorised into the non-computer and the computer-based auditory training approaches.

3.2.1.1 Non-computer based auditory training

Various non-computerised auditory interventions that target different processes have been applied to children with AP difficulties. However, the training material, the duration of training and the outcome measures reported in the literature vary considerably from one study to another. The following paragraphs will review the few outcome studies that were conducted on APD populations, in which some of the trainings were more language-based while the others were auditory focused.

Jirsa (1992) investigated the effects of a structured training programme on a group of children with APD (n=10) using both electrophysiologic and AP tests as outcome measures. The training programmes were individualised for each subject, and centred on auditory memory and language comprehension, auditory discrimination and attention, and the interpretation of auditory directions. The training was conducted twice weekly for 45 minutes per session over a period of 14 weeks. Positive training outcomes were reported, with significant decreased of P300 latency and increased in amplitude. These electrophysiologic changes were also accompanied by improvement in the behavioural test measures. No changes were reported in either an untrained APD group (n=10) or a normal control group (n=20).

Putter-Katz and colleagues (2002) incorporated an integrative approach in the management of children with APD (n=20), which comprised a classroom modification including preferential seating, using a tape-recorder, the use of an FM system, remediation therapy and compensatory strategies. The remediation therapy included speech-in-noise and dichotic listening training, and was conducted by professionals in the clinic for 45 minutes per session once a week. The AP performances of these children were compared after 4 months of intervention to individuals' baseline results. Significant improvements were found in both speech-in-noise and competing sentences tasks. However, no untrained control group was included in this study and, thus, it was not possible to exclude a developmental effect on the improvement reported. Years later the team of Putter-Katz (2008) conducted a similar study with an inclusion of APD controls (n=10). Findings were consistent with the previous report that speech performance in background noise and competing sentences improved significantly for the trained group, but no significant changes were observed in the untrained controls.

Some researchers have incorporated dichotic listening tasks as part of the AT procedures and positive auditory outcomes have been reported. English, Martonik and Moir (2003) reported improvement seen in all the 10 subjects' left-ear scores by at least 1.5 standard deviations after 10-13 weeks of 1 hour weekly individualised training, in which the main component was dichotic listening training. The children were instructed to listen to an audio book in the left ear, while the right ear was exposed without any particular input. The children were then asked to answer some simple questions related to the story heard. Another study by Moncrieff and Wertz (2008) also reported a positive auditory outcome after dichotic listening training on a group of APD children with asymmetrical dichotic performance (left ear poorer than right ear). The material ranged from digits, words, to sentences. In experiment 1, the children (n = 8) received training 3 times per week for a period of 4 weeks, whereas in experiment 2, the expanded group of children (n = 13) was trained for 4 times per week for 30 minutes over a 6 week period. The dichotic left ear performance improved significantly after the training in experiment 1; while in experiment 2 with the increased duration of training, significant gains were observed in the dichotic right ear performance as well. The authors also reported significant improvements in language comprehension as well as word recognition, suggesting that dichotic listening training may also facilitate language skills in some children. While promising outcomes were indicated in both studies by the team of English (2003) and Moncrieff and Werts (2008), no untrained controls were included and therefore it is not possible to be sure the changes in performance arouse specifically from the training.

3.2.1.2 Computer-based auditory training (CBAT)

In recent years, there is a growing trend in using CBAT as part of an intervention for APD. This is because CBAT allows for precise control of the stimulus, easy access to an appropriate training level, and the standardisation of training. Some commercially available CBAT programmes such as Fast ForWord (FFW)[1] and Earobics[2], which were originally designed for children with language-related learning difficulties, are becoming more commonly introduced to children with APD. This recommendation is based on the assumption that some children with language-related learning difficulties

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[1] FFW (Scientific Learning Corporation, USA) is an adaptive intervention programme that employs acoustically modified non-speech and speech sounds (e.g. elongated tones, slower rate speech sounds) and is designed to train temporal processing, speech perception, and language comprehension skills.

[2] Earobics is a comprehensive computer-based programme for training in phonological awareness and auditory-language processing. The activities aim to improve sound awareness, discrimination of sound in noise and quiet, sequencing sound, associating sound with letters, understanding of complex directions with and without background noise, and memory for sounds and words, and include items to strengthen reading, spelling, and comprehension.

may have coexisting auditory temporal processing deficits, and the potential benefits of these CBAT programmes may be extended to treating APD.

In view of the absence of evidence-based guidelines outlining the effectiveness of CBAT for APD, Loo and colleagues (2010) reviewed the existing evidence for CBAT in children with language-related learning difficulties and examined the extent to which CBAT programmes benefited children with APD. Key words used in the search included ‘auditory processing’, ‘auditory processing disorder’, ‘central auditory processing disorder’, ‘auditory processing deficits’, ‘temporal processing’, ‘specific language impairment’, ‘reading disorder’, ‘auditory training’, and ‘computerized’. Key words were always combined (and ⁄ or) so that all relevant papers would be identified. The following databases were searched: MEDLINE, PubMed, and Web of Science. In addition, references that met the criteria from several textbooks on auditory processing disorder were searched manually.

Twenty-one articles were identified on the basis of a search covering the years 2000-2008, which required a CBAT study to contain non-speech and/or simple speech sounds training on normal hearing children with language learning or AP difficulties. As shown in Table 3.2, Table 3.3, and Table 3.4, thirteen studies reported on FFW, three studies reported on Earobics, and five other CBAT studies reported using non-speech and simple speech sounds in training for children. These studies were rated according to the level of evidence hierarchy proposed by ASHA (2004) as shown in Appendix A.

Table 3.2: Outcome studies of Fast ForWord-Language in children (Copied from Loo et al., 2010)

Study	Evidence Level	Ages (y/m)	Subjects	Experimental Training Group	Comparison Training Group	Control Untrained Group	Language improved?	Phonologi-cal skills improved?	Reading skills improved?	Spelling skills improved?	Auditory processing improved?	Type of measure used for auditory processing
Gillam et al. 2008	Ib	6.0 - 8.11	54 SLI	FFW-L	-	-	Yes (R&E)	Yes	N.T.	N.T.	Yes	Backward masking
			54 SLI	-	CALI	-	Yes (R&E)	Yes	N.T.	N.T.	Yes	
			54 SLI	-	ILI	-	Yes (R&E)	Yes	N.T.	N.T.	Yes	
			54 SLI	-	AEP	-	Yes (R&E)	Yes	N.T.	N.T.	Yes	
Given et al. 2008	Ib	12.2 - 12.8	12 SLI/SRD	FFW-L then FFW-LR	-	-	Yes (R&E)	Yes	Yes	No	N.T.	-
			14 SLI/SRD	-	SM then SM	-	Yes (R&E)	Yes	Yes	No	N.T.	
			15 SLI/SRD	-	FFW-L then SM	-	Yes (R&E)	Yes	Yes	No	N.T.	
			11 SLI/SRD	-	SM then FFW-L	-	Yes (R&E)	Yes	Yes	No	N.T.	
			13 SLI/SRD	-	-	Regular class	Yes (R&E)	Yes	Yes	No	N.T.	
Stevens et al. 2008	III	6.0 – 8.0	8 SLI	FFW-L	-	-	Yes (R only)	N.T.	N.T.	N.T.	Yes	Speech-evoked cortical responses
			12 Normals	FFW-L	-	-	Yes (R only)	N.T.	N.T.	N.T.	Yes	
			13 Normals	-	-	No treatment	No	N.T.	N.T.	N.T.	No	
[a]Gaab et al. 2007	III	10.5 (avg)	22 SRD	FFW	-		Yes (R&E)	Yes	Yes	N.T.	No	Pitch discrimination
			12 Normals		-	No treatment	No	No	No	N.T.	No	
Valentine et al. 2006	IV	7.0 - 10.0	13 SRD (poor readers)	FFW	-	-	Yes (R&E)	Yes	No	N.T.	Yes	Backward masking
			13 SRD (low avg readers)	FFW	-	-	Yes (R&E)	Yes	No	N.T.	Yes	

[a]Associate to the FFW developer; SLI = specific language impairment; SRD = specific reading disorder; AEP = Academic Enrichment Programme; CALI = Computer assisted language intervention; FFW-L = Fast ForWord –Language; FFW-LR = Fast ForWord- Language to Reading; ILI = Individualised language intervention; SM = SuccessMaker (computer based adaptive training software that offers standard-based school development curriculum); E= expressive language; R = receptive language No = no significant gain; N.T = not tested; Yes = significant gain

Table 3.2: Outcome studies of Fast ForWord-Language in children (Copied from Loo et al., 2010) (continued)

Study	Evidence Level	Ages (y/m)	Subjects	Experimental Training Group	Comparison Training Group	Control Untrained Group	Language improved?	Phonological skills improved?	Reading skills improved?	Spelling skills improved?	Auditory processing improved?	Type of measure used for auditory processing
Cohen et al. 2005	Ib	6.0 – 10.0	23 SLI	FFW + regular SLT	-	-	Yes (R&E)	[b]Yes	Yes	N.T.	N.T.	-
			27 SLI	-	CALI + regular SLT	-	Yes (R&E)	Yes	Yes	N.T.	N.T.	
			27 SLI	-	-	Regular SLT	Yes (R&E)	Yes	Yes	N.T.	N.T.	
Pokorni et al. 2004	Ib	7.6 – 9.0	20 SLI/SRD	FFW	-	-	No	No	No	N.T.	N.T.	-
			16 SLI/SRD	-	Earobics	-	No	Yes	No	N.T.	N.T.	
			18 SLI/SRD	-	LiPS	-	No	Yes	No	N.T.	N.T.	
Rouse & Krueger 2004	Ib	Grade 3 to 6	272 SRD	FFW	-		Yes (R&E)	N.T.	Yes	N.T.	N.T.	-
			240 SRD	-	-	Regular class	Yes (R&E)	N.T.	Yes	N.T.	N.T.	-
Agnew et al. 2004	IV	7.0 – 10.0	7 non-specific poor academic performers	FFW	-	-	N.T.	No	No	N.T.	Yes	Auditory duration judgement
Troia et al. 2003	II	9.7 (avg)	25 low academic achievers	FFW	-	-	Yes (E only)	[c]Yes	No	N.T.	N.T.	-
			12 low academic achievers	-	-	Regular class	No	Yes	No	N.T.	N.T.	
[a]Temple et al. 2003	III	8.0 – 12.0	20 SRD	FFW	-	-	Yes (R&E)	Yes	Yes	N.T.	N.T.	-
			12 Normals	-	-	No treatment	No	No	No	N.T.	N.T.	

[a]Associate to the FFW developer; [b] Significantly higher scores than control group for rhyming at 6 months; [c] greater than control group but limited to blending only
SLI = specific language impairment; SRD = specific reading disorder; CALI = Computer assisted language intervention; LiPS = Lindamood Phoneme Sequencing;
E= expressive language; R = receptive language; No = no significant gain; N.T = not tested; Yes = significant gain

Table 3.2: Outcome studies of Fast ForWord-Language in children (Copied from Loo et al., 2010) (continued)

Study	Evidence Level	Ages (y/m)	Subjects	Experimental Training Group	Comparison Training Group	Control Untrained Group	Language improved?	Phonological skills improved?	Reading skills improved?	Spelling skills improved?	Auditory processing improved?	Type of measure used for auditory processing
Hook et al. 2001	II	7.0 – 12.0	11 SRD	[a] FFW	-	-	[c] Yes	Yes	No	No	N.T.	-
			9 SRD	-	[a] OG	-	N.T	Yes	[d]Yes	No	N.T.	
			11 SRD	[b] Post-FFW + MSLI (regular activities)	-	-	No	Yes	Yes	No	N.T.	
			11 SRD	-		[b] MSLI (regular activities)	No	Yes	Yes	No	N.T.	
Marler et al. 2001	III	6.10 – 9.3	2 LLI	FFW	-	-	N.T.	N.T.	N.T.	N.T.	Yes	Backward & simultaneous masking
			2 LLI	-	LLS	-	N.T.	N.T.	N.T.	N.T.	Yes	
			3 Normals	-	-	No treatment	N.T.	N.T.	N.T.	N.T.	Yes	

[a] Short-term study (3 months); [b] Longitudinal study (2 years); [c] Significant gains in speaking and syntax; [d] significant gains in word attack score (one of the subtests in Woodcock Reading Mastery Test-Revised) ; LLI = language learning impairment; SRD = specific reading disorder; LLS = Laureate Learning System; MSLI = Multisensory Structured Language Instruction; OG = Orton Gillingham programme; No = no significant gain; N.T = not tested; Yes = significant gain

Table 3.3: Outcome studies of Earobics in children (Copied from Loo et al., 2010)

Study	Evidence Level	Ages (y/m)	Subjects	Experimental Training Group	Comparison Training Group	Control Untrained Group	Language improved?	Phonological skills improved?	Reading skills improved?	Spelling skills improved?	Auditory processing improved?	Type of Auditory Processing test used
Russo et al. 2005	III	8.0 – 12.0	9 LP	Earobics	-	-	N.T.	[a] Yes	N.R.	N.R.	[b] Yes	Speech-evoked ABR, speech-evoked cortical responses in quiet and in noise, speech discrimination /da-ga/ in quiet and in noise, sentence perception in noise
			5 LP + 5 Normals	-	-	No treatment	N.T.	No	N.R.	N.R.	No	
Warrier et al. 2004	III	8.0 – 13.0	13 LP	Earobics	-	-	N.T.	[c] Yes	N.R.	N.R.	Yes	Speech-evoked cortical responses in quiet and in noise, speech discrimination /da-ga/
			4 LP + 7 Normals	-	-	No treatment	N.T.	Yes	N.R.	N.R.	No	
Hayes et al. 2003	III	8.0 – 12.0	27 LP	Earobics	-	-	N.T.	Yes	No	No	dYes	Speech-evoked ABR, speech-evoked cortical responses in quiet and in noise
			15 LP + 7 Normals	-	-	No treatment	N.T.	No	No	No	No	

[a] Significant gains on the incomplete words task; [b] Significant gains on sentence perception in noise, and changes in speech-evoked ABR & cortical responses; [c] Improvements in sound blending tasks were greater than improvements seen in the untrained control group; d significant changes in amplitude and latency of speech-evoked cortical responses only; LP = Learning problems related to language, learning and reading difficulties; ABR = Auditory Brainstem Response; No = no significant gain; N.T = not tested; N.R = Not reported (outcome not reported in the result section even though it was used as part of the assessments); Yes = significant gain

Table 3.4: Outcome studies of nonspeech and simple speech sounds training in children (Copied from Loo et al., 2010)

Study	Evidence Level	Ages (y/m)	Subjects	Experimental Training Group	Comparison Training Group	Untrained Control Group	Language improved?	Phonological skills improved?	Reading skills improved?	Spelling skills improved?	Auditory processing improved?	Type of measure used for auditory processing
McArthur et al. 2008	III	6.0 – 15.0	18 SRD/SLI	FD	-	-	[a] Yes	N.T.	No	[c] Yes	Yes	Frequency discrimination
			32 Normals	-	-	No treatment	[a] Yes	N.T.	[b] Yes	Yes	No	
			3 SRD/SLI	Masked FD	-	-	[a] Yes	N.T.	No	[c] Yes	Yes	Masked frequency discrimination
			34 Normals	-	-	No treatment	[a] Yes	N.T.	[b] Yes	Yes	No	
			4 SRD/SLI	VD	-	-	[a] Yes	N.T.	No	[c] Yes	Yes	Vowel discrimination
			32 Normals	-	-	No treatment	[a] Yes	N.T.	[b] Yes	Yes	No	
			9 SRD/SLI	CV-D	-	-	[a] Yes	N.T.	No	[c] Yes	Yes	Consonant-Vowel discrimination
			36 Normals	-	-	No treatment	[a] Yes	N.T.	[b] Yes	Yes	No	
Veuillet et al. 2007	II	9.0 – 12.0	9 SRD	AV (CV syllables)	-	-	N.T.	N.T.	Yes	N.T.	Yes	Categorical perception test, contralateral suppression OAE
			9 SRD	-	-	No treatment	N.T.	N.T.	No	N.T.	No	
Strehlow et al. 2006	II	7.8 – 8.3	15SRD	SP + Regular reading training	-	-	N.T.	N.T.	Yes	[d] Yes	[e] Yes	Tests for temporal processing of sound and phoneme stimuli
			14 SRD	PP + Regular reading training	-	-	N.T.	N.T.	Yes	No	[f] Yes	
			15 SRD	-	-	Regular reading training	N.T.	N.T.	Yes	No	No	

[a] Improvement on repeating sentences task; [b] improvement on sight word reading task; [c] improvement on irregular spelling task only in SRD group; [d] improvement at 6-month follow up but not sustainable after 12 months; [e] specific training effect on sound processing test only immediately post-training; [f] specific training effect on phoneme processing test only immediately post-training, after 6 months and 12 months follow ups; SLI = Specific Language Impairment; SRD = Specific Reading Disorder; AV = Audiovisual; CV-D= Consonant-Vowel Discrimination; FD = Frequency Discrimination; PP = Phoneme Processing; SP = Sound Processing; VD = Vowel Discrimination; No = no significant gain; N.T = not tested; Yes = significant gain

Table 3.4: Outcome studies of nonspeech and simple speech sounds training in children (Copied from Loo et al., 2010) (continued)

Study	Evidence Level	Ages (y/m)	Subjects	Experimental Training Group	Comparison Training Group	Untrained Control Group	Language improved?	Phonological skills improved?	Reading skills improved?	Spelling skills improved?	Auditory processing improved?	Type of measure used for auditory processing
Schäffler et al. 2004	IV	7.0 - 21.0	140 SRD	LLAD tasks	-		N.T.	N.T.	N.T.	N.T.	[g] Yes	Intensity discrimination, frequency discrimination, gap detection, time-order judgement & side-order judgement
	II	7.0 - 21.0	25 SRD	LLAD tasks	-	-	N.T.	Yes	N.T.	Yes	N.T.	-
			11 SRD	-	DVOD	-	N.T.	No	N.T.	No	N.T.	
			6 SRD	-	-	No treatment	N.T.	No	N.T.	No	N.T.	
Kujala et al. 2001	II	7.0 – 7.11	24 SRD	AV (Tones)	-	-	N.T.	N.T.	[h] Yes	No	[i] Yes	Electrophysiological measure (Mismatch Negativity/MMN), tonal discrimination
			24 SRD	-	-	No treatment	N.T.	N.T.	No	No	No	

[g] Mixed results; [h] Improvements on words correct task and reading speed; [i] significant increased MMN amplitude; SLI = Specific Language Impairment; SRD = Specific Reading Disorder AV = Audiovisual; LLAD = Low-Level Auditory Discrimination (include intensity discrimination, frequency discrimination, gap detection, time-order judgement, & side-order judgement); DVOD = Dynamic Visual Orientation Discrimination; No = no significant gain; N.T = not tested; Yes = significant gain

It is noteworthy that all the participants in these studies were either children with SLI, SRD, or learning problems; none reported on children with APD. Of the 21 articles identified, only 14 studies included measures of AP and listening skills. The conclusions drawn from this review article are (Loo, Bamiou, Campbell, & Luxon, 2010):

The effects of CBAT intervention on language, phonological awareness, reading and spelling skills of children

a) The genuine training effect of FFW intervention on the language skills of children with language, reading and learning difficulties is still debatable. Even though 10 studies have reported gains in the language measures after FFW intervention, three studies (Rouse and Krueger, 2004; Cohen et al., 2005; Given et al., 2008) showed similar positive training effects on other comparison training groups. Three other studies (Hook, Macaruso, & Jones, 2001; Valentine, Hedrick, Swanson, 2006; Gillam et al., 2008) did not include an untrained control group to tease out the effect of test-retest or maturation. Two studies (Temple et al., 2003; Gaab et al., 2007) are the associates of FFW developers and may support favourable outcomes of FFW; therefore, their results should be viewed with caution. So far, only two other studies – Stevens and colleagues (2008), and Troia and Whitney (2003) reported a true training effect of FFW intervention on language skills of children with SLI and low academic achievement respectively. One study reported no significant changes in the language measure after FFW intervention as well as other comparison training programmes (Pokorni, Worthington, & Jamison, 2004). On the other hand, FFW-Language may help to improve some aspects of phonological awareness skills (such as rhyming and blending) in children with SLI and SRD, but not reading skills and spelling.

b) The Earobics intervention seems to have had a positive impact on the phonological awareness skills of children (Hayes et al., 2003; Russo et al., 2005). However, no comment can be made on the language skills, as language measures were not included in the three outcome studies of Earobics. Evidence regarding the efficacy of Earobics on improving reading and spelling skills of children remains limited.

c) CBAT incorporating non-speech and simple speech sound training seems to aid in improving reading skills of children if the training is delivered using audio visual methods (Kujala et al., 2001; Veuillet et al., 2007), but not otherwise (Strehlow et al., 2006; McArthur, Ellis, Atkinson & Coltheart, 2008). This underlines the importance of ‘pairing’ of audio-visual stimuli in the acquisition of reading. The impact of non-speech and simple speech sound training on language skills remains unclear. So far, only one study (McArthur, Ellis, Atkinson, & Coltheart, 2008) included a language measure. Moreover, the improvement reported in that study is more likely the result of a maturational or test-retest effect. Three studies reported no significant training effect on the spelling skills of children (Kujala et al., 2001; Strehlow et al., 2006; McArthur, Ellis, Atkinson, & Coltheart, 2008).

The effects of CBAT intervention on the AP skills of children

a) The effects of FFW intervention on the AP skills of children with language, reading, and learning difficulties remain unclear, as the four studies that reported improvement in temporal tasks (Marler, Champlin, & Gillam, 2001; Agnew, Dorn, & Eden, 2004; Valentine, Hedrick, & Swanson, 2006; Gillam et al., 2008) included no untrained comparison group. It is not feasible to tease out a maturational or learning effect because of repeated measures in these studies; therefore it is not possible to conclude that there were any true treatment effects of FFW on children’s

AP skills. While one study showed improvement in brain potentials that are indirect measures of auditory attention (Stevens et al., 2008), another study showed no improvement in an auditory behavioural measure, i.e. frequency discrimination (Gaab et al., 2007).

b) Earobics may improve the morphology, amplitudes, and latencies of speech-evoked cortical (Hayes et al., 2003; Warrier et al., 2004; Russo et al., 2005) and subcortical responses in noise (Russo et al., 2005), which have been shown to have direct correlation with auditory perceptual changes (e.g. improved speech discrimination abilities) (Warrier et al., 2004; Russo et al., 2005). However, this conclusion is based on only three studies that were conducted by the same group of researchers; replications of results from other independent researchers are necessary.

c) CBAT incorporating auditory non-speech tasks (e.g. intensity discrimination, frequency discrimination, gap detection) and simple speech sounds like phonemes (e.g. /b/-/p/) or consonant-vowel syllables (e.g. /da/ vs /ta/) trainings seem to have specific training effect and aid in improving specific AP skills of children (Kujala et al., 2001; Strehlow et al., 2006; McArthur, Ellis, Atkinson, & Coltheart, 2008).

3.2.2 Limitations of the Current Outcome Studies

Overall, the literature search yielded 25 studies that reported the outcomes of AT interventions (both non-computer and computer-based) for children with language-related or AP difficulties. Even though many of these studies demonstrated favourable training outcomes and potential benefits for APD, it is worth highlighting some of the limitations of these studies:

1) Many studies did not include an untrained comparison group to rule out a learning or maturational effect when changes were found; therefore, it is not possible to confirm a true treatment effect of a particular AT intervention on children's language or AP skills. McArthur (2007) reported that a test-retest effect can account for significant improvements in auditory measures in a study that included an untrained control group.
2) Few or no studies employed measures of AP and listening skills (including real-life listening performance questionnaires) as primary outcome measures. Many of these studies only report measures of language, reading, and phonological awareness, and these measures cannot be directly related to AP skills (Watson et al., 2003).
3) The lack of thematically coherent AT programmes. Some studies reported interventions that were more language-based (e.g. Jisra, 1992; Hayes et al., 2003; Warrier et al., 2004; Russo et al., 2005), whereas others are more auditory-based (e.g. Kujala et al., 2001; McArthur, Ellis, Atkinson, & Coltheart, 2008; Veuillet et al., 2007). The duration of training also varies considerably from one study to another (see Table 3.5). It is therefore difficult to suggest appropriate methods or duration of training needed for use of AT in APD.
4) Many of the studies reported on the short term training effect without further follow ups. Therefore, it is unable to assess the sustainability of benefit an AT intervention had on children's AP skills.

In order to determine the efficacy of an AT programme for a specific diagnosis of APD, future research needs to address the above shortcomings, and more importantly, to focus on a well-defined APD population.

Table 3.5: The various types of AT interventions and its length of practice

Study	Type of AT	Duration (min) per session	Session(s) per week	Length of training (weeks)
Jisra (1992)	Non-CBAT (auditory + language)	45	2	14
Putter-Katz (2002)	Non-CBAT (SIN, DD)	45	1	16
English et al. (2003)	Non-CBAT (DD)	60	1	10-13
Moncrieff & Wertz (2008)	Non-CBAT (DD)	30	4	6
Gillam et al. (2008)	CBAT (FFW)	100	5	6
Given et al. (2008)	CBAT (FFW)	88 (Average)	5	12
Gaab et al. (2007)	CBAT (FFW)	100	5	8
Valentine et al. (2006)	CBAT (FFW)	120	5	6
Cohen et al. (2005)	CBAT (FFW)	90	5	6
Agnew et al. (2004)	CBAT (FFW)	100	5	4-6
Troia et al. (2003)	CBAT (FFW)	100	5	4-8
Temple et al. (2003)	CBAT (FFW)	100	5	5.5 (average)
Hook et al. (2001)	CBAT (FFW)	100	5	4-8
Marler et al. (2001)	CBAT (FFW)	100	5	4
Russo et al. (2005); Warrier et al. (2004); Haye et al. (2003)	CBAT (Earobics)	60	4-5	8
McArthur et al. (2008)	CBAT (tones)	30	4	6
Veuillet et al. (2007)	CBAT (simple speech)	30	4	5
Sthrehlow et al. (2006)	CBAT (simple speech) + reading	20 (CBAT) + 120 (reading)	5	4 (CBAT) + 10-12 (reading)
Kujala et al. (2001)	CBAT (tones)	10	2	7

3.3 Classroom Modifications and Management

Children spend much of their time learning and listening at school and, thus, classroom acoustics should be given special attention. The classroom is generally a noisy learning environment with multiple student activities. Maintaining a low ambient noise and reverberation level that improves signal-to-noise ratio (SNR) is therefore important for maximizing the accessibility of auditory information by students. ASHA recommends that the background noise of an unoccupied classroom should not exceed 30dBA and reverberation should be kept at less than 0.4 seconds (Bellis, 2003). For optimum listening for children with listening difficulties, a SNR of +30dB (i.e. a teacher's voice needs to be 30 dB more intense than the ambient noise) is required (Bamiou, Campbell, & Sirimanna, 2006).

There are probably few, if any, existing classrooms that meet these criteria. In order to meet the above recommendations, several steps can be undertaken to minimise or to eliminate, the reflective surfaces of the classroom and other noise sources. For example, the addition of sound-absorbing material such as carpet, or floor rugs, and curtains can help to reduce reverberation. Putting seals on door and windows can reduce external noise and putting rubber shoes on furniture legs can reduce in-room noise (Bamiou, Campbell, & Sirimanna, 2006). Preferential seating will also help to improve the SNR. This can be achieved by sitting the child close to the teacher(3 to 6 feet for optimal audibility (Broothroyd, 2004), so that the teacher's face is clearly visible at no more than a 45 degree angle and away from competing noise sources (Bellis, 2003).

3.4 Teacher/Speaker based Adaptations

Normal hearing listeners as well as those with auditory-based learning disabilities have been shown to benefit from listening to clear speech (Bradlow, Kraus, & Hayes, 2003). In clear speech, the speaker is required to speak naturally to produce every word, phrase, or utterance in a precise and clear fashion (Musiek, Baran, & Schochat, 1999) to enhance the spectral characteristics (e.g. improved relative consonant-to-vowel intensities) as well as the suprasegmental features of speech sounds (e.g. improved prosody) (Hazan & Simpson, 2000). Teachers who come across students with APD should be advised to use clear speech, if possible, coupled with auditory-visual presentation to further enhance speech intelligibility (Ferre, 2007).

Other than clear speech, the teacher may also help by rephrasing a “misheard” signal using a more linguistically familiar and less ambiguous target. For example, instead of “stop that!” it can be rephrased with “stop tapping your pencil” (Ferre, 2007). Keeping sentences short, adding complementary visual cues, and provision of lecture notes prior to the class presentation may help to improve understanding and to avoid division of attention that occurs during notetaking. Introducing breaks in academically challenging lessons or interspersing lecture classes with more hands-on activities would help to minimize auditory overload and, thus, reduce auditory fatigue (Ferre, 2007). Such strategies are also likely to be of benefit to all children in the class, whether APD or not.

3.5 Signal Enhancement: Personal FM and Sound Field Technology

Classroom modifications and teacher-based adaptations may not always be sufficient to improve the listening conditions. An alternative to providing an effective listening environment is the use of assistive listening devices, such as personal or sound field FM systems. This wireless system takes advantage of the transmission of the speech signal (as sensed from a microphone of which is worn near the speaker's mouth) via an FM radio wave to the receiver through a transmitter. FM systems help to address the acoustic problem of distance, and reduced the effects of background noise and reverberation, leading to SNR enhancement and better speech clarity (Crandell, Kreisman, Smaldino, & Kreisman, 2004).

Benefits arising from personal or sound field FM systems in aiding improvements in listening, literacy, and the attention of children with learning difficulties have been reported in the literature. For example, Flexer, Millin, and Brown (1990) demonstrated that a sound field FM system that increased the teacher's voice by 10dB resulted in pre-schoolers with developmental disabilities (n=9) making significantly fewer errors on a word identification task than they made without amplification. Darai (2000) reported that children from classrooms with 5 months of sound field FM system use achieved significantly greater literacy gains than children in classrooms with no FM. A randomised control trial by Blake and colleagues (1991) showed that children with learning disabilities improved in attending behaviours (i.e. established eye contact with speaker, turned their body towards the sound source, made fewer extraneous body movements and verbal interuptions) after a 24 week trial of personal FM system (n=18) compared to those without (n=18). Another randomised control study revealed that, after a 6-week trial of personal FM systems, children with reading delay (n=23) had significantly better listening abilities in difficult listening situations than before, as measured by the teacher- and student-rated LIFE-UK questionnaires, while no changes were reported for the control group (n = 23) (Purdy, Smart, Bailey, & Sharma, 2009).

Although the use of FM systems may seem promising for improving the listening and learning skills of children, a systematic review done by Lemos and colleagues (2009) revealed the lack of strong scientific evidence supporting the use of personal FM systems for APD intervention. Most of the studies (as reviewed by Lemos et al.) were based on specialists' opinions, and a few case study reports. So far, only two outcome studies of FM systems in APD population with normal controls were found in the literature search. Both the studies by Johnston and team (2009), and Friederichs and Friederichs (2005) included auditory tasks as outcome measures.

Johnston and colleagues (2009) fitted a group of children with APD (n=10) with personal FM systems mainly for classroom usage, for at least 5 months, and compared their performance with a group of normal controls (n = 13). Outcome measures included a speech perception in noise test (HINT), in addition to academic (SIFTER, LIFE) and psychosocial (BASC-2) questionnaires. In comparison to the non-FM normal control group, the APD group demonstrated a greater speech-perception advantage with an FM system. In addition, a within-group comparison showed improved speech perception ability in noise as well as significant academic and psychosocial gains from the baseline with use of the FM system. It was also noted that, after a prolonged use of FM systems, the speech perception of children with APD improved even without using the device. Similarly, Friederichs and Friederichs (2005) reported changes in the electrophysiologic late event potential pattern of children with APD (n = 10) following 1 year of FM system use, while the P2 amplitude increment was not observed in the non-FM control group (n = 10).

In conclusion, FM systems may be considered as part of the APD management process, but careful evaluation should be undertaken prior to the recommendation of FM systems. While the studies by Johnston and team (2009), and Friederichs and Friederichs (2005) indicate a positive sign of auditory plasticity induced by the use of FM system, some have raised the concern of its long term impact on the CANS. It remains unknown whether the CANS alterations may affect the ability to process binaural cues related sound localisation or taking advantage of a spatial separation of target and masker (Bellis, 2003). Hence, prior to the recommendation of an FM system, further aspects must be considered. These include the child's age, AP strengths and weaknesses, motivation, the setting where the device will be used, as well as provision of guidance to child and teacher about the use of the device, and monitoring the outcome (Rosenberg, 2002).

3.6 Central Resources Training

Individuals with APD are often seen as passive listeners, as they may fail to attend and organise the acoustic signal selectively due to the inability to deploy listening comprehension strategies, and thus, the ability to focus and maintain concentration on relevant task information (Chermak, 2007). Teaching individuals with APD, especially children, to utilise central resources (strategies) that might facilitate information processing might help to compensate to some extent for the impaired auditory processes, thereby minimizing their functional difficulties.

Central resources training may involve three components (Chermak, 2007):

I. *Metacognitive*

   Metacognitive strategies such as self-monitoring and self-regulation, developing problem solving skills, verbal rehearsal, and many others, can be applied to improve speech understanding of children with APD by teaching them to take responsibility for their listening comprehension (Bellis, 2003).

II. *Cognitive*

   Attention and memory, two primary and highly interdependent and interactive *cognitive* resources, can be improved with exercises such as auditory vigilance training [whereby target stimuli are presented at random intervals and the child is asked to raise his/her hand every time the target sound is heard (Bamiou, Campbell, & Sirimanna, 2006)], and memory enhancement techniques (e.g. mnemonic techniques such as chunking). These exercises and techniques might aid children with APD in remembering, and carrying out responses to verbal input.

III. *Metalinguistic*

   Training the rules of language, for example, or anything that can be done to strengthen top-down linguistic and *metalinguistic* skills of children with APD is likely to reinforce effective listening and learning. This is especially relevant as so many APD children appear to have comorbid language problems.

Other examples of skills and compensatory strategies training are summarised in Table 3.6. A detailed explanation of each skill, however, is beyond the scope of this thesis [refer to Chermak (2007) for more detail].

Table 3.6: Skills and strategies of central resources training for APD (Adapted from Chermak, 2007)

Metacognitive	Cognitive	Metalinguistic
Attribution retraining Self-instruction Cognitive problem solving Self-control Cognitive strategy training Cognitive style and reasoning Reciprocal teaching Assertiveness training	Sustained auditory attention (Auditory vigilance) Memory: Mnemonics Auditory Memory Enhancement (AME) Mind mapping Working memory	Schema induction and Discourse cohesion devices Auditory closure Vocabulary building Phonologic awareness Prosody (temporal processing)

Chapter 4

Pilot Study: Management of Children with Auditory Processing Disorder Associated with PAX6 Gene Mutation

4.1 Introduction

The PAX6 gene plays an essential regulating role in the formation of normal structure and function of vision and central nervous system. Mutations of the PAX6 gene are associated with visual dysfunction as well as disordered AP. The auditory dysfunction may be a result of the structural abnormalities of the brain's interhemispheric pathway that are associated with the mutations (Bamiou et al, 2004 & 2007a). The combined effect of visual and auditory difficulties in these individuals, especially children, may have detrimental impact on their academic performance. Appropriate management that aims to improve AP skills of these children may thus be imperative.

There are many different types of intervention strategies (as described in Chapter 3) that have been proposed as beneficial for neurologically normal children with APD (Bamiou, Campbell, & Sirimanna, 2006). However, it is unknown how effective these intervention strategies would be for neurological abnormal individuals with APD who are associated with PAX6 mutations, because no previous studies had reported on this group of patients.

In this chapter, we present 3 case studies that describe the outcome of an integrative intervention approach on children identified with APD and associated with PAX6 gene mutations. In particular, these children were given a 3-month computer-based auditory training (CBAT) at home while at the same time, they were fitted with personal FM system at school. This pilot study was conducted to help and inform the design and the suitability of one of the CBAT programmes developed for the main study described in Chapter 6.

4.2 PAX6 Gene Mutations – Structural and Functional Abnormalities

In humans, heterozygous PAX6 mutations are associated with aniridia (absence of iris) phenotype and other ocular anomalies (Prosser & van Heyningen, 1998; Tzoulaki, White, & Hanson, 2005). Aniridia is a relatively rare panocular disease, with a population frequency of around 1 in 60,000 – 1/100,000. The majority of the aniridia cases have a strong family history of PAX6 gene mutations, but some sporadic cases without previous family history have also been reported (Prosser & van Heyningen, 1998).

PAX6 gene mutations can be classified into 6 categories: nonsense mutations, splicing mutations, frame-shifting insertions or deletions, in-frame insertions or deletions, missense mutations and run-on mutations (Tzoulaki, White, & Hanson, 2005). Each of these has a different effect of genomic change. A brain-MRI study conducted by Free and colleagues (2003) identified a widespread impact of PAX6 gene mutations on brain development. Areas that have been shown to be abnormal in association with PAX6 mutations include the corpus callosum (CC), cerebellum, as well as regions of cortical grey and white matter. Absence and hypoplasia of the anterior commissure (AC) in patients with PAX6 mutations were also reported in some other studies (Bamiou et al., 2004; Thompson et al., 2004). However, no specific phenotype-genotype correlation, with differential effects of the mutational variations on the brain abnormalities has as yet been identified (Bamiou et al., 2007a).

The importance of the CC and AC as the interhemispheric transfer has been extensively discussed in Chapter 1 (section 1.2.6). Both of these structures are believed to have played an important role in complex AP (Bamiou, Sisodiya, Musiek, & Luxon, 2007b). Adults and children with congenital aniridia due to the PAX6 gene mutations have been found to consistently show a left ear deficit on dichotic listening tasks and impaired auditory patterning tests (Bamiou et al., 2004; 2007a). Difficulties listening in background noise and localisation of sound are some main complaints associated with it (Bamiou et al., 2004; 2007a); some even reported difficulties in understanding prosody of speech (Bamiou et al., 2007a).

4.3 Objective and Hypothesis

This pilot study aimed to examine the feasibility and effectiveness of an integrative intervention approach for children with APD associated with PAX6 gene mutations, as judged by the changes in AP and functional listening skills of these children between pre- and post-intervention. We hypothesised that the AP and functional listening skills of these children, as measured by the behavioural AP tests and questionnaires, would improve after 3-month of integrative intervention as compared to 3-month of no intervention.

4.4 Methodology

4.4.1 Study design

This pilot study was designed to follow up participants over two phases, with the first three months (phase 1) of no intervention, followed by a 3-month intensive intervention (phase 2) (see more detail in section 4.4.7 and a flowchart in Appendix B). This study design was chosen because of the limited number of new cases identified with PAX6 gene mutations (i.e. less than 10 per year in the UK) as recorded in the database obtained from the MRC Human Genetics Unit (UK). It would be ideal, but not sensible with such a small group of participants, to conduct either a cross-over study or a randomised control trial. Therefore, an observational phase of no intervention (phase 1) was included to serve as an intra-subject control to examine any developmental effects on the AP skills of the participants over time.

4.4.2 Ethics Approval

This pilot study was granted approval by the Ethics Committee of the National Hospital for Neurology and Neurosurgery and Institute of Neurology Joint REC (Reference number 08/H0716/58). Written informed consent was obtained from parent/guardian of the participant.

4.4.3 Subject Recruitment

A list of 36 families with known PAX6 gene mutations was obtained from Professor Veronica van Heyningen, geneticist from the MRC Human Genetic Unit, Scotland. The general practitioners of these patients were informed about the study, and helped to approach patients for verbal consent for their contact information to be passed on to Dr. Bamiou (Senior Consultant in Audiovestibular Medicine, National Hospital for Neurology and Neurosurgery). An invitation letter with reply slip was sent out by the principal-investigator (PI; author of this thesis) to 13 families who showed initial interest in the study, but only 9 families had children meeting the age requirement (7 to 12 years old) of this study. Of these families who replied, only 4 families gave positive response to the study invitation. Prior to the baseline assessment, one of the children withdrew from the study and therefore, only 3 children were recruited from the list given.

A few other families with PAX6 gene mutations who had participated in a previous study conducted by Dr. Bamiou had also been contacted. Only one of them agreed to have their child participated in the study. Overall, four participants were recruited over the 8 months of recruitment process. Various reasons had been given by those potential subjects who rejected the study and that included: long traveling time to London (~ 3 hours) for assessment, as most of the PAX6 families live in the northern part of England; too many medical appointments for the child; some children were not well enough to participate in the study.

4.4.4 Procedures

The participants in this study were assessed at baseline using a series of standardised tests as described below. These behavioural assessments were conducted by the PI at participants' home after obtaining verbal and written consent from each participant's parents. Brain imaging (MRI scan) was also performed on each participant at baseline to provide structural information about the CC area. The brain imaging procedure was conducted at the Great Ormond Street Hospital for Children in London.

Three months after the baseline assessments (end of phase 1), the AP skills of participant were assessed again. Then, the training software was installed on the participant’s computer. In addition, each participant was fitted with a pre-programmed FM system (Edulink, Phonak), which was used daily at school for 3 months. The use of FM system was demonstrated to teacher at school in a separate session. Upon the completion of the 3-month intervention (end of phase 2), the AP and listening skills of participants were re-assessed.

4.4.5 Baseline Assessment

The baseline behavioural assessments that consisted of AP, language, and phonological skills tests took approximately 2.5 hours to complete, with intervals given between subtests. Of note, all the assessments were carried out by the PI, a senior audiologist who has been trained and supervised to conduct language assessment by a qualified speech language therapist (Dr. Nicci Campbell, University of Southampton).

The assessments were conducted in a quiet room with ambient noise level was measured below 40dBA using a calibrated sound level meter.

4.4.5.1 Behavioural AP test battery

Before the AP assessment, participant's peripheral hearing was examined using a portable puretone audiometer (Siemens) and a TDH-39 headphone. Following that, participant was assessed using the AP test battery that included DDT, FPT, DPT, SCAN-C FW and AFG (refer to section 2.4.1 for further details of each test). Part of the iMAP test battery, i.e. backward masking, frequency discrimination and VCV words in ICRA noise, was used to supplement the other behavioural AP tests. All the AP tests were administered using a calibrated *TOSHIBA* laptop with *Sennheiser HD215* circumaural headphones.

The DDT, FPT and DPT performance scores are presented as percentage correct responses, while the two SCAN-C subtests are presented as standard scores as per normative data (Keith, 2000). On the basis of this behavioural AP test battery, using the ASHA (2005) diagnostic criteria as a guide, a child who failed (or scored more than 2SD below the mean of US norms) in two or more of the tests binaurally with at least one in non-speech task was considered as having APD.

4.4.5.2 Language Assessment

The *Clinical Evaluation of Language Fundamentals – Fourth UK Edition* (CELF-4 ^{UK}) is a UK norm-referenced standardised language assessment tool for the identification, diagnosis, and follow-up evaluation of language and communication disorders in students aged 5-16 years (Semel, Wiig & Secord, 2006). The CELF-4 ^{UK} consists of 16 subtests that constitute to 4 levels of assessment process.

- Level 1 – identifying the problem and determining eligibility
- Level 2 – describing the nature of the disorder
- Level 3 – evaluating underlying clinical behaviours
- Level 4 – evaluating language in context

For the purpose of this study, the CELF-4 ^{UK} was administered to identify whether or not there was a language disorder (Level 1) in the participants. Thus, participants were only evaluated for their core language skills, which were assessed with four of the subtests according to the individual’s chronological age as shown in Table 4.1. The sum of the subtest scaled scores was converted to a standard score. A child would be considered as having language disorder if the standard score fell below 85 (or below 16 percentile).

Table 4.1: Subtests for the CELF-4 ^{UK} Core Language test

Subtests	Objectives	Age group
Concepts and Following Directions	To evaluate the child's ability to (a) interpret spoken directions of increasing length and complexity, containing concepts that require logical operations; (b) remember the names, characteristics, and order of mention objects; (c) identify from among several choices the pictured objects that were mentioned.	5-8 years old and 9-12 years old
Word Structure	To evaluate the child's ability to (a) apply word structure rules to mark inflections, derivations, and comparison; and (b) select and use appropriate pronouns to refer to people, objects, and possessive relationships.	5-8 years old
Recalling Sentences	To evaluate the child's ability to (a) listen to spoken sentences of increasing length and complexity, and (b) repeat the sentences without changing word meanings, inflections, derivations or comparisons, or sentence structure	5-8 years old and 9-12 years old
Formulated Sentences	To evaluate the child's ability to formulate complete, semantically and grammatically correct spoken sentences of increasing length and complexity, using given words and contextual constraints imposed by illustrations.	5-8 years old and 9-12 years old
Word Classes 2 (Receptive, Expressive, and Total)	To evaluate the child's ability to understand and explain logical relationships in the meanings of associated words.	9-12 years old

Copied from the CELF-4 UK manual (Semel, Wiig, and Secord, 2006)

4.4.5.3 Phonological skills assessment

The *Phonological Assessment Battery* (PhAB; Frederickson, Frith & Reason, 1997) is a tool used for assessing the ability to process sounds in spoken words (phonological processing). The PhAB comprises of a few subcategories that measure different areas of phonology as summarised in Table 4.2. Participants in this study were assessed for phonological awareness only, because the subtests in this category are most related to reading and spelling ability. The raw score of each subtest was converted to a standardised score, in which a score falling below 80 is indicative of an abnormality.

Table 4.2 Subcategories of the PhAB test

Areas	PhAB Tests	Description of tests
Phonological awareness Perception and manipulation of sounds in words and ability to decode non words.	**a) Alliteration Test**	To assess a child's ability to isolate the initial sounds in single syllable words.
	b) Rhyme Test	To assess a child's ability to identify the rhyme in single syllable words.
	c) Spoonerisms Test	To assess whether a child can segment single syllable words and synthesise the segments to provide new words.
	d) Non-word Reading test	To assess the decoding of letter strings.
Phonological production speed Fast and automatic retrieval of phonological coding at the whole word level.	**Naming speed test (Pictures & Digits)**	To assess speed of phonological production, involving retrieval of phonological coding at the whole word level.
Phonological fluency Retrieval from memory of phonological codes based on alliteration and rhyme	**Fluency Test (Alliteration & Rhyme)**	To assess retrieval of phonological information from long-term memory; the child is asked to say as many words of a particular type as he/she can in 30 seconds.

Copied from PhAB manual (Frederickson, Frith & Reason, 1997)

4.4.5.4 Brain Imaging - Magnetic Resonance Imaging (MRI)

All participants had a high-resolution brain MRI performed on a 1.5 T MR imaging system (Magnetom Vision; Siemens, Ehrlangen, Germany). The acquisition techniques included T1- weighted 3 dimensional fast low-angles shot images for volumetric and morphometric analyses. All scans were reviewed by an experienced paediatric neuro-radiologist consultant in order to identify gross structural abnormalities of the brain.

4.4.6 Outcome measures

The AP test battery (as mentioned in section 4.4.5.1) and two validated questionnaires were used as outcome measures, both administered at the end of phase 1 and end of phase 2. The AP tests served as the clinical measure while the questionnaires provided information about the functional listening skills of the participants.

The two questionnaires used in this pilot study were:

a) CELF-4 Pragmatic Profile (PP) – this questionnaire was completed by the participant’s parents. The PP is used for identification of verbal and nonverbal pragmatic deficits that may negatively influence social and academic communication of a child. It consists of 52 items and each item is scored by rating, i.e., 1 = never, 2 = sometimes, 3 = often, 4 = always, based on the frequency of occurrence of each skill. A total raw score was calculated and compared against the age-specific criterion score, in which a raw score higher than the criterion score would be labelled as ‘meet’ while a score lower than the criterion score would be labelled as ‘do not meet/DNM’. A copy of the PP questionnaire is attached in Appendix C.

b) Children's Auditory Performance Scale - CHAPS (Smoski, Brunt, Tannahill 1998) – this questionnaire was given to each participant's teacher to rate the child's listening behaviour as compared to his/her classmates at school. This standardised questionnaire consists of 36 questions categorised under 6 conditions: noise, quiet, ideal, multiple inputs, auditory memory sequencing, and auditory attention span A child's listening behaviour is rated on a 7-point scale ranging from 1 (less difficulty than peers) to -5 (cannot function at all). A subscore was obtained for each auditory condition and a total score was calculated as a whole. A score value ranging from +1 to -1 was considered within normal range, while -1.5 to -5.0 was considered below normal range (at risk). A copy of the CHAPS can be found in Appendix D.

4.4.7 Integrative intervention approach

The participants started their intervention after the completion of 3-months no-training phase (phase 1). The types of intervention included a home-based computerised AT programme and a school-based FM system usage, which both lasted for 3 months.

4.4.7.1 Home-based auditory training

All participants were given two different CBAT programmes as summarised in Table 4.3. One was the 'Phonomena', a commercially available programme developed by the *MindWeavers*. The other programme was a non-commercial speech-in-noise training that was developed for the main study (Chapter 6) by the team from the Speech, Hearing, and Phonetic Sciences, UCL. The speech-in-noise training has 3 different listening games: DOGGY, Who-Is-Right, and Story-In-Noise. The detailed description of each of these games is provided in section 6.3.6 (Chapter 6).

The participants were advised to do the listening exercise 3 times per week, each session lasting 30 minutes, for 12 weeks. Prior to the start of the AT, the administration procedures of the tasks were explained and demonstrated to the parents and participant. A manual and a timetable were also given to parents as reference. A small token (sticker book) was given to each participant upon the completion of the training.

4.4.7.2 School-based FM system usage

Each participant was fitted with an assistive listening device (FM system “Edulink”), which was on loan for 3 months supported by the manufacturer (Phonak). “Edulink” is a miniature wireless communication system that consists of a transmitter and a tiny receiver, which are worn by the teacher and the child respectively. The transmitter picks up the teacher’s voice and sends it directly to the receiver via radio waves. This helps to improve the signal-to-noise ratio of teacher’s voice. The participants were advised to wear the device on a daily basis.

Table 4.3: A brief description of the CBAT programmes used in the pilot study

Type of training programme	Description	Duration of practice
Phonomena	This programme targets on phoneme discrimination training and it consists of a training section and a reward section. On each trial of the training section (the *Sound Game*), a tutor (a dinosaur character, 'Rex-T') first 'mimed' a syllable and followed by two cavemen characters ('Mic' and 'Mac') who separately mimed a syllable. The listener is required to click on one of the cavemen characters who mimed the identical syllable as 'Rex-T'. The following trials are presented in an adaptive staircase procedure to vary the level of difficulty. A total of 60 trials are presented in the training section. (from Moore, Rosenberg, Coleman, 2005)	20 minutes per session; 3 sessions per week
Speech-In-Noise 'Who Is Right'	This game targets the discrimination of fine phonetic detail in the presence of background noise. All target words were consonant-vowel-consonant (CVC) monosyllables, displayed in pictorial form and paired with audio input of the target words. The answer options were represented by 3 bears. The listener was required to click on the bear that produced the correct target word in noise while the other two were non-word foils in noise. The level of difficulty was adjusted in an adaptive staircase procedure.	10 minutes per session; once a week
'Doggy'	This game targets improvements in speech understanding in various types of background noises. The sentence stimuli were made up of a combination of numbers (1 to 9 except 7) and colours (green, red, white, black, blue, and yellow), presented in background noise. The listener was required to click on the box that represented the correct combination of number and colour. The level of difficulty is adjusted in an adaptive staircase procedure.	10 minutes per session; once a week

Table 4.3 (continued): A brief description of the CBAT programmes used in the pilot study

Type of training programme	Description	Duration of practice
'Story-in-noise'	This is a keywords extraction training programme, in which short phrases from a connected narrative taken from 2 stories were presented in various types of background noises. The listener was required to select keyword(s) that were present in the target phrase from a set of response buttons, which each of them has a word on it.	10 minutes per session; once a week

4.5 Participants

Three females and one male with confirmed PAX6 gene mutations participated in this pilot study. Table 4.4 summarises the demographic details of these participants and their brain MRI findings. All the participants had British English as their first language and were studying in mainstream educational settings. One of the participants (EB) required additional visual assistance in the classroom due to the severity of his aniridia condition, whereas others were fitted with spectacles only. None of them had any developmental conditions, i.e. epilepsy, global developmental delay, pervasive learning disorder such as autism that might additionally impact on auditory or cognitive performance.

Table 4.4 Summary of demographic details, the type mutation and brain MRI findings of participants

Subject (Age)	Gender	Handedness	Type of mutation	Brain imaging (MRI)
LL (9;0)	F	Right	SPL Exon11	No abnormality
MF (10;2)	F	Right	Haploinsufficiency R240X	Very small, almost absent of AC
ABR (11;6)	F	Right	Haploinsufficiency	Small AC, small splenium of CC
EB (7;0)	M	Left	M1 fs anti-initiation	Small right Heschl's gyrus

F = female; M = male; AC = anterior commissure; CC = corpus callosum

All the participants had normal peripheral hearing level in both ears (thresholds below 20 dBHL across the frequencies 250Hz-4000Hz). All but one participant fulfilled the clinical criteria of APD diagnosis (Table 4.5), and thus only three participants were given the intervention. Two of the participants (LL and ABR) were diagnosed with language disorder, and one of them had additional deficit in phonological skill (Table 4.6).

Table 4.5: A summary of the baseline AP performances for the four participants with PAX6 gene mutation

Subject	Auditory Processing Test								
	DDT	FPT	DPT	FW	AFG	BM (0ms)	BM (50ms)	FD	VCV in ICRA
LL	N	Abn (R&L)	Abn (R&L)	N	N	N	N	N	N
MF	Abn (R)	Abn (R&L)	Abn (R&L)	N	N	N	N	N	N
ABR	Abn (L)	Abn (R&L)	Abn (R&L)	N	N	N	N	N	N
EB	N	Abn (L)	N	N	N	-	-	N	N

AFG = Auditory Figure Ground (SCAN-C); BM = Backward masking (iMAP); DDT = Dichotic digits test; DPT = Duration pattern test; FD = Frequency discrimination (iMAP); FPT = Frequency pattern test; FW = Filtered Words (SCAN-C); VCV in ICRA = Vowel-consonant-vowel in ICRA noise (iMAP); N = Normal; Abn = Abnormal; R = Right ear; L = Left ear.

Note. The diagnosis of APD is based on two abnormalities in the AP tests.

Table 4.6: A summary of the baseline language and phonological assessment scores for the four participants with PAX6 gene mutation

Subject	[1]CELF-4	[2]PhAB		
	Core language	Alliteration	Rhyme	Spoonerism
LL	78	94	69	109
MF	91	90	101	99
ABR	76	84	86	106
EB	88	104	104	125

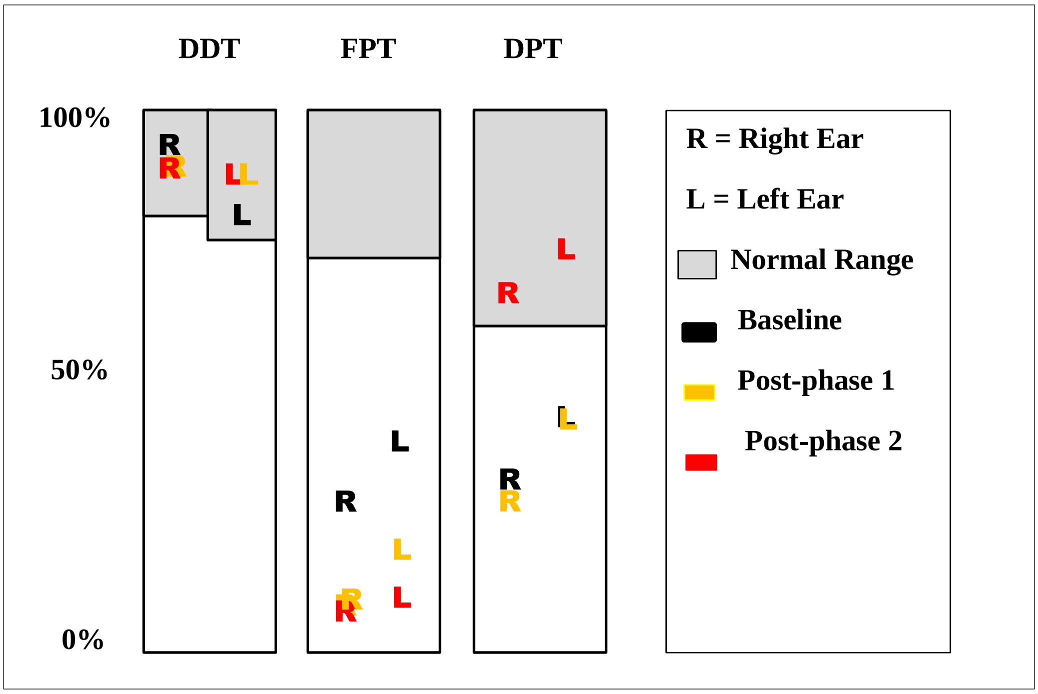
[1] Score falling below 85 is considered as having language disorder

[2] Score falling below 80 is indicative of abnormality

4.6 Results

The graphs below show the AP tests results of each participant at baseline, post-3-month (the end of phase 1) and post-intervention (the end of phase 2). Since all the participants scored within the normal range in the SCAN-C subtests (FW and AFG) and iMAP tests (backward masking, frequency discrimination and VCV in ICRA noise), these results were not displayed in the graphs below.

Participant 1: LL (Age: 9;0)

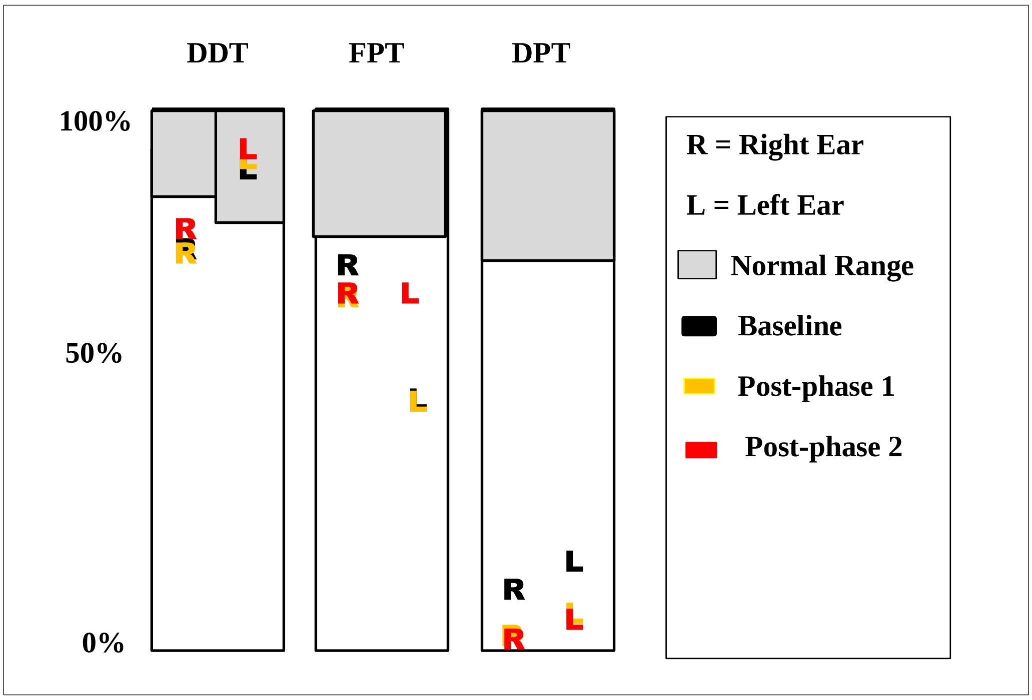


Time Point	Dichotic Digits Test (DDT, %)		Frequency Pattern Test (FPT, %)		Duration Pattern Test (DPT, %)	
Baseline	R – 98	L – 80	R – 33	L – 40	R – 37	L – 47
Post-3-month	R – 93	L – 90	R – 13	L – 27	R – 34	L – 44
Post-intervention	R – 93	L – 90	R – 13	L – 13	R – 63	L – 77

Teacher's report (CHAPS): At baseline, LL was rated within the normal range in all the auditory conditions except the auditory attention, which subsequently falling within the normal range at post-intervention.

Parental report (PP): The total score of PP could not be calculated for LL, as more than 4 questions were rated as 'not observed' at baseline and post-intervention.

Participant 2: MF (Age: 10;2)

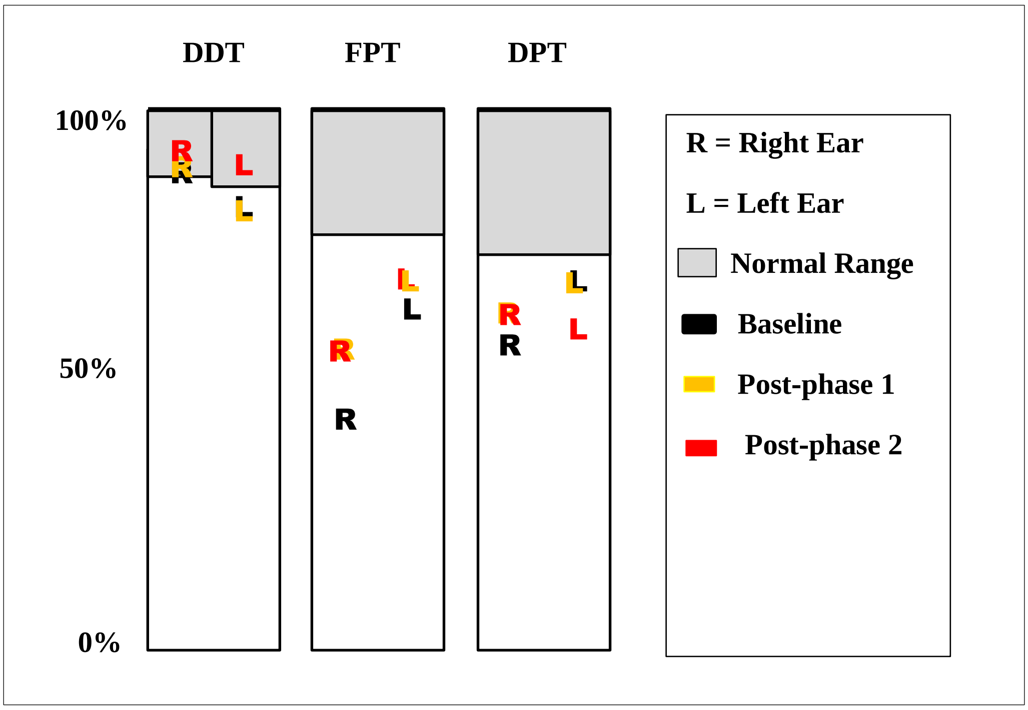


Time Point	Dichotic Digits Test (DDT, %)		Frequency Pattern Test (FPT, %)		Duration Pattern Test (DPT, %)	
Baseline	R – 75	L – 90	R – 73	L – 47	R – 20	L – 23
Post-3-month	R – 75	L – 93	R – 67	L – 47	R – 10	L – 13
Post-intervention	R – 78	L – 95	R – 67	L – 67	R – 10	L – 13

Teacher’s report (CHAPS): MF was rated within the average in all the auditory conditions at baseline and post-intervention.

Parental report (PP): The total score of PP could not be calculated for MF, as more than 4 questions were rated as ‘not observed’ at baseline and post-intervention.

Participant 3: ABR (Age: 11;6)



Time Point	Dichotic Digits Test (DDT, %)		Frequency Pattern Test (FPT, %)		Duration Pattern Test (DPT, %)	
Baseline	R – 93	L – 85	R – 40	L – 60	R – 53	L – 67
Post-3-month	R – 93	L – 85	R – 53	L – 67	R – 63	L – 67
Post-intervention	R – 95	L – 93	R – 53	L – 67	R – 63	L – 57

Teacher's report (CHAPS): ABR was rated normal in all the auditory conditions, except the auditory memory sequencing, which the teacher found insufficient evidence to compare her performance to peers in her class.

Parental report (PP): The baseline and post-intervention PP score was 113 and 124 respectively, which did not meet the criterion score for her age.

4.7 Discussion

There is a paucity of studies reporting on central auditory function of individuals with PAX6 gene mutation. In the following paragraphs, we will discuss the characteristics, i.e. AP, language and phonological skills of 4 children with PAX6 gene mutation and the intervention outcomes for 3 of these children.

a) *Characteristics of children with APD associated with PAX6 gene mutation*

In the current study, all the children with PAX6 gene mutation except EB, showed an abnormal result in at least one of the tests that require interhemispheric transfer (DDT, FPT and DPT). The bilateral ear deficits on the auditory patterning tests, i.e. FPT and DPT, in LL, MF and ABR at baseline are consistent with the findings reported in the studies by Bamiou and team (2004 & 2007a). It is noteworthy that two of these children (MF and ABR) who failed auditory patterning tests had structural abnormality around the CC and AC, indicating the importance of the interhemispheric commissures in transferring information, i.e. sequence of tones heard from the right hemisphere to the left hemisphere for labelling process (see section 1.2.6.1 for more explanation about the role of CC).

In addition, both MF and ABR showed unilateral deficit in the dichotic listening task while LL, who had normal structure of the CC and AC, passed the DDT in both ears. The abnormal asymmetric findings reported in this study are consistent with the findings reported by Bamiou and colleagues (2007a) except subtle differences. In that study, all the children (n = 7) were reported to have a left ear deficit in the DDT while in the current study, a mixed finding was observed. MF had a right ear deficit whereas ABR had a left ear deficit despite both of them were right-handed. Cases with right-handed are generally reported with reduced left ear score in dichotic task based on the notion of (1) left hemisphere dominance in speech perception, and (2) the supremacy of the contralateral auditory pathways in signal transmission when the two ears are in competition. Thus, dichotic speech stimuli presented to the left ear, which are directed to the right hemisphere, will be transferred to the left hemisphere for processing via the interhemispheric transfer (Zaidel, 1986). Therefore, abnormality in the interhemispheric transfer will result in impaired left ear performance on dichotic task. In this study, however, it is unclear why MF’s dichotic test finding did not follow the general pattern.

As expected, all the children in this study had normal performance on monaural low redundancy speech tests (FW and AFG) that do not involve any interhemispheric transfer function. Similar results have been reported in both adults and children with PAX6 gene mutation (Bamiou et al., 2004 & 2007a). In terms of language ability, two of the children (LL and ABR) performed below age-appropriate norms in recalling sentences and formulated sentences tasks, resulting in core language scores falling below the normal range. To the best of our knowledge, there is only one case study reporting on the speech and language skills of a child with PAX6 gene mutation (Bamiou et al., 2007c). In that study, the 12-year-old child was reported to have normal language ability but impaired verbal working memory. Since the number of subjects in this study is too small for any significant comparison and generalisation, it is unclear whether language disorder in the two cases reported in this current study was associated with the mutation. The phonological skills of the children in this study were generally normal except ABR who had slight difficulty in the alliteration task.

b) Intervention outcomes

Even though this pilot study was unable to provide statistical evidence about the outcomes of intervention due to the small sample size, broadly, some improvements were seen in the subjects after the intervention.

At pre-intervention, LL's performance on the FPT deteriorated bilaterally after 3 months (approximately 20% reduction in scores) but the changes in DPT scores were unremarkable. While MF's auditory patterning skills also showed a sign of deterioration (about 10% reduction in the DPT scores), ABR seemed to improve on the FPT (13% and 7% gained in scores for the right and left ear respectively). The dichotic listening scores for MF and ABR remained the same throughout 3-month of no intervention and they continued to have a unilateral deficit. Overall, the AP performance of these children did not appear to improve without intervention.

At post-intervention, LL made substantial improvement in the DPT bilaterally to the normal range, with approximately 30% gained in the score. However, she continued to have difficulty in the FPT. Her performance on the DDT remained normal. MF, on the other hand, continued to have difficulties in the right ear DDT and bilateral deficits in the auditory patterning tests, even though some improvement was observed in the left ear FPT (20% gained in the score). As for ABR, the FPT and DPT scores remained unchanged and in the abnormal range but the left ear dichotic score improved marginally to the normal range (8% gained in the score). Overall, these children seemed to have made some improvement after the intervention although individual differences were observed. Various reasons could account for the variation in performance, such as different levels of motivation to engage with the auditory training, or the effect of the different types of PAX6 gene mutation and/or different structural abnormalities of the brain on training outcomes.

Subjectively, based on the CHAPS questionnaire rated by the teachers, the children in this current study did not seem to perform more poorly than their peers in most of the auditory conditions, including noisy background. The parental reports were inconclusive as only one parent completed the PP questionnaire. As a result, we were unable to draw any conclusions on the benefit of intervention on these children's functional listening skills. Nonetheless, the parents' feedbacks were positive and the children had no difficulties following the instructions for the CBAT programme at home.

Of note, the report of no significant listening difficulties in noise in all the three children in this current study is in contrast to the study by Bamiou and colleagues (2007a), in which the authors reported significant lower scores for speech understanding in noise in the PAX6 mutation group as compared to the normal control. Two factors could possibly contribute to the observed behavioural differences between the two studies - the type of questionnaire used and the person who rated the questionnaire. The CHAPS questionnaire, which was used in the current study, was rated on the basis of the child's listening skills in comparison to his/her peers, while the structured questionnaire used in the study by Bamiou and colleagues (2007a), was rated based on the frequency of occurrence of the observed behaviours in the child without any direct comparison to his/her peers. Instead of the teachers, the parents rated the children's listening behaviour in the study by Bamiou et al. (2007a). The parents might be more observant and accurate in rating their children's listening behaviour than the teachers.

4.8 Comments

This pilot study investigated the central auditory functions of 4 children with PAX6 gene mutation and the results add to the scarce literature that, many individuals with PAX6 gene mutation suffer from auditory interhemispheric transfer deficits. While there appeared some initial evidence showing that neurologically abnormal individuals with APD who are associated with PAX6 mutations improved in their AP skills after intervention, this study was unable to make any generalisation of the intervention effect because of the lack of statistical power.

Hence, in order to substantiate this preliminary finding, a few changes ought to be undertaken to improve the current study:

1. To increase the sample size
2. To include an untrained control group
3. To increase the frequency of training sessions

These principles were applied on a subsequent study, which evaluated CBAT outcome with a bigger sample size in the general population with APD in Singapore. In order to measure the true effect of any particular intervention, an untrained control group is essential and therefore it was included in the main study (Chapter 6). The frequency of the training sessions has also been revised in the main study to produce greater enhancement in the AP skills of children with APD.

Chapter 5

Study I

The Impacts of Linguistic Background and Language Competency in Auditory Processing Assessment

5.1 Introduction

APD is becoming more widely diagnosed in the US, UK, and Australia (Emanuel, 2002; Cameron & Dillon, 2005; Hind, 2006), despite the lack of universal agreement on how this listening disorder should be diagnosed (Rosen, 2005). While most studies reported on APD were done predominantly on native English speaking (monolingual) populations, little is known about the effect of different linguistic backgrounds on AP. This issue comes to the fore in considering how to diagnose APD in a multilingual population, like Singapore, where the main study of this thesis was conducted.

In the absence of a ‘gold standard’ test battery for the diagnosis of APD, clinical groups in countries with English as their official language have often adopted both speech and non-speech AP tests (see Chapter 2, section 2.4.1) that have been developed in the US with reference to native (American) English speaking populations. But there is ample evidence that language experience has an impact on the performance of speech-based tests of the kind employed in APD batteries. For example, normal hearing bilinguals/trilinguals have poorer speech perception for their second language than monolingual native English speakers under unfavourable conditions (e.g. noise or reverberation), despite their performing equally well in quiet (Crandell & Smaldino, 1996; von Hapsburg, Champlin, & Shetty, 2004; Shi, 2009; Tabri, Chacra & Pring, 2010). It has also been found that speech perception deficits in noise persist for speakers highly proficient in their second language (Tabri, Charca & Pring, 2010). Therefore, AP tests that use degraded speech (e.g. presented in background noise or after low-pass filtering) may need careful interpretation; underperformance may either reflect disordered AP, or the effect of the individual's linguistic background.

As reviewed in Chapter 2 (section 2.2.4), APD is often reported to occur in concomitant with other language-related disorders such as LI and SRD. There has been concern that children with these language-related disorders may be more likely to underperform in speech-based tasks, and thus the inclusion of speech-based AP tests may add to the difficulties in making differential diagnosis. The validity of making an APD diagnosis based on these tests is therefore questionable, although this has been hitherto little investigated.

In this chapter, we will discuss a retrospective study that examined the extent to which different linguistic backgrounds and language competency affect performance in AP tasks that are commonly used for clinical diagnostic purposes. This study was conducted in order to inform the suitability of the types of AP tests used in the main study (Chapter 6) for diagnosing APD in children of a multilingual background. In the following section, a brief description about the cultural and linguistic background of Singapore is provided to allow readers for a better understanding of this diverse community.

5.2 Multilingualism in Singapore

Singapore is a multi-ethnic country with a total population of 5 million people, of which 75% of the people are Singapore citizens and permanent residents, while the other 25% are foreigners (Statistics Singapore, 2010). In this multicultural country with four established official languages (Mandarin, Malay, Tamil and English), English has become the language of administration and the language of academic instruction in all schools and universities (Tan, 2010). Singaporean children are typically exposed to two languages or more, including dialects, from early childhood. By the age of four when children attend preschool or kindergarten, they have been exposed to a relatively heterogeneous language environment. The proportion of exposure to each language, however, varies from child to child, depending on the languages spoken at home (Tan, 2010). At school, children from different ethnic groups (Chinese, Malay, and Indian) attend their respective mother tongue lesson as one of the academic subjects.

Professionals involved in the assessment of language-based learning disorders in a polyglot nation such of Singapore are faced with major challenges in clinical decision making regarding the presence/absence of a disorder. A major drawback is the absence of appropriately normed assessments of language function for the Singaporean population. As it is time-consuming and resource intensive to develop tests that target the mix of linguistic and cultural norms, practising professionals have currently no other option but to adopt the monolingually standardised testing material for the use on children in Singapore. For instance, the CELF (Semel, Wiig & Secord, 2006) is commonly administered by speech-language therapists for language assessment on children in Singapore, because English is the language of academic instruction in all schools.

5.3 Objectives and Hypotheses

The main objective of this study was to examine the impact of linguistic background on the performance observed in speech and non-speech AP tests that are commonly used for clinical diagnostic purposes. Here, we studied a large group of children who presented with listening complaints in Singapore. Most of these were multilingual from a diverse community, while the rest were monolingual children whose native language was English. We compared the performance of the two groups on a variety of AP tests, in addition to examining the extent to which other language-related disorders were present, and whether they had an impact on performance in AP tests. We hypothesised that performance in AP tests that have less linguistic demands would be the same for all children, without regards to their linguistic background or language competency.

5.4 Methodology

5.4.1 Procedure

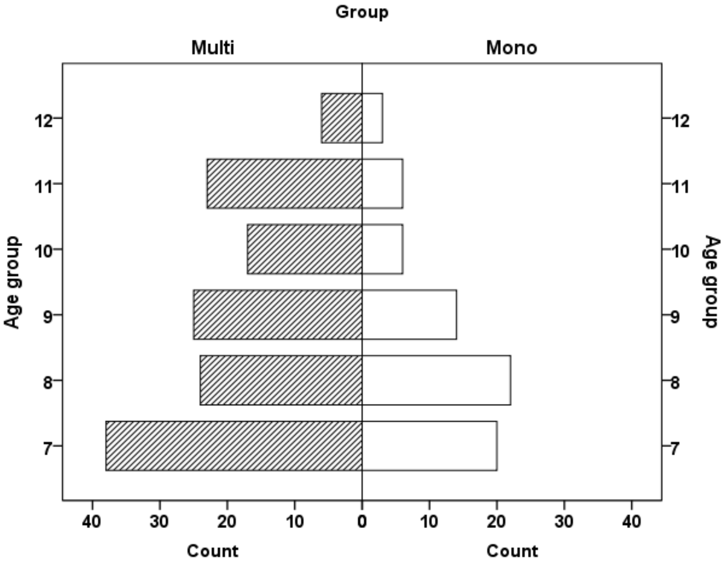
Records of children with listening concerns, who had an AP assessment at the Centre for Hearing Intervention and Language Development (CHILD), National University Hospital Singapore between January 2008 and December 2009, were retrieved and analysed retrospectively from a large clinical database. This database contained information on demographic details, co-morbid learning disabilities, and raw scores from the audiological test results.

5.4.2 Participants

Data from 234 children aged between 7 and 12 years old were extracted. All children accepted for AP assessment fulfilled the requirement of normal intelligence (Non-Verbal IQ score ≥ 85) and the absence of a diagnosis of Autistic Spectrum Disorder (ASD) as confirmed by a paediatrician. Data of children with a confirmed diagnosis of ADHD were also excluded, as it was unclear whether the AP test results would be affected by this condition, particularly since there was no information about the child's medication status recorded in the database. Of the 234 children, thirty of them did not have a complete formal language and educational psychology assessment at the point of AP assessment, thus their data were excluded and leaving 204 children for this study.

The bar charts in Figure 5.1 show the distribution of children from the multilingual (n = 133) and monolingual (n=71) groups. The average age for children in the multilingual and monolingual groups was 9.32 years (SD = 1.68) and 8.90 years (SD = 1.45) respectively, with no statistical difference found between the two groups (*p* = .134).

Figure 5.1: Number of children in the multilingual (n=133) and monolingual (n=71) groups aged between 7 to 12 years old



The multilingual group was made up of Singaporean children who were attending mainstream government schools, coming from different ethnic groups across a range of socioeconomic backgrounds. All these multilingual children were English speakers as English is the official language of instruction in all schools, but their home language(s) could be English, another language (typically Mandarin, Malay, or Tamil) or a mixture of dialects. The monolingual group, on the other hand, consisted of non-local children with English as their first language, attending international schools in Singapore (e.g. Singapore American School, Canadian International School, Australian International School, Tanglin Trust British International School). These monolingual children generally came from families who had relocated to Singapore for employment and thus tended to have higher socioeconomic backgrounds than the multilingual children. Most of them had lived in Singapore for less than 5 years with only a minority born there.

The referrals of the multilingual (local) children to the audiology clinic for AP assessment were primarily made by the multidisciplinary teams who assessed and managed children with suspected developmental disorders, either from community clinics or within the hospital. These multidisciplinary teams consisted of a paediatrician, speech-language therapist, educational psychologist and occupational therapist. Some of these children were also referred by private psychologists or speech-language therapists. For the monolingual (non-local) children, the referrals were mainly initiated by the learning support teachers from the schools they were attending. Most of the international schools in Singapore have a team of private educational psychologists and speech-language therapists who work with children with special educational needs. In both groups of children, very few cases were directly referred by the parents. Despite having a different referral route for the multilingual and monolingual children, the common referral reason was to elucidate the child’s AP skills as there was academic concern or parental feedback of listening difficulties.

5.4.3 Assessment

All children assessed for APD would have to have normal peripheral hearing sensitivity confirmed with: (1) pure tone thresholds of 20 dB HL or better at octave frequencies from 250Hz to 8kHz, (2) normal middle ear function with Type-A tympanograms (Jerger, 1970), (3) an ipsilateral acoustic reflex present at 1kHz with a threshold less than 100 dB HL, and (4) speech discrimination scores in quiet (NU6 word list) of 80% or better in both ears presented at 50 dB HL.

5.4.3.1 Auditory processing (AP) assessment

The AP skills of children were assessed using a test battery that consisted of six of the auditory measures recommended by ASHA (2005) (see Table 5.1). Three of the tests used were non-speech sounds (FPT, RGDT, and MLD) whereas the other three were speech-based (DDT, CS, and LPFW). The detailed description of each test is provided in Chapter 2 (section 2.4.1).

Due to the diversity of the studied population and the unavailability of local norms, the US-reference norms were used in this study. An unpublished preliminary study conducted at CHILD in 2006 showed that the mean scores of the non-speech AP tests collected from 80 local typically-developing children did not differ significantly from the US norms for 8 to 12 year-olds.

Table 5.1: The auditory processing (AP) tests used in the current study

AP tests & Technical Information	Presentation level & number of stimuli	Task	Scoring
Frequency Pattern Test (FPT) Child version Low: 880 Hz; High: 1430 Hz; Tone duration: 500 ms; Inter-tone interval: 300 ms; Inter-pattern interval:10 sec	50 dB HL monaurally, 30 stimuli per ear	Label the tone pattern verbally as high or low in a sequence of 3 tones (e.g. high-low-low)	% correct per ear
Random Gap Detection Test (RGDT) Stimuli: 0.5, 1, 2, & 4k Hz; Gap durations: 0, 2, 5, 10, 15, 20, 25, 30, and 40 ms. in random order.	50 dB HL binaurally, 4 sets of stimuli at different frequencies	Respond verbally to indicate whether 1 or 2 sounds were heard	Average of gap detection thresholds for 4 stimuli (ms)
Masking Level Differences (500 Hz) – MLD 5 tone bursts (500 Hz; 300 ms) in 3sec bursts of narrow band noise 10 SoNo trials (1- to -17dB S/N); 12 SπNo conditions (-7 to -29dB S/N), and 11 no tone conditions.	50 dB HL, binaurally 33 presentation	Respond verbally whether tone pulses were heard or not within the buzzing noise.	SπNo threshold minus SoNo threshold
Dichotic Digits Test (DDT) Male voice; 25 pairs of double digits (1 to 9 except 7)	50 dB HL, binaurally	Repeat verbally all 4 numbers	% correct per ear
Competing Sentences (CS) Male voice; 20 pairs sentences	35 dB HL (target ear); 50 dBHL (opposite ear)	Repeat verbally sentences heard in the target ear	% correct per ear
Low Pass Filtered Words (LPFW) Male voice; low pass filtered at 750 Hz, a list of 50 single words (NU-6)	50 dB HL monaurally 25 words per ear	Repeat the word heard verbally	% correct per ear

Note. All the test materials are of Auditec version.

5.4.3.2 Language and literacy assessment

As part of the protocol, all children referred for AP assessment at the CHILD are required to have a language and educational psychology assessment prior to attending the appointment. As all these children were assessed by different speech-language therapists and educational psychologists, the assessment tools used varied from one professional to another. For instance, different version of language measure such as the CELF-3 UK, CELF-4 UK had been used by speech-language therapists while several literacy tools had been administered by different educational psychologists. The more common literacy assessments used were the Singapore *Wechsler Objective Reading and Language Dimension* (WORLD; Rust, 2000), the *Phonological Awareness Battery* (PhAB; Frederickson, Frith & Reason, 1997), and the *British Ability Scale Second Edition* (BSA-II; Elliot, Smith, & McCulloch, 2008) The language and reading scores of the children were not recorded in the database, only an indication of whether they had a diagnosis of LI or SRD or not.

The diagnosis of a language or reading impairment in Singaporean children (multilinguals) was done in accordance with guidelines published that take into account the different expectations of language development for children acquiring English as an additional language (Brebner, McCormak, & Rickard-Liow, 2004), or on the basis of personal clinical experiences (Lew & Cannon, 2010). The diagnosis of LI and SRD was otherwise based on general guidelines. LI was diagnosed when a child showed significant language difficulty (receptive or expressive) despite having normal hearing sensitivity and nonverbal intelligence, with no other physical or emotional difficulties (Bishop, 1992). SRD was diagnosed when there was a deficit in reading fluency and spelling in the presence of adequate hearing and general intelligence (Castles & Coltheart, 1993).

5.5 Statistical Analysis

Data were analysed using the Statistical Package for the Social Science SPSS 19.0. Descriptive analysis was conducted to examine the distributions of all quantitative data. The data were mostly non-normally distributed, thus the following non-parametric tests were used:

1. Mann Whitney test was used to compare the performance scores between the multilingual and monolingual groups in each of the 6 AP tests.
2. Pearson's Chi Square test was used to examine the association between the AP test performance (passed/failed) and linguistic background (multilingual/monolingual).
3. Kruskal-Wallis test was conducted to test for any differences in the AP performance scores among children with LI, SRD, LI&SRD, and no other language-related disorders. This was followed by post-hoc Mann-Whitney tests on the three different groups: (1) LI versus no other language-related disorders, (2) SRD versus no other language-related disorders, (3) LI&SRD versus no other language-related disorders.

5.6 Results

5.6.1 The AP Performances of the Multilingual and Monolingual Children

To study the impact of different linguistic backgrounds on performance in AP test, we first examined the distributions of the raw performance scores of children in the multilingual and monolingual groups in each of the 6 AP tests, with age appropriate US norm represented by the dashed line (Figure 5.2). Of note, the performance scores for the RGDT and MLD tests represent the binaural ear results, while the FPT and LPFW tests are the average combined scores from the left and right ears (as the performance scores in both ears were highly correlated for the 2 AP tests). For the DDT and CS tests, ear specific performance scores are displayed.

A visual inspection of the data indicates great variation in performance on most of the AP tests within each age group. In brief, the overall conclusions that can be drawn from the boxplots are:

1) Most, but not all, children from both groups performed within the normal range (with reference to the US norms) in the non-speech tests and DDT, but many of them had their performance scores falling within the abnormal range in the CS and LPFW tests.
2) The multilingual group, particularly those younger age children, appeared to perform more poorly than their monolingual counterparts in the CS and LPFW tests. Otherwise, the two groups' performances were quite comparable at all ages in other AP tests.

The results from separate Mann Whitney tests further showed that the two groups did not differ significantly in their performances on the non-speech tests, as well as DDT at all ages, but they did differ significantly in the CS [for children aged 7 (p = .016) in both ears, and 8 years old (p = .03) in the right ear] and LPFW tests [for children aged 7 (p < .001), 8 (p = .018), and 10 years old (p = .014)].

Figure 5.2: The performance scores of the multilingual (n = 133) and monolingual (n = 71) children in the 6 AP tests, with age appropriate US norms represented by the dashed line

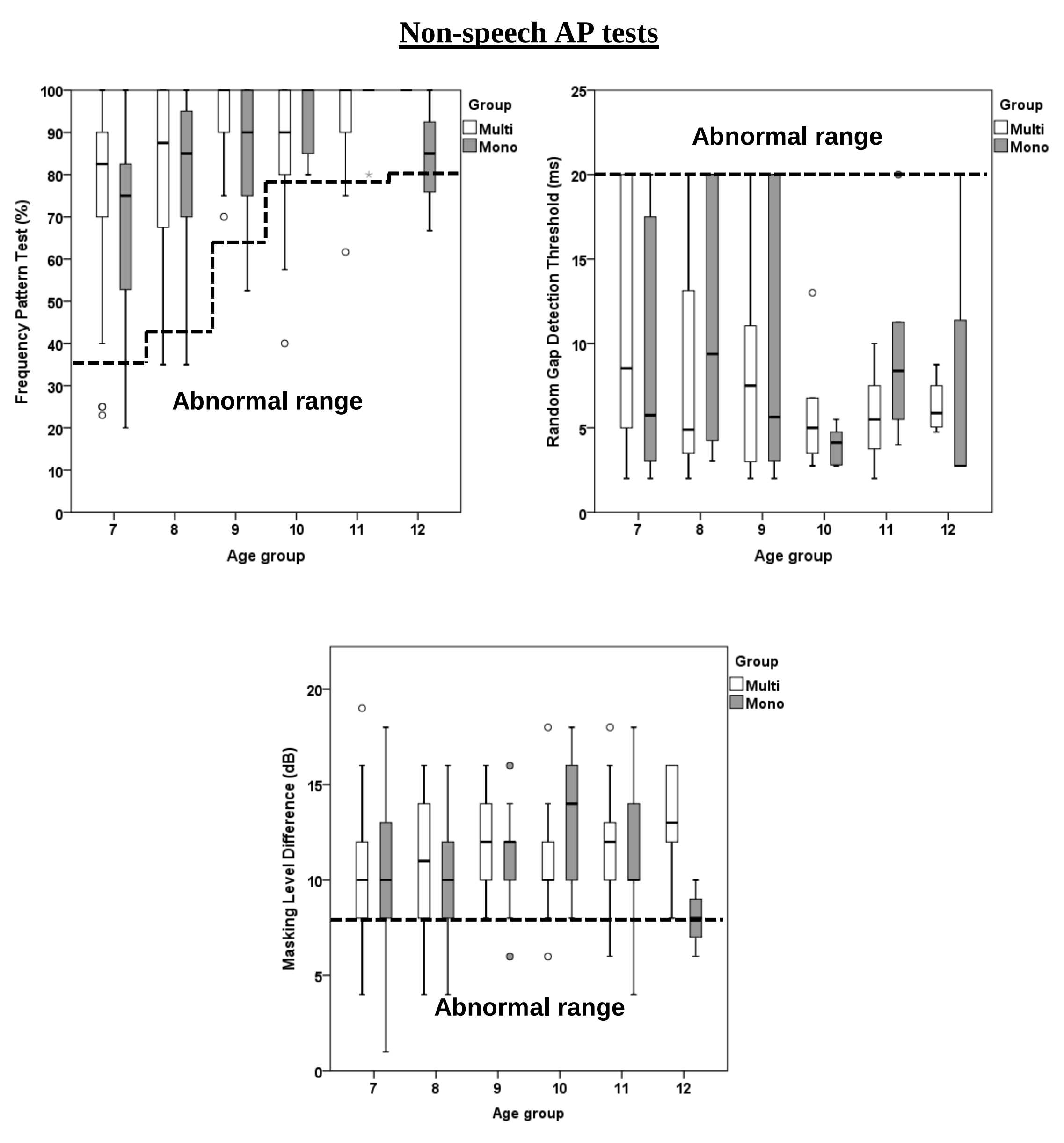
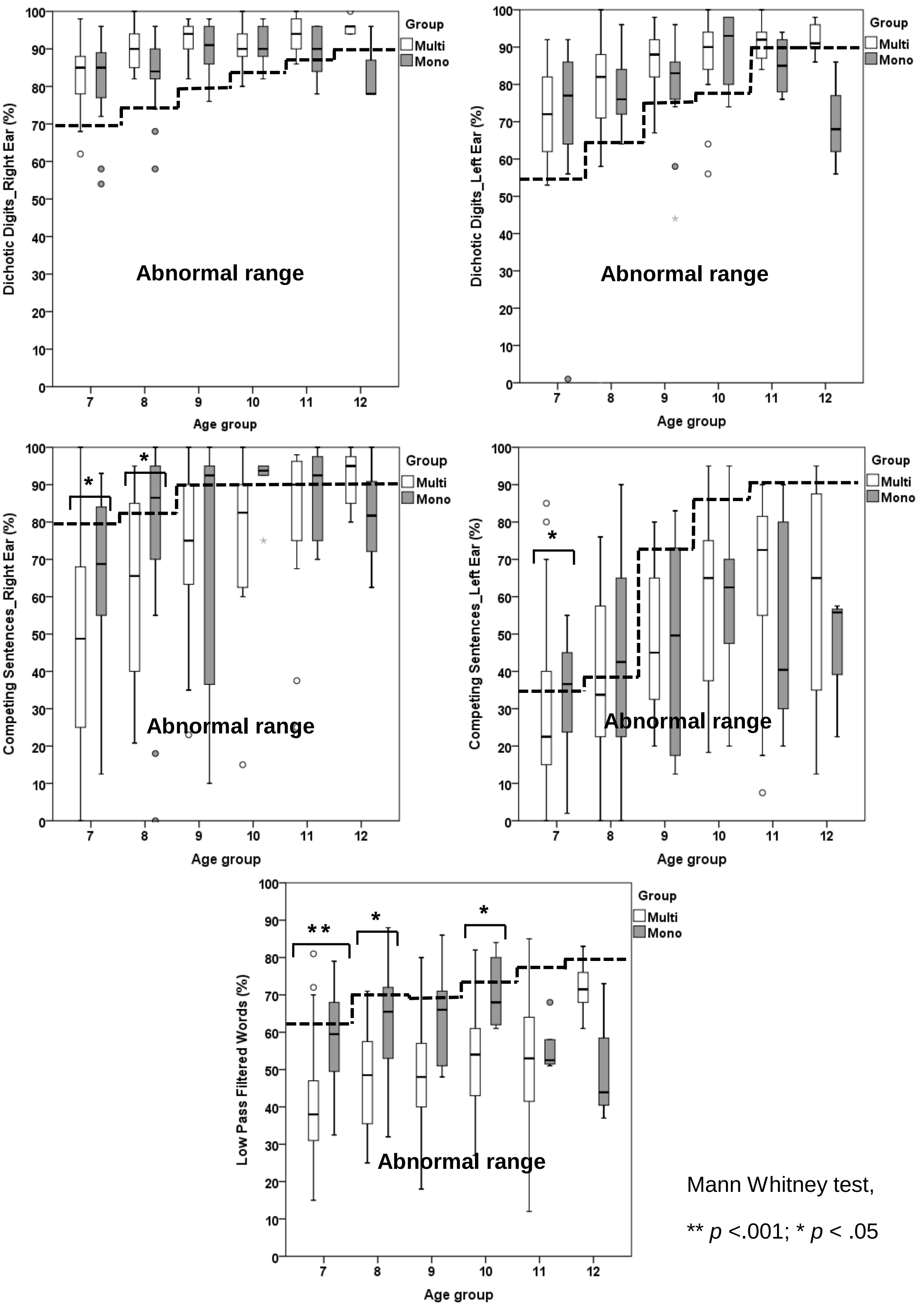

Non-speech AP tests

Figure 5.2 (continued): The performance scores of the multilingual (n = 133) and monolingual (n = 71) children in the 6 AP tests, with age appropriate US norms represented by the dashed line

Speech-based AP tests



Mann Whitney test,

** p <.001; * p < .05

To help determining the number of children who passed or failed a particular AP test, individuals' AP performance scores were converted to categorical data (pass/fail). Table 5.2 shows the proportion of children from both groups who performed above (passed) and below (failed) the age appropriate US norms on each AP test. Of note, none of the children failed only one non-speech test and passed all others.

To examine if the performance in each of the 6 AP tests (pass/fail) was associated with the linguistic background of an individual (multilingual/monolingual), separate Pearson Chi Square tests were performed. The results show significant association between the linguistic background and auditory performance in two of the AP tests – CS and LPFW, but not the others (Table 5.2). These findings suggest that children of a multilingual background are more likely to fail the two highly linguistically-loaded tests (CS and LPFW) than children of a monolingual background.

Table 5.2: Crosstabulation results showing the proportion of multilingual and monolingual children who passed and failed each individual AP test

Tests	Multilingual children (n=133)		Monolingual children (n=71)		p-value
	Passed	Failed	Passed	Failed	
FPT	124 (93.2%)	9 (6.8%)	67 (94.4%)	4 (5.6%)	.505
MLD	121 (91.0%)	12 (9.0%)	61 (86.0%)	10 (14.0%)	.267
RGDT	106 (79.7%)	27 (20.3%)	53 (74.6%)	18 (25.4%)	.407
DDT_R	118 (88.7%)	15 (11.3%)	58 (81.7%)	13 (18.3%)	.164
DDT_L	117 (88.0%)	16 (12.0%)	60 (84.5%)	11 (15.5%)	.487
CS_R	42 (31.6%)	91 (68.4%)	42 (59.2%)	29 (40.8%)	**.000
CS_L	29 (21.8%)	104 (78.2%)	29 (40.8%)	42 (59.2%)	*.004
LPFW	16 (12.0%)	117 (88.0%)	26 (36.6%)	45 (63.4%)	**.000

DDT = Dichotic Digit Test; CS = Competing Sentences; FPT = Frequency Pattern Test; LPFW= Low Pass Filtered Words; RGDT = Random Gap Detection Test; MLD = Masking Level Difference-500Hz; R = right ear, L = left ear. Significant * p < .005; ** p < .001; (Critical level of significance = .006, after Bonferroni correction).

5.6.2 The AP Performances of Children with and without Language-Related Disorders

Table 5.3 shows the number of children with a prior diagnosis of LI, SRD, LI and SRD, and no other disabilities in the multilingual and monolingual groups. The Pearson’s Chi Square test revealed that the proportion of children with and without language-related disorders did not differ significantly between the two groups [χ^2 (3, n=204) = 6.35, $p = .096$]. Therefore, the data from both multilingual and monolingual groups were merged for further analysis.

Table 5.3: The proportion of children with a provisional diagnosis of a language-related disorder in the referred population (n = 204)

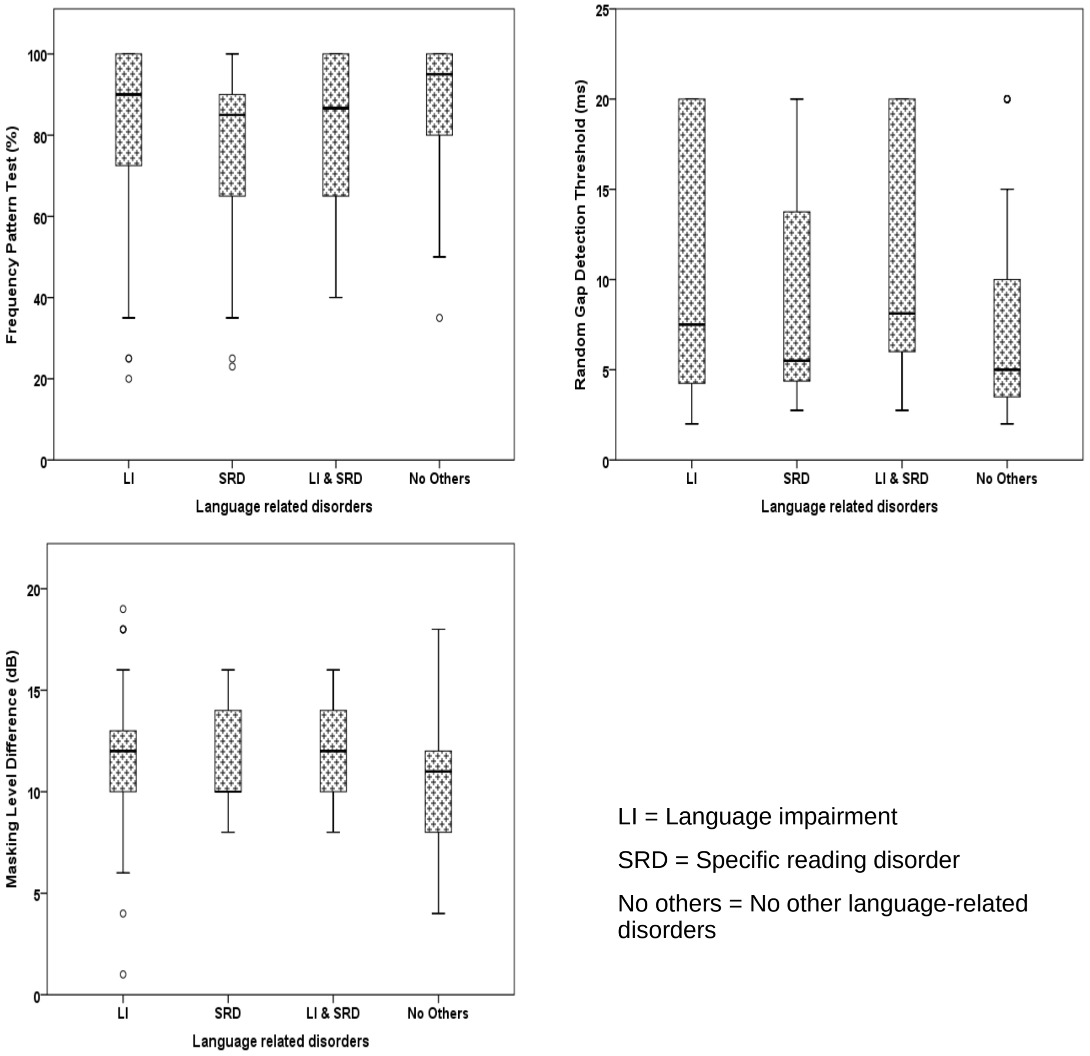
Study groups	LI	SRD	LI & SRD	No Other Disabilities
Multilingual (n = 133)	55 (41.4%)	9 (6.8%)	12 (9.0%)	57 (42.9%)
Monolingual (n = 71)	20 (28.2%)	6 (8.5%)	3 (4.2%)	42 (59.2%)

LI = language impairment; SRD = specific reading disorder

To study the effects of language-related disorders on AP test performance, the combined groups were re-categorized into 4 subgroups: LI (n = 75), SRD (n = 15), LI and SRD (n = 15), and no other language-related disorders (n = 99). The distributions of the performance scores of these individual subgroups on each of the AP test were summarized in the boxplots as shown in Figure 5.3.

Figure 5.3: The performance scores of children with and without language-related disorders on individual AP test

Non-speech AP tests

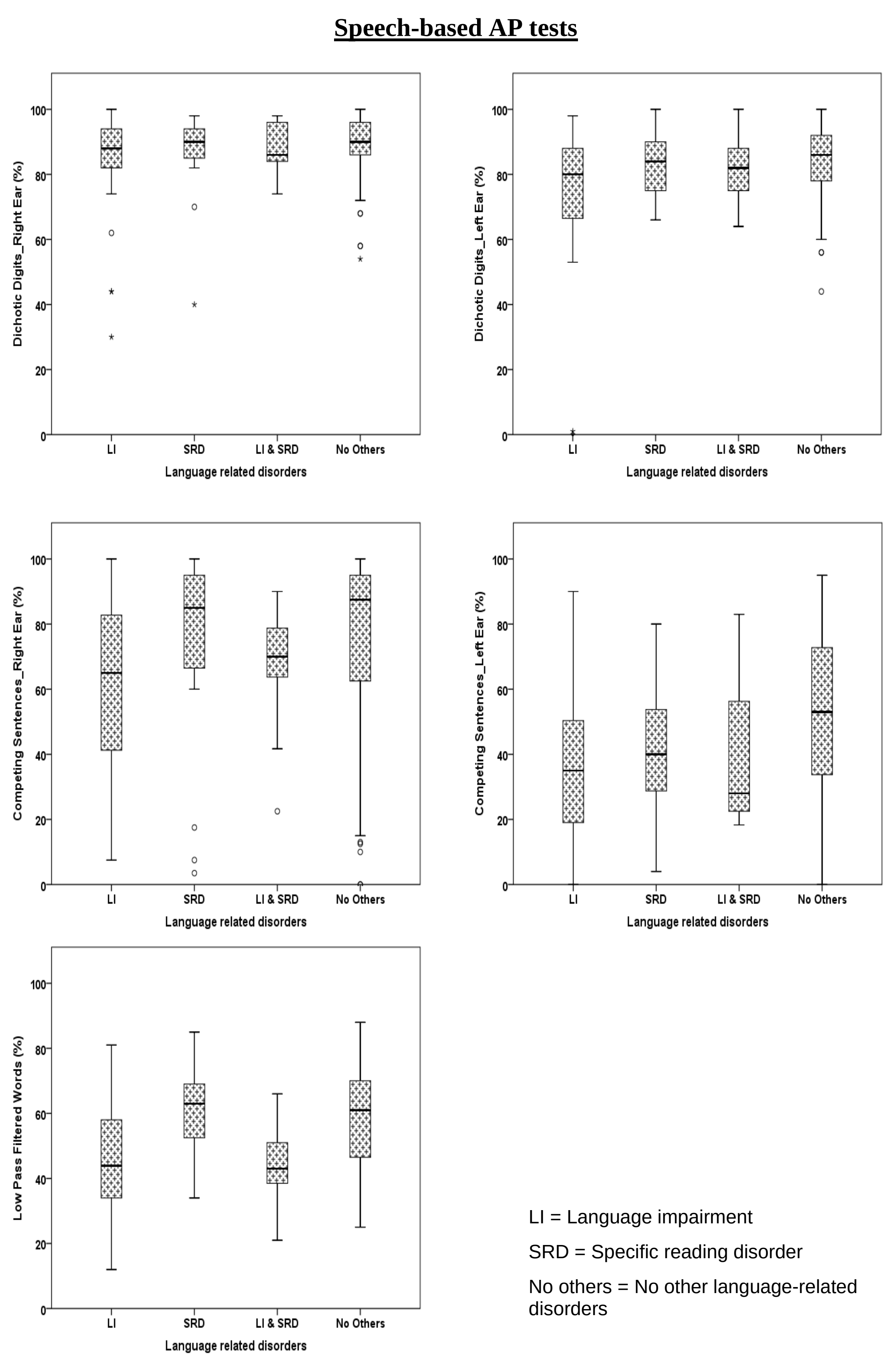


LI = Language impairment

SRD = Specific reading disorder

No others = No other language-related disorders

Figure 5.3 (continued): The performance scores of children with and without language-related disorders on individual AP test



A visual inspection of the data suggests that the median performance scores of children with and without language-related disorders were quite similar in most of the AP tests except the CS and LPFW. The results from Kruskal-Wallis tests revealed that the groups differed in performance on the CS [right ear, $H(3) = 18.26$, $p <.001$; left ear, $H(3) = 16.57$, $p < .005$] and LPFW [$H(3) = 31.02$, $p <.001$] tests, but not the others (critical level of significance = .006 after Bonferroni correction). Mann-Whitney tests were conducted to follow up these findings (Table 5.4). It appeared that the performance scores of LI group were significantly poorer than those without language-related disorders in the CS and LPFW tests. In contrast, no significant differences were noted between the SRD group and those without language-related disorders in any of these tests. The LI&SRD group, on the other hand, performed significantly poorer than those without language-related disorders only in the LPFW test.

Table 5.4: Post-hoc Mann-Whitney tests comparing the performance scores between LI and no others, SRD and no others, LI&SRD and no others in the CS and LPFW tests

AP tests	**LI vs No Others**		**SRD vs No Others**		**LI&SRD vs No Others**	
	U	***Effect size***	***U***	***Effect size***	***U***	***Effect size***
CS_R	2403**	-0.302	735 (n.s)	-0.006	477 (n.s)	-0.209
CS_L	2438**	-0.293	561 (n.s)	-0.143	518 (n.s)	-0.176
LPFW	2188**	-0.351	667 (n.s)	-0.059	351**	-0.307

CS = Competing Sentences; LPFW= Low Pass Filtered Words; R = right ear; L = left ear

LI = language impairment; SRD = specific reading disorder; No others = no other language-related disorders

Significant ** $p < .001$ (critical level of significance = .006; after Bonferroni correction);

n.s = non-significant

5.7 Discussions

The clinical diagnosis of APD remains a challenge. To date, there is no ‘gold standard’ test battery for the diagnosis of APD; neither is there a minimal set of AP tests that are universally agreed upon. Audiologists who are involved in the assessment of APD are guided only by test principles recommended by professional organizations (e.g. ASHA, 2005; AAA, 2010; BSA, 2011), and they are given a variety of test options to be used. For example, the guidelines published by the ASHA (2005, p.12-13) and AAA (2010, p.16-22) list five behavioural auditory domains, i.e. auditory discrimination, dichotic listening, temporal processing, monaural low-redundancy speech perception, binaural interaction/localisation, with at least two different tests to assess each auditory domain.

A recent survey to determine current protocols used by 195 audiologists in the US revealed that majority of the respondents used a test battery approach with four to six AP tests, mostly focusing on speech based tasks (Emanuel, Ficca, & Korczak, 2011). A similar trend was observed in the UK whereby different types of direct and indirect AP tests (e.g. language, cognitive, memory, questionnaires) were used randomly in the diagnosis of APD in different clinics, with SCAN-C being the most commonly used test (Hind, 2006). These studies reflect a lack of consistency and uniformity in the APD diagnosis among audiology professionals, both on a national and international level.

In the present study, our findings suggest that the diagnosis of APD in a multicultural community is probably best done on the basis of non-speech or minimally linguistic-loaded AP tests. In the context of an international perspective, the current findings render further support to the need of developing non-speech AP tests that can be applied universally (as stated in the AAA guidelines, 2010; p.23). Further discussion on this aspect is provided below.

5.7.1 The Impact of Linguistic Background on AP Performance

While the impacts of multilingualism on language and literacy assessment has been extensively discussed (Cline, 2000; Langdon & Wiig, 2009; Cruz-Ferreira, 2010), there is however none, if any, studies that directly assessed the effect of multilingualism on performance in AP tests that are commonly used for clinical diagnostic purposes. To the best of our knowledge, this is the first study that examined the performance observed in speech and non-speech AP tests from a large clinical database and compared it between a group of multilingual and monolingual children.

As suspected, when linguistic demand increases in an AP task, the effect of linguistic background on the performance becomes more apparent. In comparison to monolingual children, a significantly greater number of multilingual children failed the two highly linguistically loaded tasks, i.e. CS and LPFW, while the performances of the two groups were comparable in the non-speech, i.e. FPT, RGDT, and MLD, as well as in minimally linguistically-loaded tasks (i.e. DDT). These findings are hardly surprising. The CS test itself is a particularly difficult task even to native English listeners, which is evident from the considerable variation in performance on this task among children in the monolingual group (Figure 5.2). The CS test contains long sentences and the performance is affected by intralingual interference, as both the target and competing speech are in the same language. Listening in such condition is always harder than when both the target and competing speech were in different languages (interlingual interference) (Lew & Jerger, 1991). For the multilingual group, the CS test may present a greater challenge than it does for the monolingual English-speaking children. Furthermore, some of the sentences in the CS test may be contextually irrelevant to the local culture and unfamiliar to the multilingual children in this study (e.g. *summer* *holiday, Easter week)*. Hence, this increases the likelihood of these children making error in their responses even though the sentences were audible to them.

Ample evidence has shown that listeners whose English as their second language can hardly perform on par with monolingual listeners in English-based speech tasks (e.g. monosyllabic word recognition test, speech-in-noise test, synthesized sentence test) (Axmear et al., 2005; Stuart, Zhang, & Swink, 2010; Shi, 2011; Tabri, Chacra, & Pring, 2011). Non-native listeners have been found to be less able to make use of acoustic and linguistic cues that are readily accessible to native English listeners (Mayo, Florentine, & Buus, 1997). Attending to speech task that contains limited linguistic and acoustic cues like the LPFW test, which uses monosyllabic words after low-pass filtering, is undoubtedly more difficult to the multilingual children.

In this study, we noted that age may be an additional factor to the differing linguistic background in affecting the performance of children in the CS and LPFW tests. Multilingual children of younger age group were found to perform significantly poorer than their monolingual counterparts on these tasks, but not when they were older. The observed phenomenon could be attributed to the improvement in English proficiency in multilingual children over the years, as English is the language of academic instruction in all local schools. The multilingual children’s weak foundation in English, which mainly resulted from the lack of exposure to this language during early childhood, has put them in disadvantage when performing speech-based AP tests like CS and LPFW at a young age. As these children progressed academically, their English language abilities developed and improved. Hence, when tested with speech-based tasks at older age, the multilingual children made less error and therefore, their performances were comparable to those of the monolingual counterparts. While this explanation deemed reasonable, we should be cautioned that the insignificant difference in performance between the older children from both groups could be the result of insufficient data point within this age range (10 to 12 years old). As seen in Figure 5.1, the overall distributions of data in both multilingual and monolingual groups were skewed towards the younger age range (7 to 9 years old).

As explained above, highly linguistically loaded tasks like the CS and LPFW tests are not suitable to be used in the diagnosis of APD in children of a multilingual background. A criticism could be made that the high failing rate in these tasks among the multilingual children in this study was because of using the native (American) English referenced norms. However, a considerably high percentage of monolingual children also failed these tests, despite them being native English speakers. Notably, in the monolingual group, many of them were Australian, some American and British. Applying US norms on other English-speaking population in linguistic-based testing has been shown to be inappropriate (Marriage, King, Briggs, & Lutman, 2001; Dawes & Bishop, 2007). This implies that in a diverse community, if highly linguistically-loaded tests were to be used for APD assessment, separate norms would be needed for each subgroup. However, this raises the question of practicality of such measures in current clinical use. Therefore, non-speech or minimally linguistic-based tests should be considered as universally applicable AP test battery, as it would be less sensitive to language background differences.

Ideally, the solution to applying speech-based AP tests more generally is to have a test developed in the native language or dialects used in the community. However, this may not be viable in a polyglot country with a number of minority subgroups, because of the expense and effort required for each language or dialect (Lew & Canon, 2010).

Furthermore, it is uncertain whether specific speech-based AP tests translated into other languages would still be assessing the same auditory processes, as different languages have different neurophysiological representation in the brain (Valaki et al., 2004). While re-norming of existing speech-based AP tests seems more achievable, it may not address the problem of accent differences and word familiarity effects in diverse communities. For example, Dawes and Bishop (2007) found that primary school children in the UK scored significantly worse than the US norms in SCAN-C (a speech-based screening test for APD), primarily due to the difference in accent. A similar problem was reported in an earlier study by Marriage and colleagues (2001) with SCAN test. While these authors recognised the desirability of re-recording the test with a British speaker, they also pointed out that this would not solve the possible problem of regional variation in accents impacting on performance. Therefore, for practical reasons, the utilisation of non-speech AP tests may be more appropriate in ensuring uniformity in the assessment and diagnosis of APD.

5.7.2 The Impact of Language-Related Disorders on AP Performance

This study provides a rare opportunity to examine the performance of children with language related disorders on some of the most popular tests of AP (Figure 5.3). A close inspection of the data reveals that children with LI and/or SRD showed higher intra-group performance variation in the FPT and RGDT as compared to those without. The FPT and RGDT are tasks of temporal processing. These data illustrate that some, but not all, LI and SRD children had poor temporal processing skills. This adds to the existing evidence in literature (see review by Bailey and Snowling, 2002; Rosen, 2003) that poor temporal processing skills do not underpin LI or SRD in all individuals as proposed by some studies (e.g. Tallal, 1980; Cestnick & Jerger, 2000; Cohen-Mimran & Sapir, 2007). In this study, at least 25% of the children with LI and/or SRD had fairly good scores in the FPT and achieved very small gap detection threshold (RGDT < 5ms), which was comparable to those without language-related disorders. As for the MLD test, low variation was observed within group and the inter-group performances were fairly uniform. This is consistent with the literature that tonal MLD is not easily affected by language factor.

Similarly, there was less intra-group variability in the performance on the DDT and the scores were overall better than those on the CS test, despite both tests being dichotic listening tasks. This reflects the effect of linguistic content of the stimuli on dichotic listening. The DDT has minimal linguistic demand as compared to the CS test, and thus requires less memory load. Notably, the interaural asymmetry with right ear advantage (REA) was only observed in the CS test (not in the DDT) is consistent with the literature that REA generally increases with stimuli of higher linguistic content (Keith and Anderson, 2007). In contrast to some of the reports in literature, enhanced left ear performance compared to the right ear in dichotic listening task was not observed in the children with language-related disorders in the studied population. Nonetheless, it needs to be made clear that the present study only examined the group data; it is possible that abnormal left-ear enhancement may be present in individual participant.

Of the six AP tests, the two highly linguistically loaded tasks (CS and LPFW tests) were found to be easily affected by language factor, as evidenced from the significant difference in performance on these tasks between children with LI and those without. These findings are not unexpected, as these two tasks involve language processing, and therefore are more challenging for children with language learning difficulties.

Furthermore, the CS test taps into an individual’s higher cognitive function, in particular, the short-term auditory memory. There is good evidence that children with LI have short-term verbal memory constraints (Ellis-Weismer, Evans, & Hesketh, 1999; Nickisch & von Kries, 2009; Hutchinson, Bavin, Efron, & Sciberras, 2011) and they perform significantly more poorly than typically developing children in sentence repetition task in quiet, which lead to this task being the best predictor for LI (Conti-Ramsden, Botting, & Faragher, 2001). It is therefore hardly surprising that children with LI would perform poorly on sentence repetition with competing signals, as in the CS test.

Of particular interest is the result of present study indicating that children with and without SRD did not perform significantly different in all tests of AP. This either suggests that the presence of SRD does not affect the performance on any AP tests, or there is no clear association between literacy problems and deficit in AP skill. It should, however, be made clear that those without SRD were referring to children with no language-related disorders and some, but not all, could fit a clinical diagnosis of APD. In the study by Dawes and Bishop (2010), children with SRD were found to score similarly to the APD group on a speech-based test, i.e. SCAN-C. Nevertheless, it has been proposed that only a minority of individuals with SRD truly exhibit auditory deficits (Rosen, 2003), thus literacy performance cannot be used to determine an individual’s AP skills and vice versa. It should be cautioned that the non-significant differences between those with and without SRD in the present study could also be due to insufficient statistical power, as there is a small sample of 15 children only with a clinical diagnosis of SRD.

In a nutshell, the inclusion of highly linguistically loaded tasks in the assessment of APD may easily be confounded by language factor and thus making differential diagnosis between language and AP disorder very difficult. In a study like that of Ferguson and colleagues (2010), whereby participants with APD were recruited from various Audiology or ENT centres in the UK with different approaches were adopted in the APD diagnosis [typically on the basis of two or more failures in the AP tests with the SCAN-C being one of the most commonly used tests (Hind, 2006; Dawes and Bishop, 2010)], it seems unsurprising for the authors to conclude that children with clinical diagnosis of APD and SLI had very similar behavioural profiles. An US-based study by Miller and Wagstaff (2011), which was in agreement with the study by Ferguson and colleagues (2010), had a similar pitfall as the diagnosis of APD was based on two failures in 4 of the AP tests, in which one of them is a speech-based task.

5.8 Limitations

Like in any other retrospective studies, the main disadvantage of the current study is the dependency of the availability and accuracy of patients' record. As the data was not originally recorded for research purposes, we have no control over how a diagnosis of language or reading disorder was made in the studied sample; neither is there information on the type of assessment tools used for the diagnosis, nor there children's language and literacy scores. Misclassification of individuals' clinical diagnoses due to record-keeping error or clinical diagnostic biases could negatively impact on the interpretation of the current results.

Other limitation of the current study is the lack of information regarding the language status of participants (e.g. language dominance, age of acquisition, stability of the use of second language), particularly for the multilingual group, and the country of origin of the monolingual group. The unavailability of these data makes it impossible to run further analysis for examining the impact of linguistic background on the performance observed in speech and non-speech tests of AP.

Nonetheless, this retrospective study presents some useful information about the behavioural profile of children with language, literacy and AP difficulties in a diverse community. In contrast to most prospective studies, participants in this study were not recruited on the basis of any pre-defined criteria; therefore the results of this current study will be more meaningful and of direct relevance to the real clinical practice for determining the appropriate type of AP tests for diagnosis purposes.

5.9 Conclusions:

Despite having a different linguistic background and literacy competency, the AP performance of children from the multilingual and monolingual groups was indistinguishable based on a non-speech AP test battery. While linguistic tasks remain an important component in the APD test battery, as it is believed that the central auditory nervous system has different processing mechanisms for speech and nonspeech signals (AAA Clinical Practice Guideline, 2010), the practicality of using these tasks in a multilingual population with separate norms is questionable. Moreover, highly-linguistically loaded tasks like CS and LPFW are easily influenced by language factor, particularly LPFW, which has a very low sensitivity and may not be truly assessing central auditory processing per se. Thus, the finding in this study has a strong implication on the development of a universally applicable AP test battery, with the need to utilize non-speech tests for the identification of APD.

Chapter 6

Study II

The Effectiveness of Computerized Auditory Training Programme on Children with Auditory Processing Disorder

6.1 Background

To date, there is a dearth of robust clinical studies assessing the efficacy of auditory training (AT) for a well-defined APD population. Even though there is emerging evidence (as discussed in section 3.2) indicating that AT may benefit children with APD and associated learning disabilities, previous studies have some significant limitations. Firstly, it is difficult to be sure of a true treatment effect, as many studies do not include an untrained comparison group to estimate practice or maturational effects. Secondly, few studies, if any, employed outcome measures that can be directly related to AP skills. Thirdly, a long term training effect was not often assessed and therefore, the sustainability of any benefits obtained from an AT intervention remains unclear.

In this chapter, we describe a randomised controlled trial (RCT) that examined the effectiveness of a computer-based auditory training (CBAT) intervention for children identified with APD. This study was designed to address the limitations mentioned above by including:

(1) an untrained control group with APD,

(2) an auditory test and listening questionnaires as outcome measures, and

(3) 3-month post-intervention follow up.

A CBAT approach was chosen for its many advantages. First, it allows for precise control of the stimuli and the difficulty level is automatically adjusted. Secondly, it is user-friendly and can be easily applied by non-professionals, including parents. As compared to a conventional intervention for APD, which is generally conducted once a week in a clinic, a home-based therapy programme allows more flexibility for parents and greater opportunity for the child to participate. Finally, AT delivered through a computer-assisted approach can be presented in the format of arcade-style computer games, which should help in ensuring high levels of engagement for the children during the listening exercises (Moore, 2011).

6.2 Objectives & Hypotheses

The current study aimed to examine the effectiveness of a CBAT intervention for children with APD by comparing the changes in AP and functional listening skills of these children immediately post-intervention, to that of the untrained controls. The AP skills of the trained group were evaluated again at 3 months post-intervention to examine the sustainability of any improvements made from the CBAT intervention. We hypothesised that after intervention, children from the AT group would improve in their AP skills, and that improvement would be greater than the changes in AP skills of those untrained controls. We also hypothesised that the improvement made from the intervention would sustain for at least 3 months after the end of intervention. Finally, we examined if the training outcomes are predictable from any underlying factors such as the initial AP, language, or cognitive skills of these children.

6.3 Methodology

6.3.1 Study Design

This prospective study incorporated a parallel group design that randomly assigned participants identified with APD to an auditory training (AT) group or a no intervention (Control) group. Both groups were matched for age and gender. Baseline measures were conducted prior to the randomisation process. An auditory test and questionnaires were used as the outcome measures.

Participants from the AT group were given a 3-month home therapy using a CBAT programme developed for this study, while participants from the control group received no intervention for the same period of time. Apart from regular school attendance and activities, all participants were requested to discontinue any other auditory-based interventions, which might affect the outcomes of this study. All the participants were assessed again after the conclusion of the training period.

After the end of the intervention, participants from the AT group were requested to undergo a no-intervention phase for a period of 3 months before another assessment. This was intended to examine the sustainability of any improvement made through the CBAT programme.

[The flowchart of the study design is available in Appendix E]

6.3.2 Ethics Approval

This study was granted approval by the National Healthcare Group Singapore (DSRB reference number: D/09/485) for a period of two years, between 22 October 2009 and 22 September 2011, under the title: “Management of children with auditory processing disorders (APD)”.

6.3.3 Procedures

Potential children (aged between 7;0 and 11;11 years old) who had newly been diagnosed with APD by experienced audiologists from the Centre for Hearing Intervention and Language Development (CHILD), National University Hospital, Singapore, were referred for this study. Using the ASHA (2005) diagnostic criteria as a guide, a child who failed (or scored more than 2SDs below the mean of US norms) in two or more of the AP tests binaurally (as listed in Table 6.1) was considered as having APD. The 5 AP tests (FPT, DPT, RGDT, MLD, and DDT) were selected as being suitable for children of a multilingual background based on the findings obtained in Study I (refer to section 2.4.1 for further details of each test).

The children who agreed to take part in this study underwent a baseline assessment in the clinic within 2 weeks of referral. Written consent was obtained from each participant’s parent prior to the start of the assessment. The baseline assessment (which took place in a sound-treated room) included a series of language, phonological, nonverbal intelligence, and short-term auditory memory tests (as described below). The LiSN-S test (see section 2.4.2.2 for its detailed description) that served as the objective outcome measure was also administered within the same session.

Table 6.1: A brief description of the AP tests used for clinical diagnosis of APD

AP tests & Technical Information	Presentation level & number of stimuli	Task	Scoring
Frequency Pattern Test (FPT) Auditec – Child version Low: 880 Hz; High: 1430 Hz; Tone duration: 500 ms; Inter-tone interval: 300 ms; Inter-pattern interval:10 sec	50 dB HL monaurally, 30 stimuli per ear	Label the tone pattern verbally as high or low in a sequence of 3 tones (e.g. high-low-low)	% correct per ear
Duration Pattern Test (DPT) Auditec Tone: 1000 Hz; Tone durations: 250 ms (short) or 500 ms (long); Inter-tone interval: 300 ms; Inter-pattern interval: 10 sec	50 dB HL monaurally, 30 stimuli per ear	Label the tone pattern verbally as long or short in a sequence of 3 tones (e.g. long-short-short)	% correct per ear
Random Gap Detection Test (RGDT) Auditec Stimuli: 0.5, 1, 2, & 4kHz; Gap durations: 0, 2, 5, 10, 15, 20, 25, 30, and 40 ms. in random order.	50 dB HL binaurally, 4 sets of stimuli at different frequencies	Respond verbally to indicate whether 1 or 2 sounds were heard	Average of gap detection thresholds for 4 stimuli (ms)
Masking Level Differences (500Hz) – MLD Auditec 5 tone bursts (500Hz; 300 ms) in 3sec bursts of narrow band noise 10 SoNo trials (1- to -17dB S/N); 12 SπNo conditions (-7 to -29dB S/N), and 11 no tone conditions.	50 dB HL, binaurally 33 presentation	Respond verbally whether tone pulses were heard or not within the buzzing noise.	SπNo threshold minus SoNo threshold
Dichotic Digits Test (DDT) Auditec Male voice; 25 pairs of double digits (1 to 9 except 7)	50 dB HL, binaurally	Repeat verbally all 4 numbers	% correct per ear

Since the basic audiometric assessment i.e. puretone audiometry, tympanometry, and a speech reception test in quiet, were conducted as part of the routine clinical tests prior to a child being assessed for APD, it was not repeated in this study. Of note, all participants had normal peripheral hearing and speech discrimination scores of more than 80% in both ears.

During the first session (baseline assessment), parent(s) of each participant were interviewed by the principal investigator (PI; author of this thesis) using a self-developed case history questionnaire (see Appendix F). This questionnaire helps in guiding the PI to obtain information related to the parents’ educational background, any previous clinical diagnoses the child had, any intervention the child had received, the educational setting of the child, the child’s perception of his/her own listening difficulties, and the parents’ perception of the child’s listening problems. As part of the study, the parents and teachers of all participants were also given two different validated questionnaires to rate the child’s listening and learning behaviour at home and at school, respectively.

After the baseline assessment, participants in the AT group started their home-based CBAT intervention within 1 week from the assessment, while the controls received no additional intervention. The installation of the AT programmes was done by the PI and it took place either in the clinic, if it was on a laptop, or at participant’s home, if it was a desktop. Prior to the start of AT, PI explained the procedures to the parents and participant to ensure appropriate administration of the tasks at home. An instruction manual containing each listening exercise (refer to section 6.3.7) and a timetable was also provided to parents as reference.

Three month after the baseline assessment, participants from both study groups were assessed again using the LiSN-S test. The parents and teachers of all participants were asked to rate the child's listening and learning behaviour again using the same set of questionnaires. For participants in the AT group, a final LiSN-S test was administered at 3 months post-intervention (or 6 months relative to the baseline assessment) to measure any changes in the AP skills.

6.3.4 Baseline Assessment

All participants in this study were assessed using the same standardised test battery and tests sequence for core language skills, phonological skills, non-verbal intelligence, and short-term auditory memory. The assessments were conducted within a 3.5 hour session by the PI. Sufficient short intervals were given to participants between tests to avoid fatigue and to reduce the effect of inattention on test performance. The baseline assessments data were used for examining participants' associated language-related difficulties.

6.3.4.1 Language assessment

The *Clinical Evaluation of Language Fundamentals – Fourth UK Edition* (CELF-4 ^{UK}; Semel, Wiig & Secord, 2006) was administered to each participant to assess his/her core language skill. The assessment consisted of the following subtests, according to a child's chronological age:

- Concepts and following directions (5 to 12 years old),
- Word structure (5 to 8 years old),

- Recalling sentences (5 to 12 years old),
- Formulated sentences (5 to 12 years old)
- Word classes 2 (receptive, expressive, and total) (9 to 12 years old).

The description of each of the subtest was provided in Table 4.1 (Chapter 4). The sum of the subtests' scaled scores was converted to a standard score.

6.3.4.2 Phonological skills assessment

The *Phonological Assessment Battery* (PhAB; Frederickson, Frith & Reason, 1997) was used to examine the participants' phonological skills which are most related to reading and spelling ability. The subtests included were:

- Alliteration
- Rhyme
- Spoonerisms
- Non-word Reading

The description of each subtest was provided in Table 4.2 (Chapter 4). The raw score of each subtest was converted to a standardised score.

6.3.4.3 Nonverbal intelligence (NVIQ) test

The *Test of Nonverbal Intelligence – 3rd Edition (TONI-3;* Brown, Sherbenou & Johnsen, 1982) was used to assess the participants' cognitive skills in abstract/figural problem solving. The TONI-3 is a US norm-referenced, language free measure that can be used in individuals ages 6;0 through 89;11, which is ideal for those who have linguistic difficulties or who are culturally different. The participant was asked to look at the stimulus items and to respond by means of pointing at one of the 6 choices given. The raw score was converted to a deviation quotient (or IQ score).

6.3.4.4 Short-term auditory memory test

The participants were assessed for their short-term auditory memory skills using the *Test of Auditory Perceptual Skills-Revised* (TAPS-R; Gardner, 1996). The test consisted of four subtests as described in Table 6.2. The raw score of each subtest was converted to a standard score.

Table 6.2: TAPS-R subtests

Subtest	Description & Task
Auditory Number Forward Memory (ANFM)	A set of digits containing the numbers from 1 to 9 was presented in a random order in live voice, and the child was required to recall the numbers in a forward sequence.
Auditory Number Backward Memory (ANBM)	A set of digits containing the numbers from 1 to 9 was presented in a random order in live voice, and the child was required to repeat the numbers in a backward sequence.
Auditory Word Memory (AWM)	A set of one-syllable, two-syllable, or compound words which increased in number through each test was presented in live voice. The child was required to recall all the words perceived.
Auditory Sentence Memory (ASM)	A list of sentences with gradual increment in the number of words in each sentence was presented in live voice. The child was required to repeat the whole sentence without any omissions or substitutions of words.

6.3.5 Outcome measures

An auditory test and two validated questionnaires were used as outcome measures, administered at baseline, and at post-3 months (immediately post-intervention).

6.3.5.1 LiSN-S (Objective Measure)

The LiSN-S is an auditory task that assesses the ability of children to understand speech in the background of two other talkers. The detailed description of LiSN-S has been provided elsewhere (Chapter 2, section 2.4.2.2). In summary, LISN-S produces a three-dimensional auditory environment under headphones. By manipulating the location and the vocal quality of talker(s), four listening conditions are created: different voices at ± 90° azimuth (DV90; high cue), same voice at ± 90° azimuth (SV90), different voices at 0° azimuth (DV0), and same voice at 0° azimuth (SV0; low cue). From these four listening conditions, three advantage measures are derived: talker advantage (TA), spatial advantage (SA), and total advantage (ToA) (see Figure 2.7; Chapter 2).

The LiSN-S test was administered using an *Acer* (*Aspire 3820TG)* laptop; with Sennheiser HD215 circumaural headphones connected to a Buddy 6G USB soundcard. The target sentences were presented at an initial level of 62 dB SPL, whereas the distracter stories ("Loopy Lizard's Tail" and "The Great Big Tiny Traffic Jam") were presented at a constant level of 55 dB SPL. The target stimuli and distracter discourse were presented to both ears simultaneously. A maximum of 30 sentences were presented in each of the four listening conditions. The participant was required to repeat the targeted sentences verbally in every listening condition and correct responses were scored manually by the PI on the computer. The stimulus presentation level was adjusted adaptively depending on the participant’s response. The assessment took approximately 20 minutes to complete.

The LiSN-S performance was measured as a signal-to-noise ratio (SNR) in dB (or known as the speech reception threshold) for the four listening conditions, and as SNR difference in dB for the three advantage measures.

6.3.5.2 Questionnaires (Subjective Measure)

The same questionnaires, i.e. the PP and CHAPS, that have been used in the pilot study were used in the current study (refer to section 4.4.6 for detailed description of each questionnaire). In brief, the PP questionnaire consisted of 52 items concerning the rituals and conversational skills of a child, how a child asks for information and gives responses, and nonverbal communication skills. Whereas the CHAPS questionnaire consisted of 36 questions evaluating a child’s listening skills in 6 different auditory conditions (noise, quiet, ideal, multiple inputs, auditory memory sequencing, and auditory attention span) in comparison to his/her peers. The PP and CHAPS questionnaire was completed by each participant’s parents and teacher respectively.

6.3.6 Participants

Fifty-five potential children with APD were referred for this study. Parents of 16 suitable children declined to allow their child to participate, leaving 39 children for this study. There were 32 boys and 7 girls. All the participants were local children attending the mainstream schools, and they fulfilled the following criteria:

1. Presentation to the clinic with reported symptoms of listening difficulties.

2. No measurable peripheral hearing anomalies in both ears, i.e. normal cochlea and middle ear function, as judged by normal audiometric thresholds of 20dB HL or better in the speech frequency range of 250-8000 Hz, and normal impedance audiometry.
3. Performance on the behavioural AP test battery (Table 6.1) which met the following criteria:
    a. At least two abnormalities in the non-speech or minimally-linguistic loaded tasks.
    b. No indication of any other underlying higher order cognitive problems as judged by abnormal performance scores in all the tasks in AP test battery.
4. Normal intelligence, as judged by having a nonverbal IQ score of more than 85 (*Test of Nonverbal Intelligence, TONI*).
5. No medical or developmental conditions, i.e. epilepsy, global developmental delay, pervasive learning disorder such as autism, which may additionally impact on auditory or cognitive performance.

Of the 39 participants, four children had a diagnosis of ADHD confirmed by paediatricians. The children with ADHD were equally distributed to AT and control groups. All of them were medicated, presumably reducing the effects of inattentiveness on the assessments.

6.3.7 Intervention

The CBAT programmes in the current study were specifically designed to improve speech-in-noise and dichotic listening skills of children diagnosed with APD. Three different listening games (DOGGY, WHO-IS-RIGHT, and Story-In-Noise) were developed for speech-in-noise training, while the dichotic listening training was incorporated in another programme (TATP). All the training programmes were designed to be installed on home-user's computer, and they were visually attractive and appealing to children.

The development of the software for the speech-in-noise and dichotic listening training was done by two different teams in the UK and Singapore, respectively. In general, each of the listening games' graphical user interfaces was created in MATLAB and the results were output to Microsoft Excel files. Relevant information such as user response, SNR, response time, and training time was stored, which enabled checks on the child's progress. There was also the flexibility to configure various settings in the software including the type of speech and masker stimuli, the initial presentation level, the step value (increase or decrease in SNR), the respond options and the type of feedback provided to the listener. Each of the 4 listening games is further described below.

6.3.7.1 DOGGY

The *DOGGY* is a child friendly listening game designed by Rosen and Mair (2009), which was modelled after the Coordinate Response Measure for adults developed by Bolia, Nelson, Ericson, and Simpson (2000). This listening game targets improvement in speech understanding in various types of stored background noises, such as theatre noise, multitalker babble, competing speech by male talker, and [3]steady- state speech-shaped noise. A target sentence "show the dog where the [*colour*] [*number*] is" spoken by a female adult with a general southern British accent is presented concurrently with the background masking noise. The listener is required to click on the corresponding number (1 to 9 excluding the bisyllabic 7) in one of the coloured boxes (black, red,

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[3] The speech-spectrum shaped noise modulated by the amplitude envelope of a single male talker.

white, blue, green or pink) as shown in Figure 6.1. The presentation order of the colour and number in the target sentences is randomly assigned by the software. Visual feedback on accuracy is given, with a smiley face indicating a correct answer, while a sad face indicates an incorrect answer.

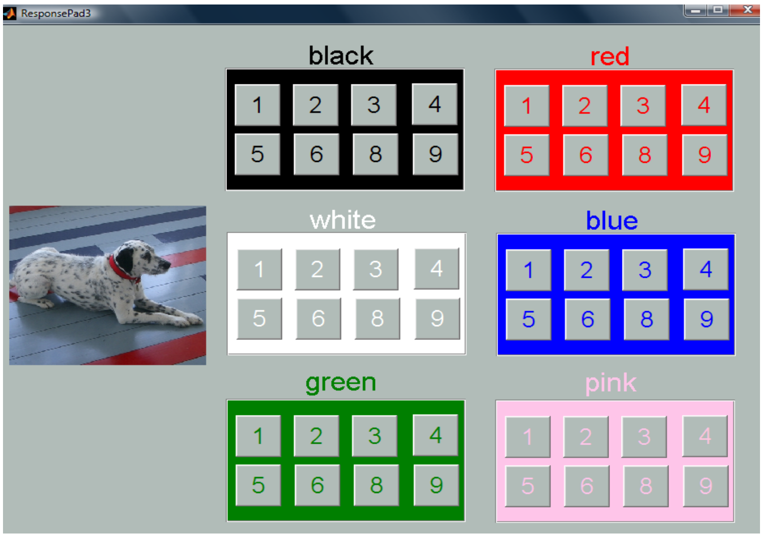
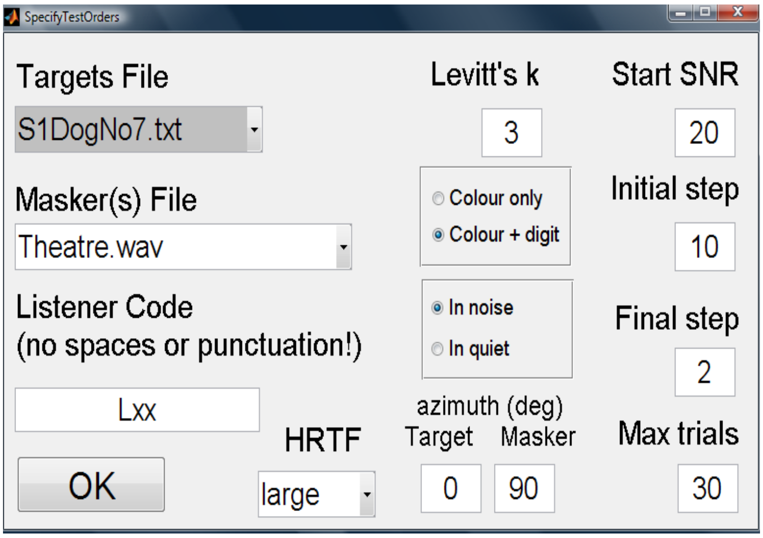


Figure 6.1: Screen shot showing the *DOGGY* game.

This low-linguistically loaded speech-in-noise training uses a 3-down, 1-up adaptive staircase paradigm (Levitt, 1971) to control the signal-to-noise ratio (SNR). The initial presentation level of the target speech is set at a SNR of +20 dB, with the output level fixed at 65 dB SPL measured over the frequency range of 100-5000Hz. Initially, the presentation level (SNR) reduces in a step size of 10 dB after each correct answer until the first incorrect response is detected, then the level increases. Subsequently, it requires 3 consecutive correct responses before the level is decreased to make the task more difficult. The final step size is decreased to 2 dB after the first two reversals. The training stops after six reversals or after a maximum of 30 trials. Figure 6.2 shows a screen shot of the possible settings for the *DOGGY* game.



Targets File: S1DogNo7.txt

Masker(s) File: Theatre.wav

Listener Code (no spaces or punctuation!): Lxx

Levitt's k: 3

○ Colour only
● Colour + digit

● In noise
○ In quiet

azimuth (deg) Target: 0 Masker: 90

HRTF: large

Start SNR: 20

Initial step: 10

Final step: 2

Max trials: 30

Figure 6.2: Screen shot showing Matlab set up for the *DOGGY* game with 'theatre noise' as masker presented at 90° azimuth relative to the target speech at 0° azimuth.

Twelve different tasks that vary in terms of the type of maskers and with respect to its location were created (as shown in Table 6.3). Each of the tasks was to be done once over the 12-week programme. Of note, the target stimuli were always spoken by the same female speaker. The masker stimuli were also mostly not related to the target speech, except tasks 5 and 6 that the same sentence was spoken by a male speaker with the *colour* and *number* differed from the target.

Table 6.3: Twelve different tasks with respect to the type of masker and location in the *DOGGY* game

Doggy training	Type of Masker	Azimuth (degree)	
		Target Speech	**Masker**
Task 1	Theatre noise	0	0
Task 2	Theatre noise	0	90
Task 3	Speech noise	0	0
Task 4	Speech noise	90	0
Task 5	Male speakers	0	0
Task 6	Male speakers	0	90
Task 7	Steady-state speech-shaped noise	0	0
Task 8	Steady-state speech-shaped noise	180	90
Task 9	1 talker babble	90	180
Task 10	1 talker babble	180	90
Task 11	2 talker babble	90	180
Task 12	2 talker babble	180	90

6.3.7.2 WHO-IS-RIGHT

Who-Is-Right is a word-in-noise listening game that targets on the discrimination of fine phonetic detail in the presence of background noise. On each trial, the target word is first displayed in a pictorial form while a male speaker simultaneously pronounces the word in quiet. Following this, a female talker utters 3 ‘words’ in noise, of which each is presented simultaneously with the bear moving its mouth. The listener is required to click on one of the 3 bears that produced the correct target word while the other two are non-word foils. An example of the picture displayed in the game is shown in Figure 6.3.

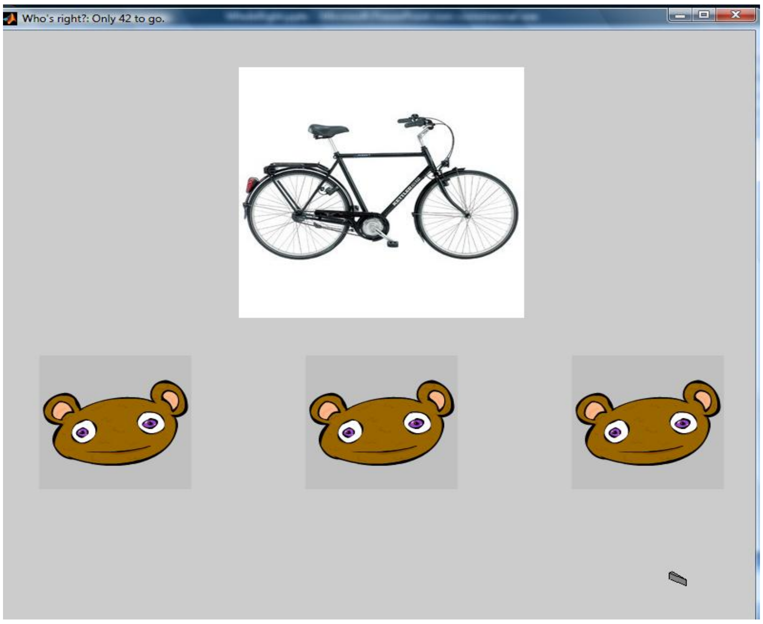


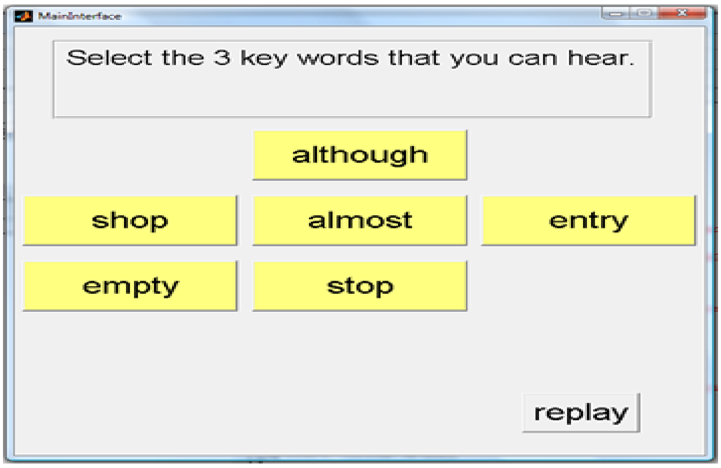
Figure 6.3: An example of a trial in the *Who-Is-Right* game, with the target word being 'bike'. The foils are 'wike' and 'gike'

All target words are CVC monosyllables selected to be acquired early (mean age of acquisition = 32 months; SD = 8 months), obtained from the databases of Bird, Franklin and Howard (2001). The two non-word foils differ in a single phonetic feature in the initial consonant of voicing, place, or manner. For example, when the target word is 'bike' (/baik/), the foils are /gaik/ and /waik/. The order of the target word and non-word foils being produced by the bears is randomised by the software. Speech-shaped noise is presented continuously during the time the 3 utterances are presented. The SNR is controlled using a 2-down 1-up adaptive staircase method (Levitt, 1971), in which it decreases after every two correct responses and increases after every error, except the initial descent that only requires 1 correct response. The initial presentation level is set at 20 dB SNR and the game stops after the completion of 42 trials.

6.3.7.3 Story-in-Noise

Story-in-noise is a keyword extraction task adapted from the CBAT programme used in the study by Faulkner, Rosen, Watt, and Gedgaudaite (2010), which was modelled after the method proposed by Stacey and Summerfield (2007). Speech materials used in this training are phrases from a connected narrative taken from the upper levels of the Heinemann Guided Readers series ("Money for Sale" and "Madeline") (Milne, 1977), recorded by a female talker with a British accent. Steady-state speech-shaped noise is used as the background noise and the presentation level is fixed at a SNR of +10 dB.

On each trial, a short phrase is presented in noise and 2- 6 response buttons appear, each of which has a word on it and randomly positioned on the computer screen. The listener is instructed to select the keyword(s) that were present in the target phrase from the set (as shown in Figure 6.4).



Select the 3 key words that you can hear.

Figure 6.4: Screen shot showing an example of the trials in the *Story-In-Noise* training, with the instruction of 3 keywords selection

For each keyword, there is another button containing a quasi-minimal pair to the target keyword. For example, for the phrase '*the shop was almost empty'*, the foils created for the three keywords of 'shop', 'almost', and 'empty' were 'stop', although', and 'entry'.

Visual feedback is provided by showing a green check for a correct word selected and a red cross for an incorrect word selected. An incorrect response also leads to the phrase being repeated. The listener is also allowed to replay the phrase if he/she missed out the first time. Once all the keywords are identified or after 3 replays, the phrase is displayed as text and played once more for the listener to hear. The training stops automatically after 15 minutes.

6.3.7.4 TATP

The TATP (*Temasek Auditory Training Programme*) was developed by a team from the Biomedical Informatics and Engineering school, Temasek Polytechnic (Singapore) as part of the students' projects. The design of the signal processing application programme (for dichotic listening training) was done by the students' project supervisor (Mr. Gary Lee) in collaboration with the author of this thesis.

The TATP incorporated the training technique called *dichotic interaural intensity difference* (*DIID*) first developed by Musiek (2004). The DIID method directs the stimuli to the better-performing ear (normally the right) at a reduced intensity level while maintaining a higher level to the weaker ear (normally the left). Nine dichotic listening games that vary in terms of the speech stimuli and the type of response (multiple choice or open ended) were created. The target stimuli and competing speech are presented via the home-user's computer through stereo headphones.

Using the principle of DIID, each of the listening games starts with attention directed to the left ear. The presentation level in the right ear is fixed at 55 dB SPL while the initial level in the left ear is set 10 dB more intense. Depending on the listener's response, the presentation level in the left ear is automatically adjusted in a step size of 5 dB using an adaptive simple up-down method (Levitt, 1971) with reference to the right ear. The step size is reduced to 3 dB after completing half of the 16 reversals for the entire training. Upon the completion of the left ear training, the listener will be instructed to direct attention to the right ear to continue the listening game.

The speech stimuli used in the TATP include digits, mono- and bi-syllabic words, and sentences not longer than 8 words. The lists of monosyllabic words and sentences were obtained from local primary school English textbooks. All the speech stimuli were recorded by a local Singaporean male speaker. The order of the target stimuli and competing speech is randomly generated by the software.

As illustrated in Figure 6.5, the listener first begins the training by clicking the ‘start’ button. Then the listener chooses one of the 9 boxes according to the schedule provided (see section 6.3.7.5) to start the listening game. Seven of the listening games use a 4-AFC paradigm while the other two listening require the listener to type the answer in a text box (Figure 6.6).

Figure 6.5: The start screen and game options screen of the TATP

(a) Main screen

(b) Game options

Figure 6.6: Sample of different animations and type of response in the TATP

(a) 4 AFC (Multiple choices)

(b) Open ended

Listen carefully...

Which is the correct answer?

Listen carefully...

Which is the correct answer?

6.3.7.5 Training schedule

The participants in the AT group were given a 12-week (5 sessions per week) CBAT programme to be completed at home with parental supervision. An example of a one week programme is provided in Table 6.4. Each session of training consisted of two different programmes, each lasting 10-15 minutes, depending on the speed of the child's response.

Table 6.4: An overview of a week 1 training programme for children in the AT group

Day	Training 1 (15 min)	Training 2 (15 min)
Monday	TATP_1	Story-in-Noise 1
Tuesday	DOGGY_1	Story-in-Noise 1
Wednesday	TATP_2	Story-in-Noise 1
Thursday	WHO-IS-RIGHT	Story-in-Noise 1
Friday	TATP_3	Story-in-Noise 1

Note. The above training schedule was repeated for 12 weeks with different tasks being pre-programmed in each listening game.

As noted before, the frequency and duration of training varied greatly in previous studies. Thirty minutes per day for 5 days per week was thought to be manageable by parents at home. A critical amount of training per day is needed to transfer from procedural to perceptual learning, but training beyond that critical amount yields no additional learning on the trained condition (Wright & Sabin, 2007). Although we do not know what duration training is necessary for the kinds of skills we hoped to train, we kept all the listening games to 15 minutes in this study. We believed that this training duration was about right to sustain a child's best attention on one game.

6.3.7.6 Monitoring of compliance

To promote compliance with training, the parents were advised to reward the child upon the completion of each training session with a small token (e.g. stickers) or some fun activities (e.g. playing computer games, outdoor games). Other measures to monitor compliance included: (1) the parents keeping a log book of the training dates, (2) the PI keeping in touch with the parents in every fortnight, and (3) the training data being stored in the computer. Upon the conclusion of the training programme, the PI retrieved the training data from each participant's computer and counterchecked with the training dates recorded in the parents' log book. On average, most participants completed more than 80% of the targeted training sessions for each listening game (see Table 6.5), while only a few of them (ID: 5, 22 and 35) completed less than 50% of the training on some of the listening games.

Table 6.5: The number of training sessions for each listening game retrieved from each participant's computer (AT group only)

Participant ID	Listening Games			
	DOGGY (12 sessions)	*Who-Is-Right* (12 sessions)	*Story-In-Noise* (60 sessions)	TATP (36 sessions)
2	12	12	60	36
*5	5	9	24	21
11	12	12	60	36
12	12	12	60	36
14	8	9	50	33
18	12	12	60	36
20	12	12	50	18
*22	12	12	23	18
23	18	11	20	36
26	12	12	60	36
29	12	12	60	36
31	12	12	60	36
34	12	12	60	36
*35	9	5	24	15
39	10	9	55	30

Note. Five participants' (ID: 1, 3, 9, 24, and 38) data were not available because of technical problems with the computers.

* These children completed less than 50% of the training sessions on some of the listening games.

6.4 Data analysis

Statistical analysis was conducted using the *SPSS* version 19.0. All the quantitative data were examined for distribution types and outliers. Normal distributions were obtained for the LiSN-S speech reception thresholds, baseline language (*CELF-4*) and NVIQ (*TONI-3*) scores. The data from other baseline measures, i.e. *PhAB*, *TAPS-R*, and questionnaires scores were mostly non-normally distributed. To ensure that the characteristics of the participants from both groups were comparable at baseline (pre-intervention), a series of separate t-tests and Mann-Whitney tests were performed to assess for potential differences between the groups.

To answer the main research questions, a mixed design ANOVA was used to compare the changes in AP skills from pre-intervention to post-intervention, between the AT and control groups. Then, a repeated measure ANOVA was performed to evaluate the sustainability of any improvements obtained from the intervention. Finally, a series of separate Spearman Rho correlation tests were performed to examine the relation between changes in the AP (as measured in LiSN-S test) and changes in the functional listening skills (as measured by questionnaires), and the relation between training outcome (gain in AP skills) and baseline measures in the AT group.

6.5 Results

6.5.1 Subject characteristics

All the 39 participants in this study were diagnosed with APD on the basis of failure in at least two of the behavioural AP tests. These participants were randomly assigned to AT (n=20) and control (n=19) groups. The average age for participants in the AT and control groups was 9.1 years (SD = 1.33) and 9.0 years (SD = 1.32) respectively, with no statistical difference found between the two groups [*t* (37) = 0.34, *p* = .74].

A summary of the baseline data for the AT and control groups is shown in Table 6.6. The two groups were comparable in terms of their AP, language, phonological skills, NVIQ and auditory memory, with no significant differences found between the groups in all these baseline measures.

Table 6.6: A summary of the baseline data (AP, language, phonological skills, memory and NVIQ) for the AT and control groups

Non-normally distributed measures		**AT, n = 20**		**Control, n = 19**		
		Median	**Range**	**Median**	**Range**	**p-value**[1]
Behavioural AP	**DDT_R** [a]	88	66-98	90	24-98	.91
	DDT_L [a]	84	68-96	85	42-93	1.00
	FPT_R [a]	80	7-100	76	25-100	.91
	FPT_L [a]	80	33-100	76.5	25-100	.71
	DPT_R [a]	50	10-100	40	10-100	.59
	DPT_L [a]	60	0-100	51.50	0-90	.52
	RGDT [b]	8.75	3-25	6.75	3-25	.30
	MLD [c]	12	4-14	12	4-18	.84
Phonological awareness (PhAB)	**Alliteration**	100	77-101	96	76-101	.08
	Rhyming	93	69-113	92	69-113	.99
	Spoonerism	103	71-119	106	69-128	.72
	Nonword reading	109	93-131	115	84-131	.79
Auditory memory (TAPS-R)	**ANFM**	97	79-127	92	72-133	.87
	ANBM	100	81-130	98	76-118	.55
	AWM	90	70-100	85	72-116	.97
	ASM	91	70-110	87	72-110	.79
Normally distributed measures		**Mean**	**SD**	**Mean**	**SD**	**p-value**[2]
Language (CELF-4)	**Core language**	85.6	13.3	79.5	15.6	.20
Nonverbal IQ (TONI)	**NVIQ score**	108.0	13.4	109.7	13.7	.69

ANBM = auditory number backward memory; ANFM = auditory number forward memory; ASM = auditory sentence memory; AWM = auditory word memory; DDT = dichotic digits test; DPT = duration pattern test; FPT = frequency pattern test; MLD = masking level differences; RGDT = random gap detection test; R = right ear; L = left ear, [1] Mann-Whitney test; [2] t-test.

Note. Unless stated otherwise, value is standard score. [a] score in %; [b] score in ms; [c] score in dB;

6.5.2 Changes in AP skills (objective measures) following training: Between-group analysis

The LiSN-S performance was evaluated in 4 listening conditions: DV90, SV90, DV0, and SV0. The distributions of the pre- and post-intervention LiSN-S performance of the AT and control groups are shown in Figure 6.7. Of note, a negative sign in SNR indicates that the competing speech (distractor) is more intense than the target speech; hence, the more negative the value of the SNR, the better the listener is performing. It can be seen that the listening skills of children in both groups became poorer when the LiSN-S conditions became more challenging (from DV90 to SV0).

A mixed design ANOVA was conducted to compare the LiSN-S performance of the AT and control groups at pre-intervention, with the group as the between-subject variable and the LiSN-S conditions as the within-subject variable. There was no significant interaction effect noted between the condition and group, *F* (3, 111) = .73, *p* = .53, indicating that the performance in the 4 LiSN-S conditions did not differ between the groups at baseline.

To examine the training effect after 3 months, a mixed design ANOVA was performed with the different time points (baseline and post-3-months) and the LiSN-S conditions as the within-subject variable, while the group remained as the between-subject variable. The results revealed a significant interaction effect between the time of testing and the group, *F* (1, 37) = 27.95; *p* < .001; partial eta squared [4]= .43. This indicates that the changes of LiSN-S performance between baseline and post-3-months differed in the AT and control groups. By comparing the changes in the 4 LiSN-S conditions separately between the groups (Table 6.7), it can be seen that the AT group showed greater improvement than the control group in all LiSN-S conditions.

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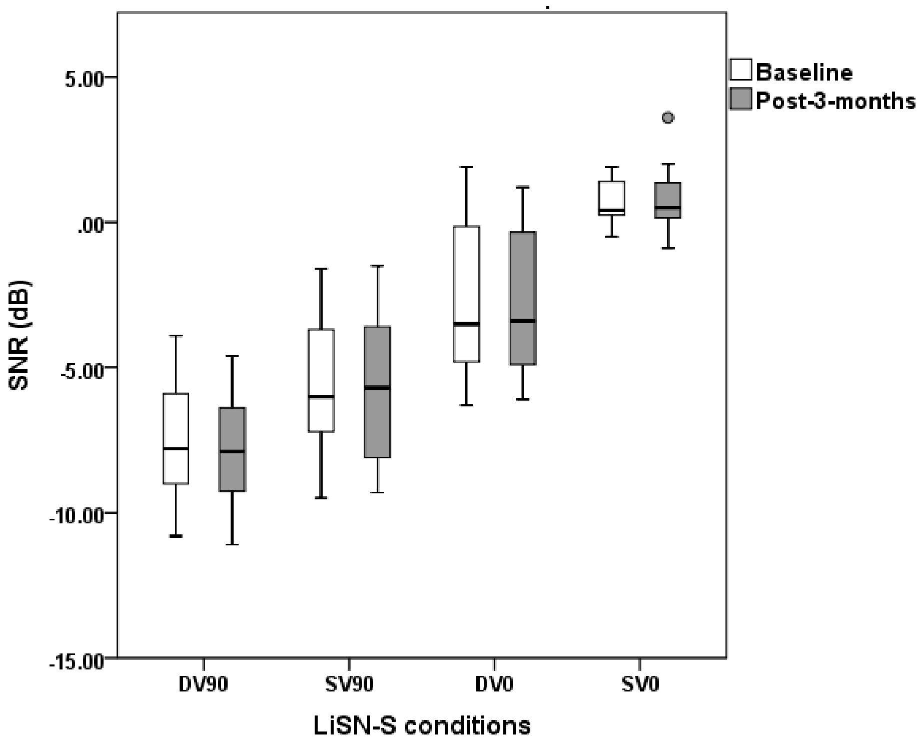
[4] Partial eta squared = effect size.

Figure 6.7: Boxplots showing the LiSN-S performance of the AT and control groups at baseline and post-3-months (or post-intervention).

Control Group



AT Group

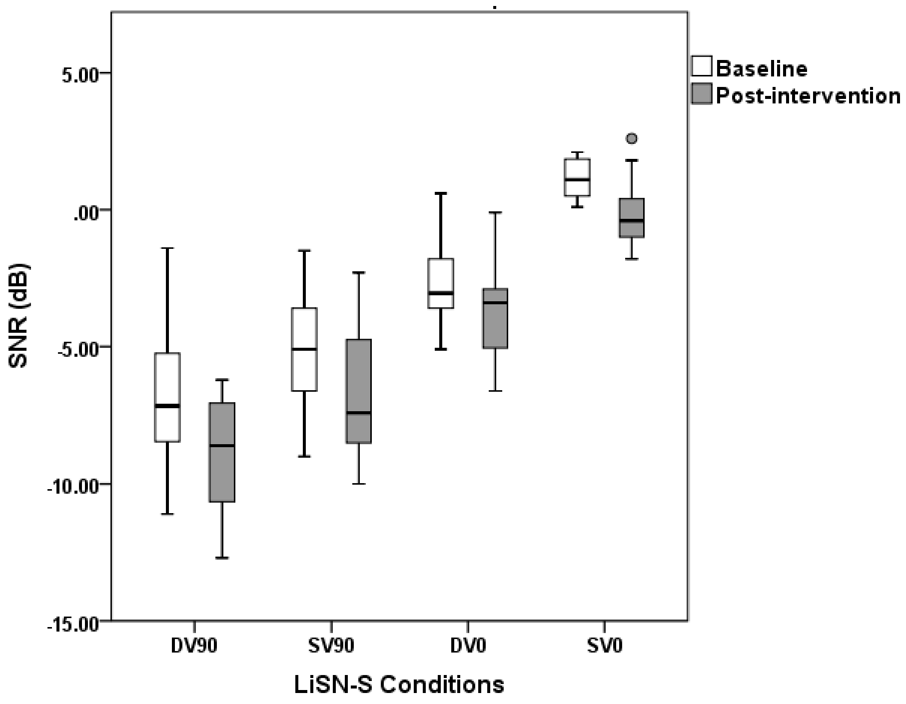
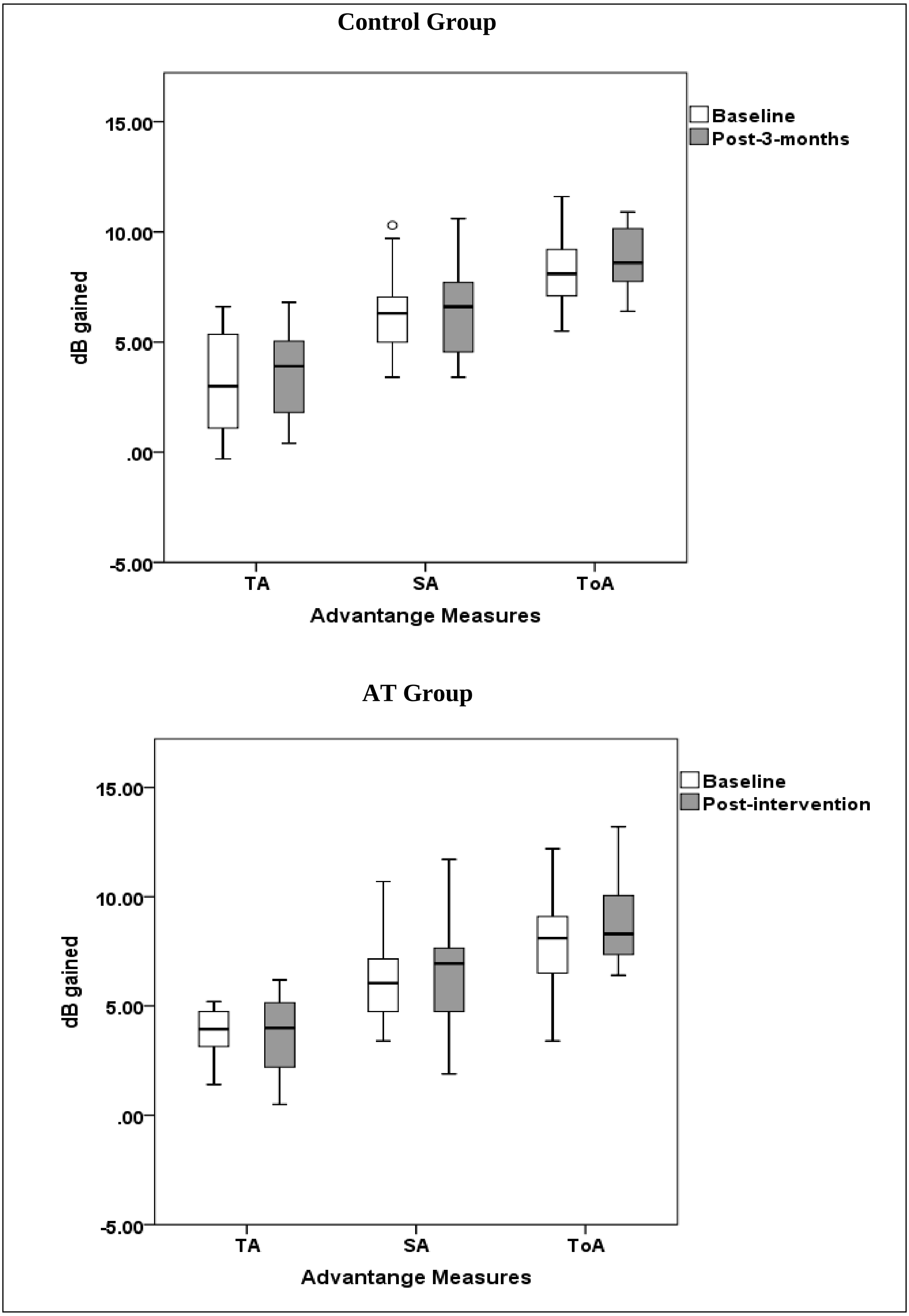


Table 6.7: A summary of group effect for each LiSN-S condition

LiSN-S Conditions	Mean difference between baseline and post-3-months (dB difference)		Partial Eta Squared, η_p^2
	AT Group	Control Group	
DV90	-2.05	-0.37	.29
SV90	-1.55	0.04	.31
DV0	-1.01	-.026	.09
SV0	-1.22	0.11	.37

The LiSN-S performance of the two groups can also be examined in the three derived advantage measures as shown in Figure 6.8. A mixed design ANOVA was performed to compare the differences between the two groups, with the three derived measures at different time points (baseline and post-3-months) as within-subject variable. The results showed no significant interaction between the time of testing and the group, F (1, 37) = .02; p = .90, indicating that the changes in the advantage measures between baseline and post-3-months are similar in the AT and control groups.

Figure 6.8: Boxplots showing the performance of the AT and control groups in the three advantage measures (TA = Talker Advantage; SA = Spatial Advantage; ToA = Total Advantage).

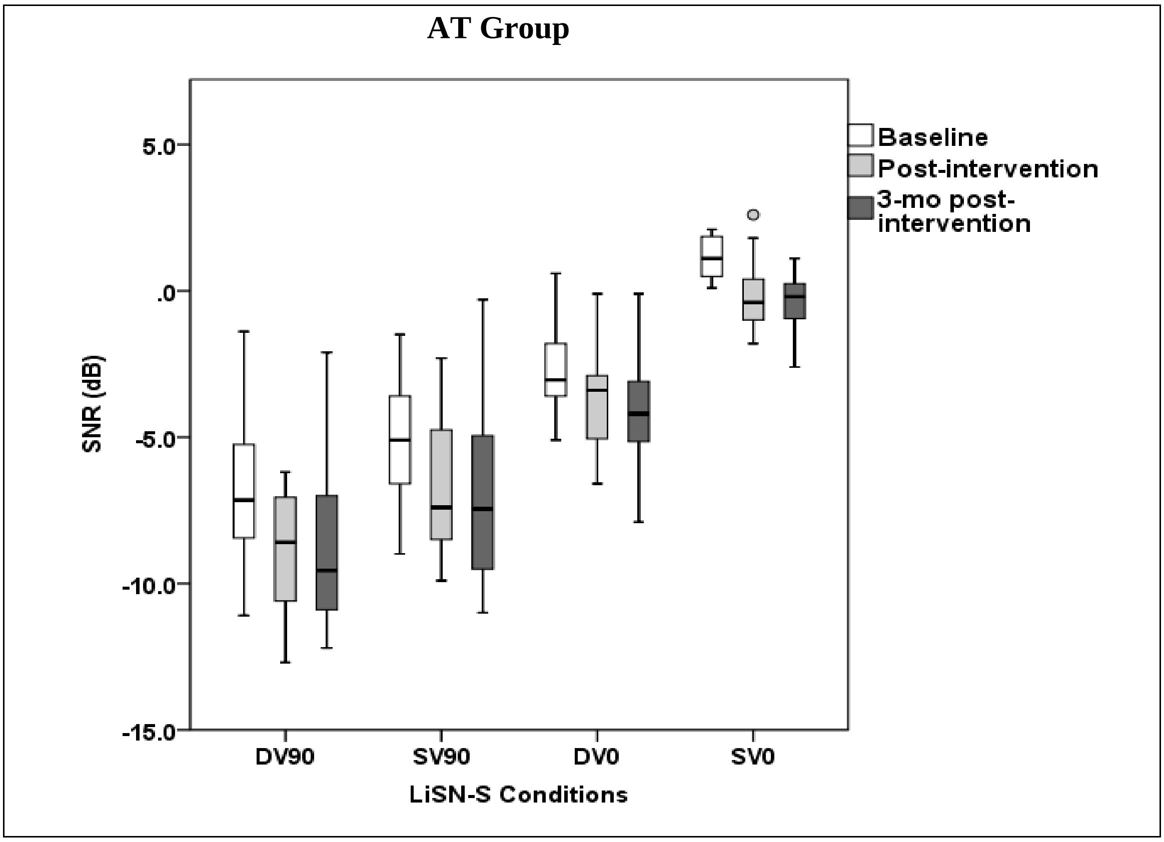


6.5.3 Changes in AP skills over time: Within-group analysis (AT group only)

The boxplots in Figure 6.9 show the AT group performance in the 4 LiSN-S conditions across different time points. The results from repeated-measures ANOVA revealed a significant main effect of time on the LiSN-S performance, *F* (1, 38) = 23.80; *p* < .001; partial eta squared = .56, indicating that the LiSN-S performance differed at different time of testing. Helmert contrast was used to compare the mean of LiSN-S scores at each time point to the subsequent time points. The results showed significant difference in the LiSN-S scores between the baseline and the subsequent testing points (post-intervention and 3-month post-intervention), *F* (1, 19) = 93.41; *p* < .001; partial eta squared = .83, but no significant difference in the LiSN-S scores between immediately post-intervention and 3-month post-intervention, *F* (1, 19) = .49; *p* = .49. This suggests that the improvement was sustained for at least 3 months with no further significant changes after the end of intervention.

There was also no significant interaction effect noted between the conditions and time of testing, *F* (1, 37) = .02; *p* = .90, indicating that the changes in LiSN-S performance over time did not differ among the conditions.

Figure 6.9: Boxplots showing the changes of LiSN-S conditions (DV90, SV90, DV0, and SV0) over a period of 6 months (AT group only).



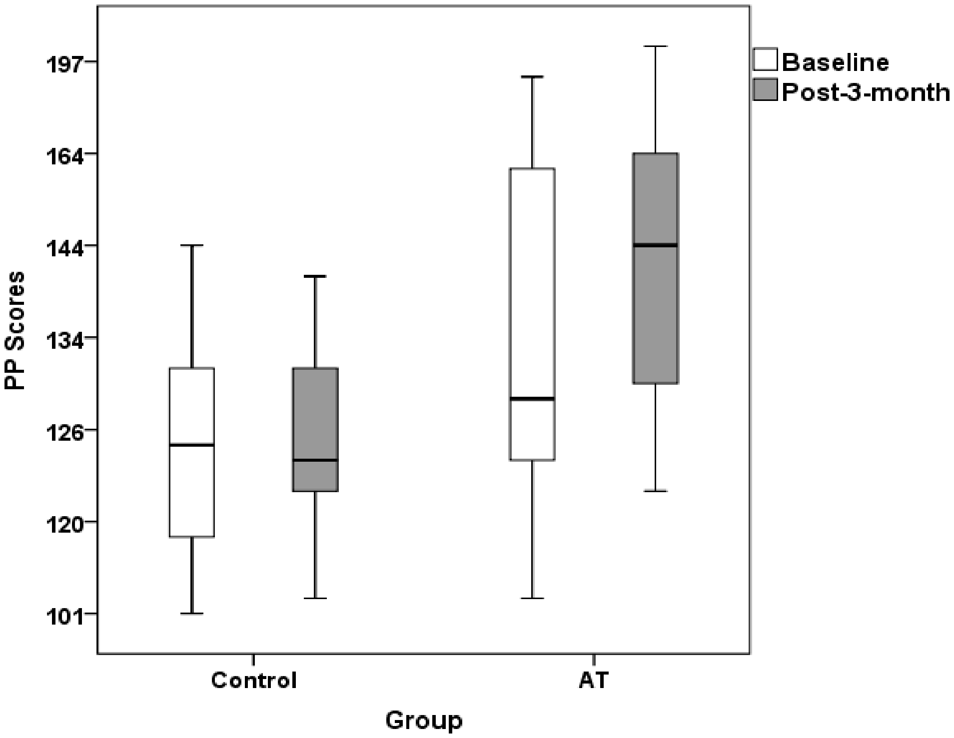
6.5.4 Changes in functional listening skills (subjective measures) following training: Between-group analysis

a) <u>Pragmatic Profile - PP</u>

The parents of all participants were asked to fill out the PP questionnaire twice, once at baseline and another time at post-3-month. Six of the questionnaires (2 from the AT group; 4 from the control group) were incomplete with more than one question rated as 'not applicable'; hence, the raw scores were not tabulated. Therefore, the following analysis was based on 33 questionnaires only.

The boxplots in Figure 6.10 show the distribution of PP raw scores for the AT and control groups at baseline and post-3-month (post-intervention). The higher the score, the better the observed behaviour is. Results from the Mann Whitney tests showed no significant difference between the AT and control groups in terms of the PP raw scores at baseline (*U* = 91.5, *z* = -1.575, *p* = .115), but the two groups did differ significantly at post-3-month (*U* = 43.0, *z* = -3.330, *p* = .001).

Figure 6.10: Boxplots showing the distribution of PP raw scores as rated by the parents of AT and control groups at baseline and post-3-month.



The difference between the baseline and post-3-month PP raw scores of the AT group was further compared to that of the control group using an independent t-test. There was a significant difference in the mean score differences between the AT (mean score difference = 9.94, SD = 9.93) and control (mean score difference = 1.67, SD = 5.97) groups [t (31) = 2.83, p = .008 (two-tailed)]. The magnitude of the differences between the two groups (mean difference = 8.28, 95% CI: 2.31-14.25) was large (eta squared = .205), suggesting that changes in the PP scores of children from the AT group were significantly greater than those of the control group.

b) *Children's Auditory Performance Scale – CHAPS*

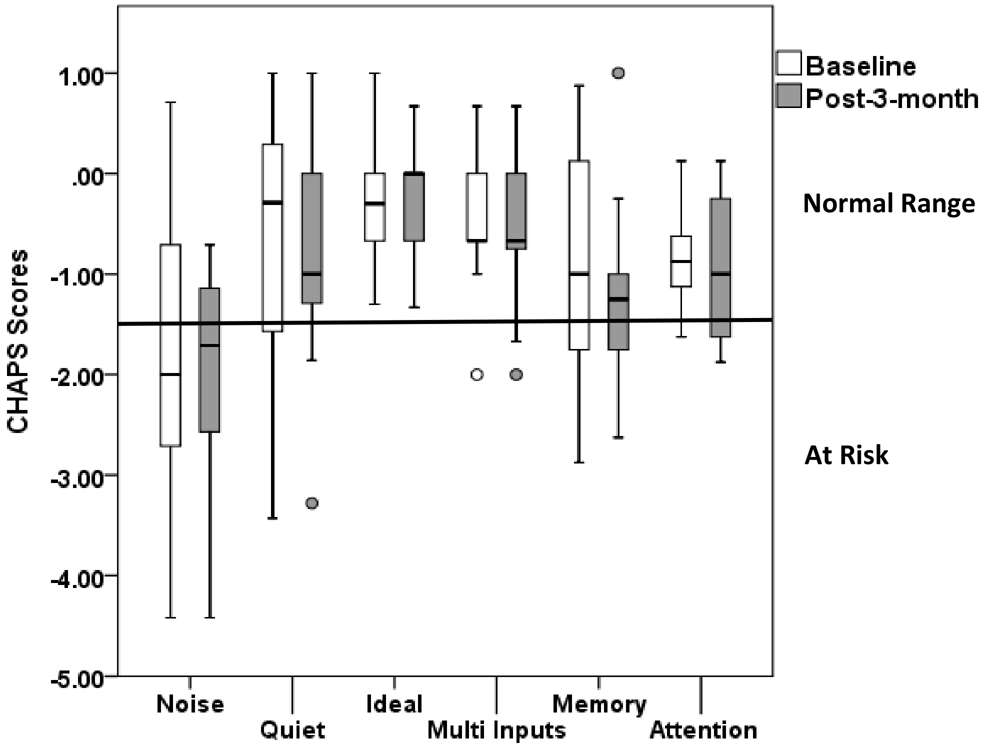
The CHAPS questionnaire was given to each participant's teacher to be filled out at baseline and at post-3-month. Four questionnaires from the AT group and 2 from the control group were excluded from the following analysis, as some of the questions were unrated and therefore, the subscores could not be tabulated.

The boxplots in Figure 6.11 show the subscores of the 6 auditory conditions in the CHAPS questionnaire for the AT and control groups at baseline and post-3-month. A total score is calculated from the average of the 6 subscores. Of note, a value ranging from +1 to -1 is considered within the normal range, while -1.5 to -5.0 is considered below normal range (at risk).

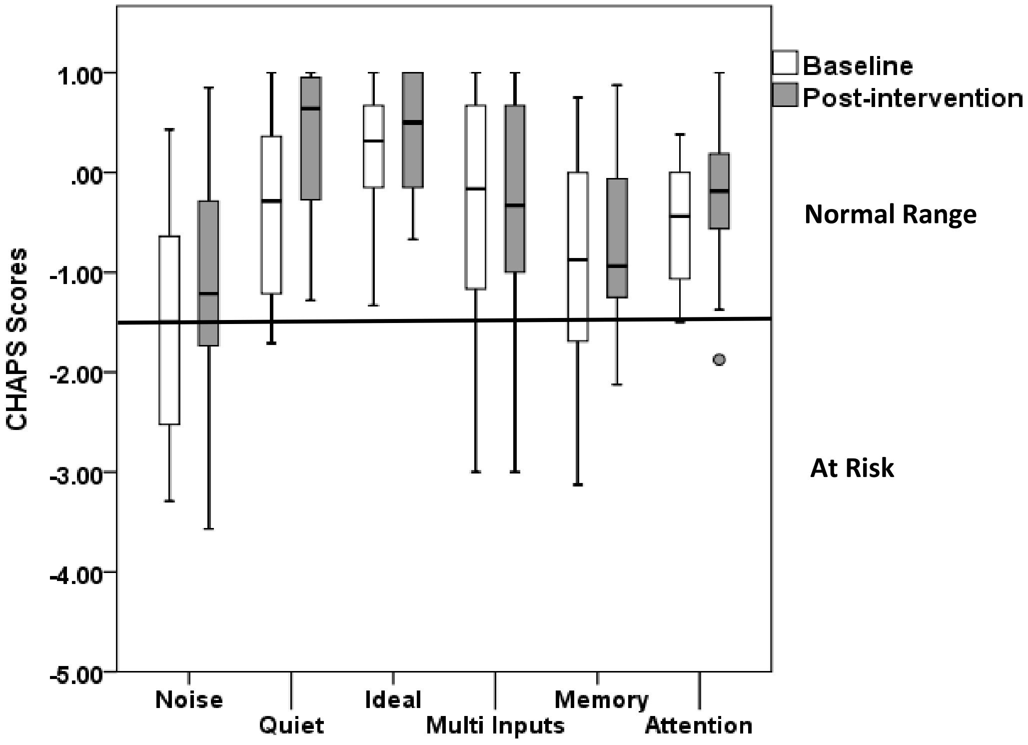
At baseline, both AT and control groups were rated relatively poorer in noise as compared to other auditory conditions. At post-3-month, the CHAPS subscore in noise for most cases in the AT group has improved to the normal range; while the control group continued to have listening concerns in noise.

Figure 6.11: Boxplots showing the distributions of the six subscores in CHAPS questionnaire for the AT and control groups at baseline and post-3-month

Control Group

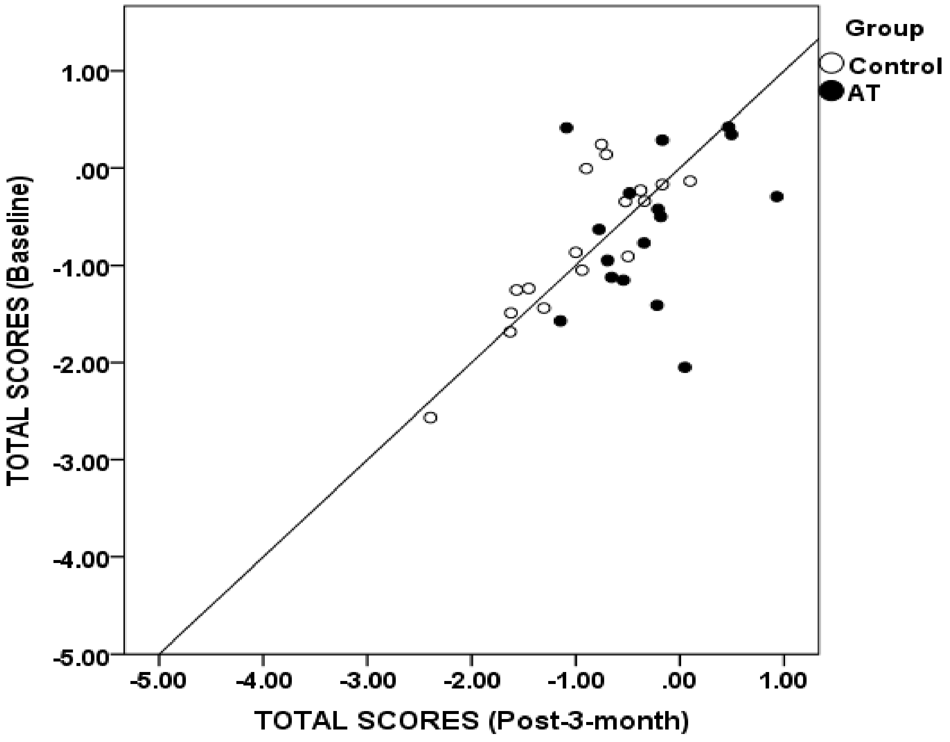


AT Group



The distributions of the CHAPS total scores for the AT and control groups at baseline and post-3-month are shown in Figure 6.12. The scatterplot shows that most children in the AT group had higher total scores at post-3-month relative to the baseline, whereas many of the children in the control group had little changes in their total scores after 3 months.

Figure 6.12: Scatterplot showing the distribution of CHAPS total scores for the AT and control groups at baseline and post-3-month. The diagonal straight line represents the reference line.



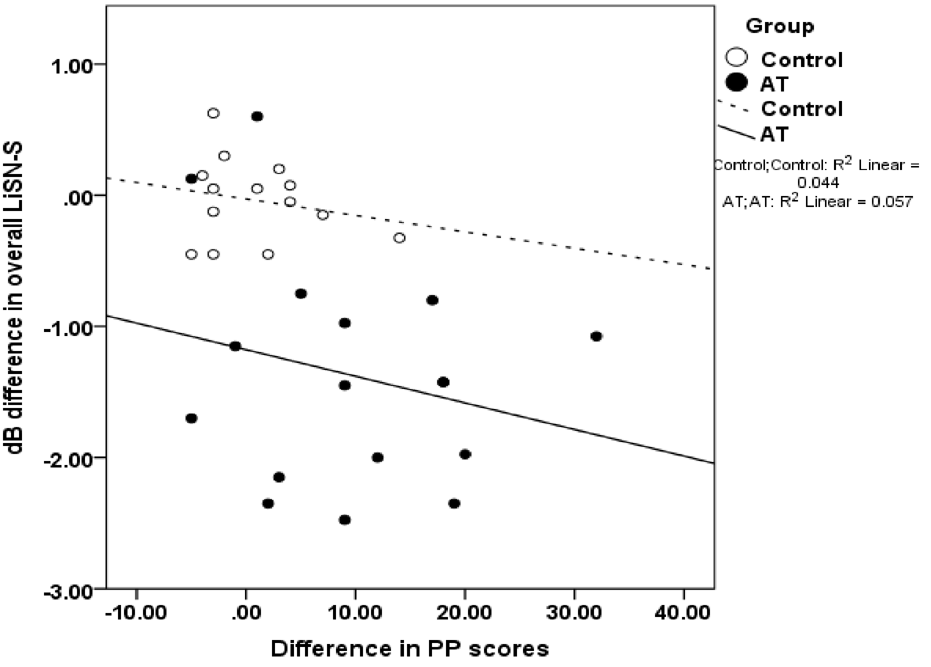
To examine whether changes in the CHAPS subscores over time in the AT group were truly greater than the control group, a mixed design ANOVA was performed. The CHAPS auditory conditions (noise, quiet, ideal, multiple input, auditory memory and auditory attention) and time (baseline and post-3-month) served as the within-subject variables, and the group as the between-group variable. The results revealed no significant interaction effect between the CHAPS conditions and group, *F* (4.2, 130.2) = 1.03; *p* = .39, indicating that the subscore in each CHAPS condition did not differ between the AT and control groups. However, there was a significant interaction effect noted between the time and group, *F* (1, 31) = 4.87; *p* = .035; partial eta squared = .14, indicating that the changes in the CHAPS subscores over different rating time points differed between the two groups. These results suggest that the two groups were comparable in the CHAPS ratings at baseline but differed significantly after 3 months, with the AT group scored better than the control group as proven by the higher CHAPS total scores in the former (mean score = -0.29, SD = 0.57) than the latter group (mean score = -0.95, SD = 0.65) at post-3-months.

6.5.5 Correlation between changes in AP skills and changes in functional listening abilities of children with APD

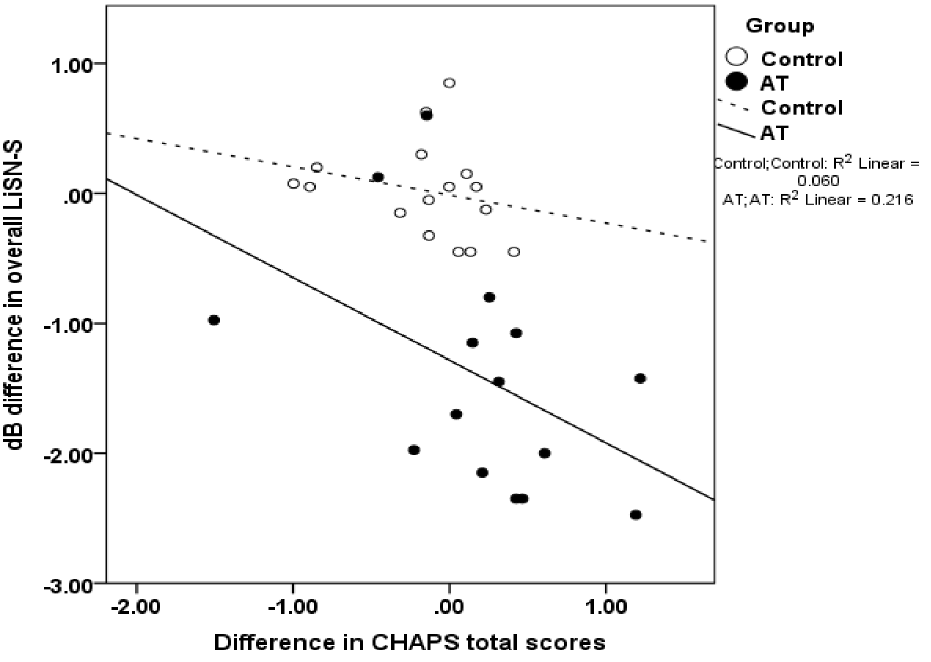
To examine the relation between the changes in the overall LiSN-S performance and the changes in the PP and CHAPS questionnaires scores after 3 months, scatterplots are presented in Figure 6.13. The overall LiSN-S performance was obtained from the average of the 4 LiSN-S conditions. Looking at the scatterplots, there appeared a trend of inverse relationship between the changes in the overall LiSN-S performance and the changes in both the questionnaires scores. However, separate Spearman rho correlation tests revealed that this relationship reached statistical significance only in the AT group with CHAPS questionnaire (*r* = -0.55; *p* = .03). This implies that when the AP skills improved (more negative value in the changes in the overall LiSN-S), the functional listening skills of the children, as rated by the teachers also improved (more positive value in the difference in CHAPS total scores).

Figure 6.13: Scatterplots showing the individual participants' changes in the overall LiSN-S performance versus changes in the PP and CHAPS questionnaires scores between baseline and post-3-month.

LiSN-S difference vs PP scores difference



LiSN-S difference vs CHAPS scores difference



6.5.6 Correlation between training outcome and baseline measures

To investigate whether the amount of improvement in AP skills made through intervention has any relation with other underlying factors, individual participants' changes in the overall LiSN-S performance were plotted as a function of the baseline LiSN-S performance, core language, nonverbal IQ, auditory memory and phonological skills (Figure 6.14). Of note, three outliers (2 from the AT group, 1 from the control group) were deleted from the scatterplots shown below.

Figure 6.14: Scatterplots showing the distribution of participants' changes in LiSN-S performance after intervention versus baseline LiSN-S performance, core language, nonverbal IQ, auditory memory and phonological skills.

LiSN-S difference vs Baseline LiSN-S Performance

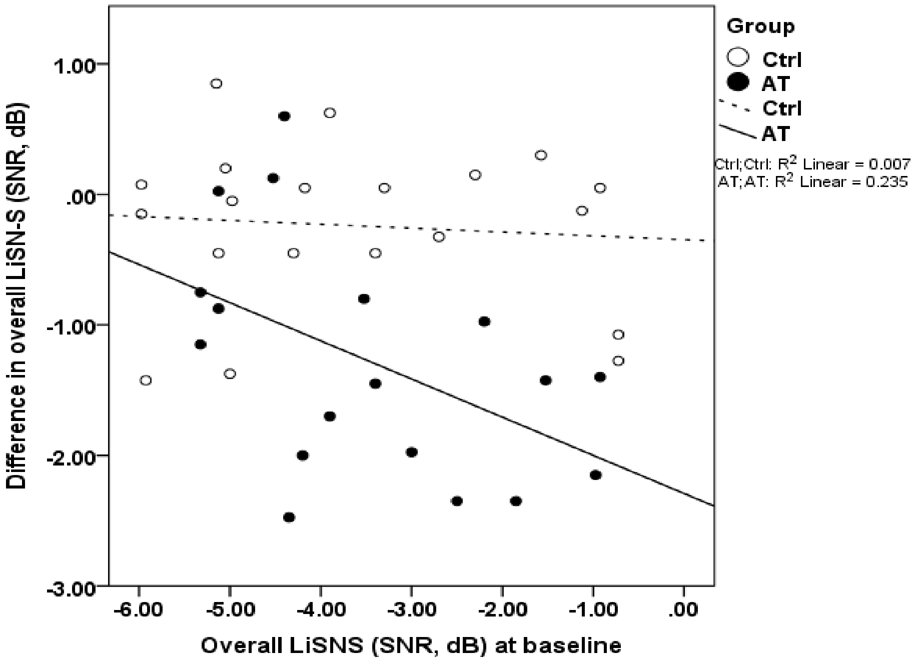
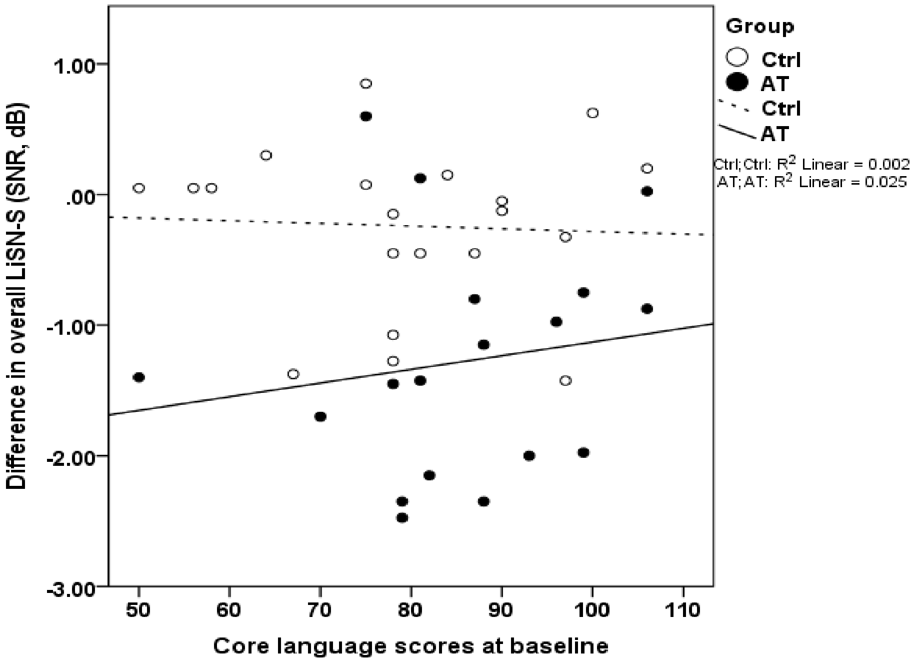


Figure 6.14 (continued): Scatterplots showing the distribution of participants' changes in LiSN-S performance after intervention versus baseline LiSN-S performance, core language, nonverbal IQ, auditory memory and phonological skills.

LiSN-S difference vs Baseline Core Language



LiSN-S difference vs Baseline Nonverbal IQ

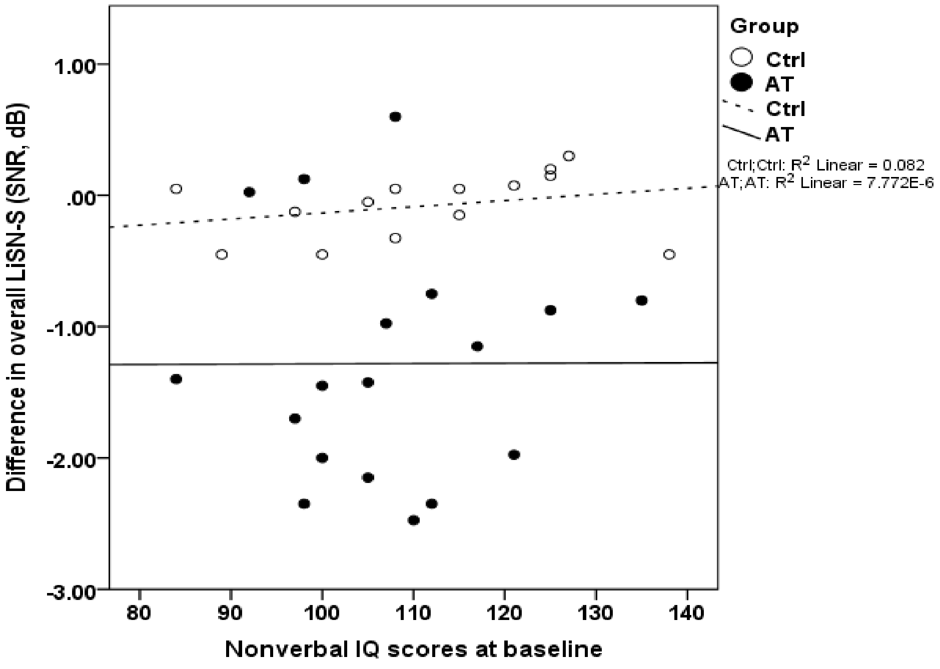
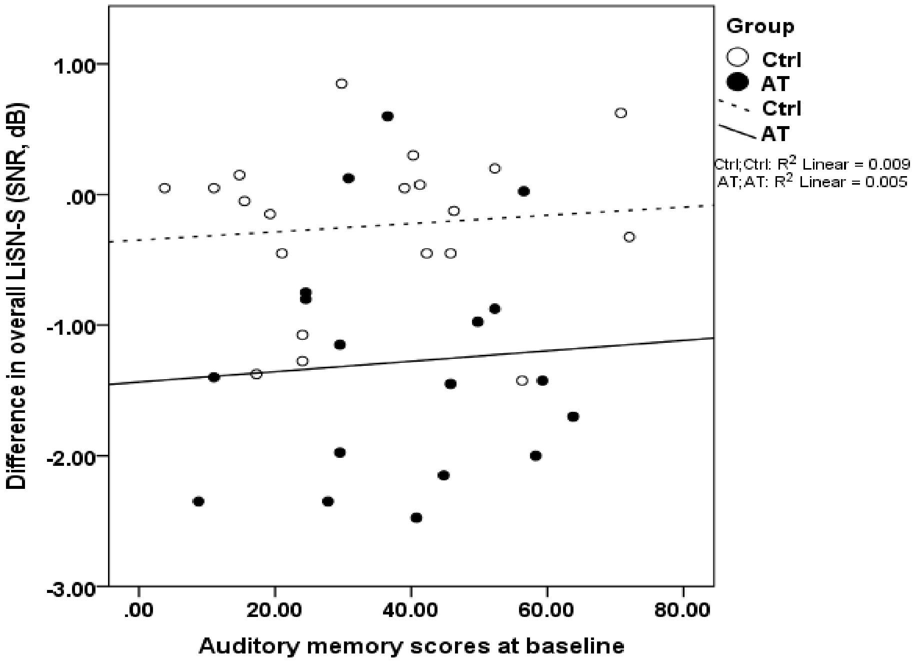
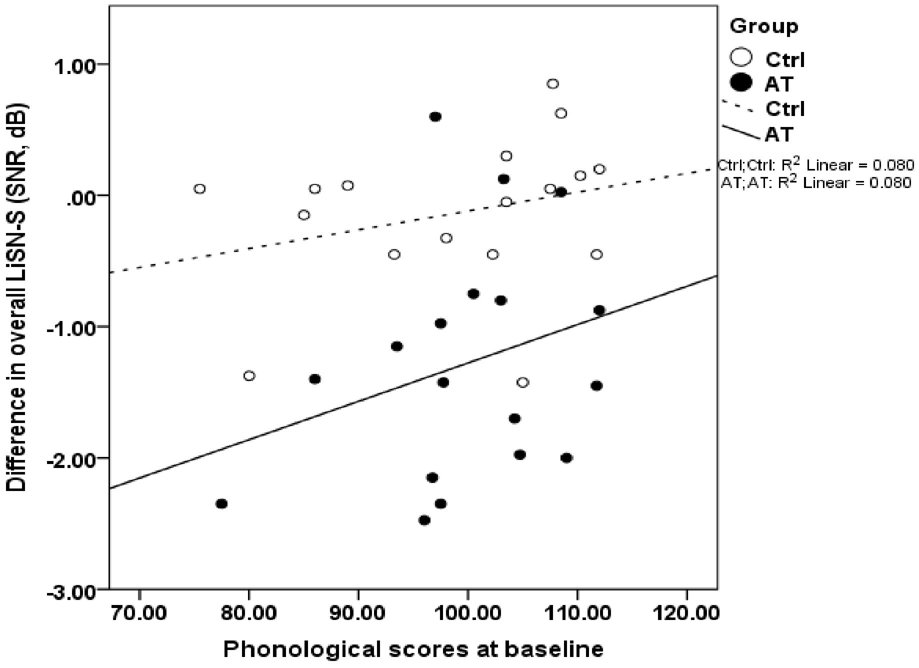


Figure 6.14 (continued): Scatterplots showing the distribution of participants' changes in LiSN-S performance after intervention versus baseline LiSN-S performance, core language, nonverbal IQ, auditory memory and phonological skills.

LiSN-S difference vs Baseline Auditory Memory



LiSN-S difference vs Baseline Phonological Skills



Based on the scatterplots, neither the language, i.e. core language and phonological skills, nor the cognitive abilities, i.e. nonverbal IQ and auditory memor, appear to have any direct relations with the changes in the overall LiSN-S performance. However, the baseline AP skills is significantly correlated with the changes in the overall LiSN-S performance (Spearman rho r = -0.52, p = 0.03), indicating that children with poor LiSN-S performance at baseline gained more after intervention as compared to those initial good performers.

6.6 Discussions

The LiSN-S test was used as the primary outcome measure in this study because it is a direct measure of auditory behaviour, particularly assessing an individual’s ability to extract meaningful speech from the various distracting acoustic signals. Unlike the traditional AP test battery, in which performance often reaches ceiling, the LiSN-S performance is measured in SNR and thus, allows changes to be measured over a much wider range. While local norms are not available for the LiSN-S tasks (norms established in one country cannot be readily transferred to others), individual participants’ baseline scores served as reference for the post-intervention comparisons. Hence, the drawback is that we were unable to determine whether the APD children in this current study had any speech-in-noise deficits per se.

Nonetheless, it is noteworthy that the LiSN-S performances of children in this current study are consistent with the general performing trend reported in the study by Cameron and Dillon (2008) – the developers of LiSN-S test, in which children had the worst listening skills in the low-cued condition (SV0) but the best in the high-cued condition (DV90). Similarly, children in the current study had the highest gain in the ToA and followed by the SA, and the least in the TA. However, without any typically developing normal listeners serving as controls in the current study, we were unable to address whether children with APD had specific deficits in spatial processing as reported by Cameron and Dillon (2008). In that study, the authors reported that children with suspected APD (n = 9) performed significantly poorer than listeners who were typically-developing (n = 70) or those had a number of specific disabilities (n = 11) in conditions where the target speech was spatially separated from the distracter speech (e.g. DV90 condition, SA and ToA). In other words, these children with suspected APD were unable to make use of the spatial cue in binaural hearing to suppress background competing noise, and this deficit is defined as *spatial processing disorder* (SPD; Cameron and Dillon, 2008). However, this pattern of findings has yet to be reported by other researchers.

6.6.1 Did children's AP skills improve after a 3-month CBAT intervention?

The current study revealed that children with APD who had undergone AT showed greater changes in their AP skills than that of the untrained controls; these changes are reflected as improvement across the four LiSN-S listening conditions (Figure 6.7). This suggests that the CBAT intervention developed for the current study, which incorporated a wide variety of noise maskers presented in various conditions, is effective in improving the AP skills of children with APD, particularly the speech-in-noise perception.

Speech-in-noise perception involves complex processing that requires bottom-up (sensory) and top-down (cognitive) processes (Anderson & Kraus, 2010a). When an individual is required to listen for speech against other competing speech (e.g. in a cocktail party), auditory scene analysis takes place in the brain – a process whereby complex acoustic signals are segregated into an auditory stream and an auditory object is formed in the scene (Bregman, 1990). This process allows the listener to track different aspects of the target speech, i.e. the fundamental frequency (F0) contour, the timing and timber, to separate them from the competing speech, and to collectively form a perceptual representation of the acoustic entity (e.g. tag it with particular speaker's voice) in a dynamic auditory environment (Bregman, 1990; Synder & Alain, 2007; Anderson & Kraus, 2010; Fishman & Steinschneider, 2010). This sensory-cognitive linked process that occurs at both cortical and subcortical level (Anderson & Kraus, 2010b; Deike, Scheich, & Brechmann, 2010), to some extent, can be improved via training.

The benefits of CBAT with noise have been reported in typically developing listeners in a few recent studies (e.g. Song, Skoe, Banai, & Kraus, 2011; Millward, Hall, Ferguson, & Moore, 2011). Song and colleagues (2011) reported significant improvement in the speech-in-noise perception of 28 young adults after undergoing a commercially available CBAT programme (*LACE;* Neurotone, Inc., 2005) for 4 weeks (5 sessions a week). The training-induced improvement in the speech-in-noise perception was also accompanied by an enhancement of the neural representation of pitch-related cues in noise at the subcortical level, i.e. auditory brainstem, in which these perceptual and neurophysiological changes were not observed in the untrained controls (n = 32). The authors, however, commented that they were unable to tease out the overall improvement was driven by a specific training programme or the cumulative effects of all exercises, as the *LACE* programme consisted of speech-in-noise training tasks, i.e. sentence in multitalker noise and speech with competing speaker, as well as other tasks that trained cognitive skills and communication strategies.

In the study by Millward and colleagues (2011), typically-developing children who were trained either with tones (n = 10) or single words (n = 11) in modulated speech-shaped noise were found to show significantly greater improvement in sentence perception in modulated noise than the untrained controls (n = 10) or those trained with tones only (n = 10). Training with a speech stimulus was found more effective than a non-speech stimulus, as the group trained with word stimuli in noise performed better in sentence perceptions in both modulated and non-modulated noise; whereas the group trained with tone in noise only improved in speech perception in modulated tone. Hence, the authors suggested that similarities in the stimulus dimensions between training tasks and outcomes promote better transfer of the trained skills (Millward, Hall, Ferguson, and Moore, 2011).

This notion appears to be generally true. The finding from another recent CBAT outcome study by Cameron and Dillon (in press) seemed to support the suggestion by Millward and colleagues. The *LiSN & Learn* programme designed by Cameron and Dillon incorporates spatial cues in the AT to specifically remediate SPD. The training paradigm and stimulus dimensions (sentences as the target, and distracter stories as the masker) used in the *LiSN & Learn* programme are very similar to that of the LiSN-S outcome measure. A preliminary study showed significant improvements at post-training in 9 children with SPD. In particular, these children improved significantly in the LiSN-S measures that involve spatial cues (e.g. DV90, SA and ToA) but not in those without (e.g. SV0 and TA) (Cameron and Dillon, in press). While these results appeared to suggest that the *LiSN & Learn* training has a specific treatment effect in remediating SPD, but no untrained controls were included to tease out any maturational or practice effects. Moreover, the same female voice was being used as the target voice in training and outcome measure; it is thus unclear if the improvement shown was the result of task familiarity (learning about the voice of a particular talker).

In the current CBAT programme, in spite of just training general listening skills for speech in various background noises, one of the listening games did train listening with specific cues. This particular listening game – the *DOGGY*, has many similarities to the LiSN-S test, in which the target speech and masker noises were manipulated with respect to its location using head-related transfer functions (HRTFs). A three-dimensional listening environment was produced with some tasks involving spatial and/or talker cues in aiding listening, while others had minimal cues (as shown in Table 6.3). This training is believed to have helped, to a large extent, in improving the listening skills of children in the AT group, particularly listening in the DV90, SV90 and DV0 conditions.

The fact that the AT group in the current study also improved significantly in the low cue listening condition (SV0) is noteworthy, as the same result was not reported in the study by Cameron and Dillon (in press) despite the close similarity between the training tasks and outcome measure. We speculate that the intensive and broad training paradigm (speech-in-noise and dichotic listening) in the current study have not only trained and improved the sensory aspect of speech-in-noise perception, but also the cognitive processes, i.e. attention and memory in general, which these skills subsequently benefit the children in performing any of the tasks at post-intervention. Even though attention was not measured directly in the current study, verbal feedback from the majority of the parents revealed improvement in their child's attentiveness in daily performance after the training. In fact, improvement in general cognition and motivational skills of children following AT has been reported in several studies. For example, Steven and colleagues (2008) found that children with SLI improved significantly in the neural mechanisms of selective auditory attention after undergoing six weeks of intensive CBAT, i.e. *Fast ForWord* programme. In some studies (e.g. Gillam et al., 2008; Cohen et al., 2005), similar gain was observed in children from different intervention programmes (regardless whether it was a computer-based or interpersonally-delivered), which reflect the effect of any AT on the general attention and cognitive skills of children.

As mentioned earlier, the three advantage measures (TA, SA, and ToA) in the LiSN-S test were derived from the difference in performance between the conditions with talker and/or spatial cues (DV90, SV90, and DV0) and the low cue condition (SV0). The results clearly showed that the improvements made across the four listening conditions were about the same, thus led to no further or little increment in dB gained in the three advantage measures at post-intervention. This explains the non-significant difference found between the AT and control groups in the three advantage measures at the post-3-month reassessment. This finding has a clinical implication on the use of derived measures as outcome measure, in which it may not be sensitive enough to capture the benefits of a particular intervention.

6.6.2 Is the improvement made through intervention sustainable for at least 3 months?

The improvement made through the intervention, as reported in the AT group, was sustained for at least 3 months across the listening conditions, even though individual differences were observed. This finding is consistent with the study by Cameron and Dillon (in press), showing that children with SPD improved after training with the *LiSN & Learn* and the gain lasted for 3 months.

Few studies in the literature have attempted to determine the long term training effect of a particular CBAT intervention. This is because it is a very time consuming and resource intensive process, and it gets more challenging as the interval of follow up gets longer. The influence of other extrinsic factor (e.g. extra-curriculum, other enrichment classes) on the measured skills becomes inevitable. Of the very few CBAT outcome studies that incorporated auditory measures and included a 12-month post-intervention follow up is the study by Strehlow and colleagues (2006). In that study, children with SRD (n = 15) who had undergone phoneme training showed improvement at post-intervention, and the specific training effect remained fairly stable even 12 months post-intervention. In contrast, a comparison group of children with SRD (n = 14) who had undergone sound processing training did not show a long term specific training effect despite making pronounced improvement immediately post-intervention. No significant improvement was noted either in the phoneme or sound processing in the untrained control group with SRD (n = 15). The results suggest that different training materials may have different impacts on the long term treatment effect.

In the current study, follow up was made only at the 3-month post-intervention. Hence, we were unable to determine if the improved AP skills of children in the AT group would remain stable over the next 12 months. This is a limitation of the current study, and it has an implication for the management of children with APD, whether to continue further with other CBAT or a need for referral to a speech-language therapist for continuous therapy. Future research will need to consider a longer post-intervention follow up point.

6.6.3 Did the functional listening skills of children improve after 3-month of CBAT intervention?

A critical question to consider when evaluating the effectiveness of a particular intervention programme is the impact on real-world listening. The functional listening abilities of children in the current study were measured using two validated questionnaires: the PP and CHAPS filled out by the parents and teachers respectively.

In overall, children who had undergone the training showed significantly better PP and CHAPS total scores than those untrained controls, suggesting improvements in the functional abilities of these children. While the improved PP scores are debatable, that it could be the result of parental bias (as the parents were aware of their children’s participation in the intervention thus rated those skills higher on the basis of no evidence), the improvement in the CHAPS total scores as rated by the teachers who were blinded from the participants' intervention, suggest a generalisation effect of training to functional abilities. In particular, the benefit of CBAT can be seen from the improvements on listening in noise, as well as in quiet in the AT group (Figure 6.11).

In the study by Cameron and Dillon (in press), the children with SPD who had undergone training with the *LiSN & Learn* reported marked improvements in their own ability to listen in noise. Similarly, in the study by Tyler and colleagues (2010), positive feedback based on questionnaire was obtained from hearing impaired individuals with amplification who had completed a computerised spatially-separated speech-in-noise and localisation training programme. Taken together all these studies, including the current study, the data seems to suggest a generalisation effect of AT to functional listening abilities, despite the fact that there is potential inherent bias in the previous two studies as the subjective reports were based on participants self-rated questionnaires.

The significant moderate correlation between the changes in objective measure (the overall LiSN-S performance) and the changes in subjective measure (the CHAPS total scores) in the current study renders further support to the transfer of training to functional listening skills. In other words, the improved AP skills are consistent with the improved functional listening skills. In contrast to the PP that evaluates children's language and communication skills in context, the CHAPS questionnaire evaluates children's functional listening abilities in different auditory environments, hence deemed more relevant to the measured auditory skills. While some studies (e.g. Wilson et al., 2011; Lam & Sanchez, 2007) reported no correlation between the CHAPS subscores/total score and the clinical diagnosis of APD, the study by Iliadou and Bamiou (in press) showed otherwise. These authors commented that the CHAPS can be a clinical useful tool to evaluate listening ability in older children suspected of APD. The current study further suggests that the CHAPS questionnaire may be a sensitive tool to measure functional changes in children's listening skills after undergoing an intervention.

6.6.4 What predicts the training outcome?

Many AT studies have shown that the improvement made through training is dependent on the initial performance of the measured skill (Amitay, Hawkey, & Moore, 2005; de Boer & Thornton, 2008; Song et al., 2011), but such relationship has so far been reported only in the typically-developing listeners. To the best of our knowledge, this is the first study that presented an evidence of such relationship in a population with APD, in which children with poor initial performance in the LiSN-S test showed greater improvement than those good performers. The current study also revealed that the language and cognitive abilities of a child cannot be used to predict the outcome of an intervention, which is in agreement with the findings by Watson and colleagues (2003) that language competency, is not a direct correlate of AP skill.

The work by de Boer and Thornton (2008) helped to explain the phenomena - "*poor initial performers tended to show greater learning*" based on the neurophysiology mechanism of the efferent pathways of the central auditory system. In their study, poor speech-in-noise perception was correlated with weak neural activity of the medial olivocochlear bundles (MOCB) at the brainstem level. These authors suggested that the "antimasking [5]" mechanism could explain the observed link. It was believed that poor

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[5] Based on the antimasking model, MOCB plays an important role in reducing cochlear responses to continuous noise; hence enhances the auditory nerve responsiveness to rapidly changing acoustic signals embedded in the noise (Kawase and Liberman, 1993).

initial performers had reduced “antimasking” as reflected by weaker MOCB activity. As observed that speech-in-noise training induced significantly greater MOCB activity, and thus “antimasking” was enhanced, which resulted in the subsequent perceptual improvement. In contrast to listeners who had good initial performance as a result of stronger MOCB activity, they had already used maximal “antimasking” mechanisms from the start, therefore had a reduced range of improvement.

6.7 Limitations

There are some limitations in this study. First, despite all the participants in this study were diagnosed with APD based on the current clinical AP test battery, we were unsure if all of them had speech-in-noise deficits per se. The presence or absence of speech-in-noise deficits in participants may potentially affect the training outcomes and the conclusion of the study. Ideally, a matched-group of typically developing listeners should be included as a reference control group.

Second, the current CBAT incorporated both speech-in-noise and dichotic listening training in the programme. Thus, it is unclear if the improvement in the AT group was driven by a specific training programme or a cumulative effect of all the listening exercises. Further study would need to consider separating the two types of training to examine the effectiveness of each programme. This will help to address the question if any AT programmes are beneficial in improving an individual’s AP skills,

Finally, there were some technical issues with the software installation and the retrieval of data. Some computers with older operating system were unable to support the running of the programme fully, and consequently affected the speed of the task. In a few cases that the TATP listening game stopped working before the completion of the task. All these technical problems could affect a child's engagement on the training task and eventually loss of interest. A solution to this problem would be to design a web-based CBAT that will allow instant access and online transfer of data to the clinician.

6.8 Conclusion

In conclusion, the current self-developed CBAT intervention was proven to be effective in improving the AP skills of children with APD. In fact, it has a few advantages over the other CBAT programmes discussed earlier. First, some, but not all, training tasks in the current study shared similar stimulus dimensions (e.g. target and masker are both speech stimulus) as the outcome measure (i.e. LiSN-S test), but they differ totally in talker voice and language accent (the training tasks were in British and Singapore English accent, while the LiSN-S test was in Australian English). This eliminates the effect of task familiarity as commented in the study by Cameron and Dillon (in press) with the *LiSN & Learn* programme. The improvements reported here are thus more likely to reflect a genuine learning effect. Second, the training paradigm in the current study made use of a variety of conditions [e.g. keywords extraction in noise (*Story-In-Noise*), dichotic listening (*TATP*)]. In contrast to the *LiSN & Learn* programme that is specific to individuals with SPD, the current CBAT is suitable for training a general population with listening difficulties. Finally, speech stimuli ranging from single words to complex sentences were used in the current CBAT and therefore, the training resembles more of a real-life listening condition.

Chapter 7

Summary and Conclusions

The main focus of this thesis was to determine the benefits of a self-developed computerised AT programme as part of the intervention strategies in managing children with APD. While it remains debatable to what extent auditory intervention provides unique benefit to auditory, language or academic outcomes in contrast to language interventions (Fey et al., 2011; Kamhi, 2011), there is some initial evidence (e.g. English, Martonik & Moir, 2003; Putter-Katz et al., 2008; Moncrieff & Wertz, 2008; Cameron & Dillon, in press) to indicate that AT may remediate AP deficits. The findings from the current study further add to the literature that AT is beneficial for children with APD.

To provide the readers a review of all the work presented in this thesis, the following sections will summarise each of the studies and highlight the main findings in this concluding chapter. In addition, the main conclusions of this thesis and some suggestions for further research will be presented.

7.1 Summary for the Pilot Study

This pilot study was conducted to determine the feasibility and suitability of the various speech-in-noise training programmes developed for the main study, with the initial intention to examine if neurological abnormal individuals with APD who were associated with PAX gene mutations would benefit from the intervention.

Due to subject recruitment issues, only 3 case studies were presented to describe the outcome of an integrative intervention approach on children identified with APD associated with PAX6 gene mutations. Three children with varying type of PAX6 gene mutations and structural abnormality consistently presented with deficits in AP tests that require interhemispheric transfer. These children had initially undergone a phase of 3-month no intervention to serve as own control, and subsequently received a 3-month CBAT at home in addition to using a wireless FM system at school.

In overall, there was an initial evidence to show some broad improvement in the AP skills of these children after the intervention as compared to the no-intervention phase, even though there was considerable variation in the performance among the individuals. This was mainly due to the effects of the mutational variations on the brain abnormalities. As there was a lack of statistical power, this study was unable to make any conclusion on the true training effect on these neurological abnormal individuals associated with PAX6 gene mutation. Further research to increase the sample size of individuals with PAX6 gene mutation will be needed to substantiate this preliminary finding.

7.2 Summary for Study I

This retrospective study was undertaken to help inform the suitability of the type of AP tests to be used in the main study for the clinical diagnosis of APD. It was in view that most studies reported on APD were done predominantly on native English speaking (monolingual) populations, and little is known about the effect of different linguistic backgrounds on AP, in which concerns the diagnosis of APD in a multilingual population where the main study would be taken place.

A large clinical database with information concerning 133 multilingual and 71 monolingual children aged 7 to 12 years old was reviewed retrospectively. The findings showed that the performance of the multilingual and monolingual children did not differ significantly in the non-speech, i.e. FPT, MLD, and RGDT, and the minimally linguistic-loaded test, i.e. DDT. The two groups, however, differed significantly in their performance on the highly linguistically-loaded tasks, i.e. CS and LPFW. This study also revealed that, children with a diagnosis of LI performed significantly more poorly than those without language-related disorders in the two highly-linguistically-loaded tasks, indicating the influence of language factor on the performance in these two speech-based AP tests.

Taken together all these results, it was suggested that the diagnosis of APD in a multilingual community was best done on the basis of non-speech or minimally linguistic-loaded AP tests. In the context of an international perspective, AP tests that have less linguistic demands may thus be more appropriate in the construction of universally applicable AP test battery to ensure the uniformity of the diagnosis of APD.

7.3 Summary for Study II

This prospective study was conducted to examine the effectiveness of a CBAT programme that incorporated speech-in-noise and dichotic listening training to improve the AP and functional listening skills of children with APD. Twenty children with APD received a 3-months home-based training while 19 others had no intervention for the same period of time. All children were assessed for language, phonological skill, NVIQ, and auditory memory at baseline. An auditory test (LiSN-S) and two validated questionnaires (PP and CHAPS) were used as outcome measures, administered at baseline as well as at post-intervention.

The results from this study showed that the AP skills of children who had undergone a 3-month CBAT improved significantly more than that of the untrained controls. The improvement made through the CBAT intervention was proven to last for at least 3-month after the conclusion of training. The functional listening skills of children, as judged by the teachers, were also reported to have improved following training. This was consistent with the improvement in AP skills measured clinically, suggestive of a genuine transfer of training effect to real life listening ability. Finally, children with poor initial AP skills appeared to gain more improvement than those good performers, indicating that the initial AP performance, but not the language and cognitive skills, is predictive of the training outcome.

7.4 Conclusions

A few conclusions can be drawn from the studies presented in this thesis and they have clinical implications for the diagnosis and management of APD:

- Non-speech or minimally linguistic-loaded AP tests are less likely to be influenced by different linguistic backgrounds and language factor; thus may deem more appropriate to be used in the clinical diagnosis of APD in a diverse community.
- AT with noise and competing speech is proven to be effective in improving the speech-in-noise perception of children with APD.
- The AT programme developed for the study in this thesis can potentially be used as a supplement to the traditional language intervention for children with other learning difficulties.
- A computerised AT programme is feasible to be conducted at home with parental supervision. This provides parents an alternative to the clinic-based therapy programme and allows more flexibility for parents and the child to participate.
- Since the training effect is evident to last for at least 3 months after the completion of intervention, a home-based CBAT programme can be considered and offered by therapists upon the diagnosis of APD to allow the child an opportunity to start intervention immediately while waiting for a conventional therapy in the clinic.
- Finally, the main findings and the preliminary results from the pilot study further add to the substantial body of literature demonstrating the CANS has the

capacity to change in response to the experience of the individual – learning-induced plasticity of the brain.

7.5 Further Research

The impact of different linguistic backgrounds on the performance in AP has received little attention in the past studies. The work carried out in Study I has highlighted a few potential areas for further research. First, Study I was conducted based on the assumption that all the data in the clinical record were correctly captured. It would be interesting to examine the effects of different linguistic backgrounds on the performance in AP in a prospective study by including more detailed information such as participants' language status (e.g. language dominance, age of acquisition, stability of second language usage), ethnicity, socioeconomic background, language and cognitive skills. Second, the difference in performance on the highly linguistic-loaded tests between the multilingual and monolingual group appeared to be influenced by age factor. Further study with larger sample size, especially in the older age group, would be necessary to follow up this finding.

As for Study II, few areas for improvement are needed for further research. First, local norms were not available for the LiSN-S test; hence we were unable to determine if children with APD in the studied sample did have any speech-in-noise deficits. Further study would need to consider including typically developing children as normal controls for a comparison, and at the same time to address the question if children with APD do present with deficits in spatial processing. Second, the CBAT intervention included both speech-in-noise and dichotic listening training; thus it is unclear if the observed improvement was driven by a cumulative effect of all the listening exercises or a specific training programme. Further research would need to separate the two different AT programmes to examine how different children with APD would perform at post-intervention. This will provide useful information for therapists in designing appropriate intervention programme for children with APD.

Finally, it would be interesting to examine the true benefits of AT in neurologically abnormal individuals by extending the pilot study to increase the sample size of children with APD associated with PAX6 gene mutation. However, the design of the pilot study should be modified to include a matched control group to tease out developmental effects on the outcome.

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APPENDICES

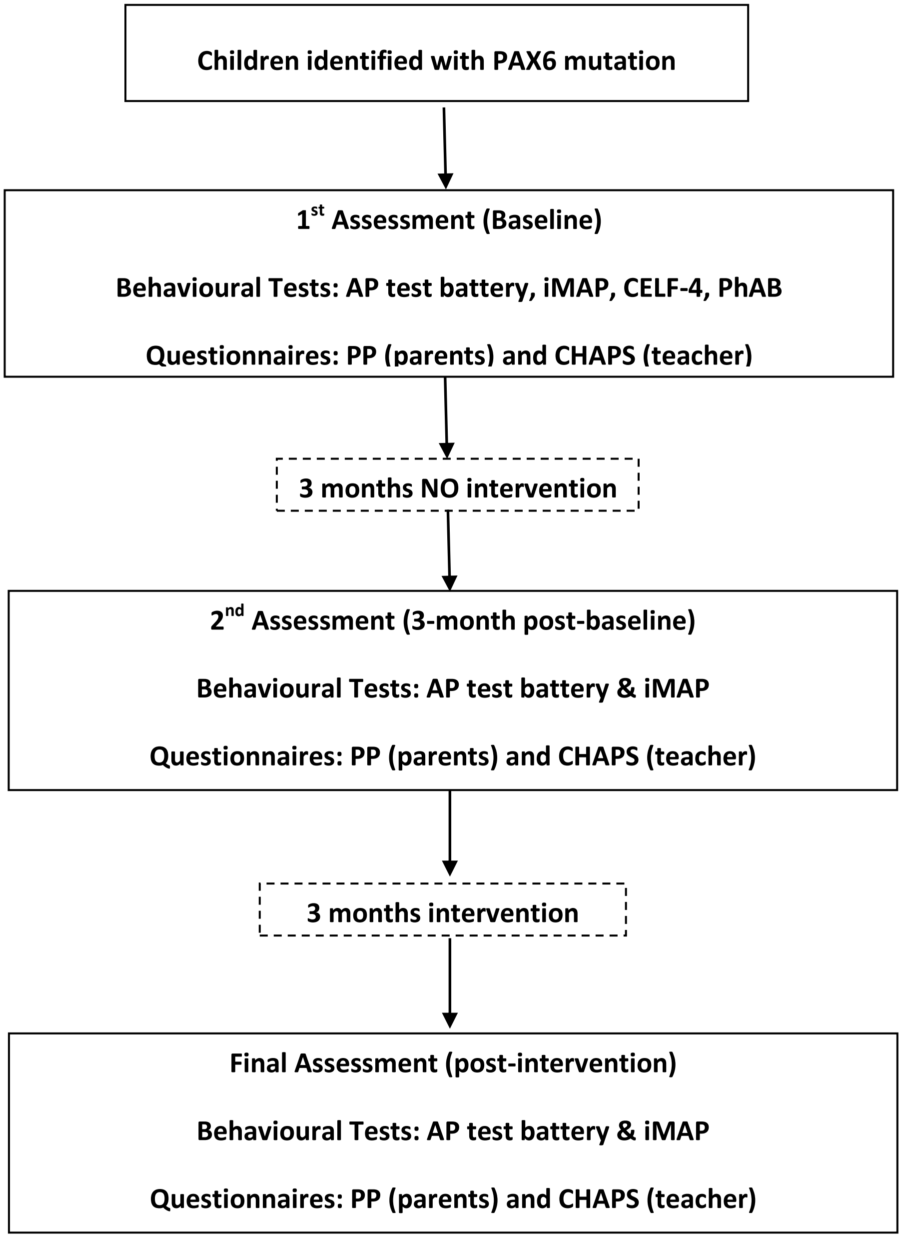
Appendix A

Level of evidence hierarchy (presented by ASHA as modified from the Scottish Intercollegiate Guideline Network)

Level	Sources of evidence
Ia	Meta-analysis including more than one randomized clinical trial
Ib	Randomized controlled study
IIa	Controlled study without randomization
IIb	Quasi-experimental study
III	Non-experimental study (e.g. case studies with controls, observational studies with controls, retrospective studies, and cohort studies with controls)
IV	Expert reports (committees, consensus conference), clinical experience of respected authorities; case, observational, and cohort studies without controls

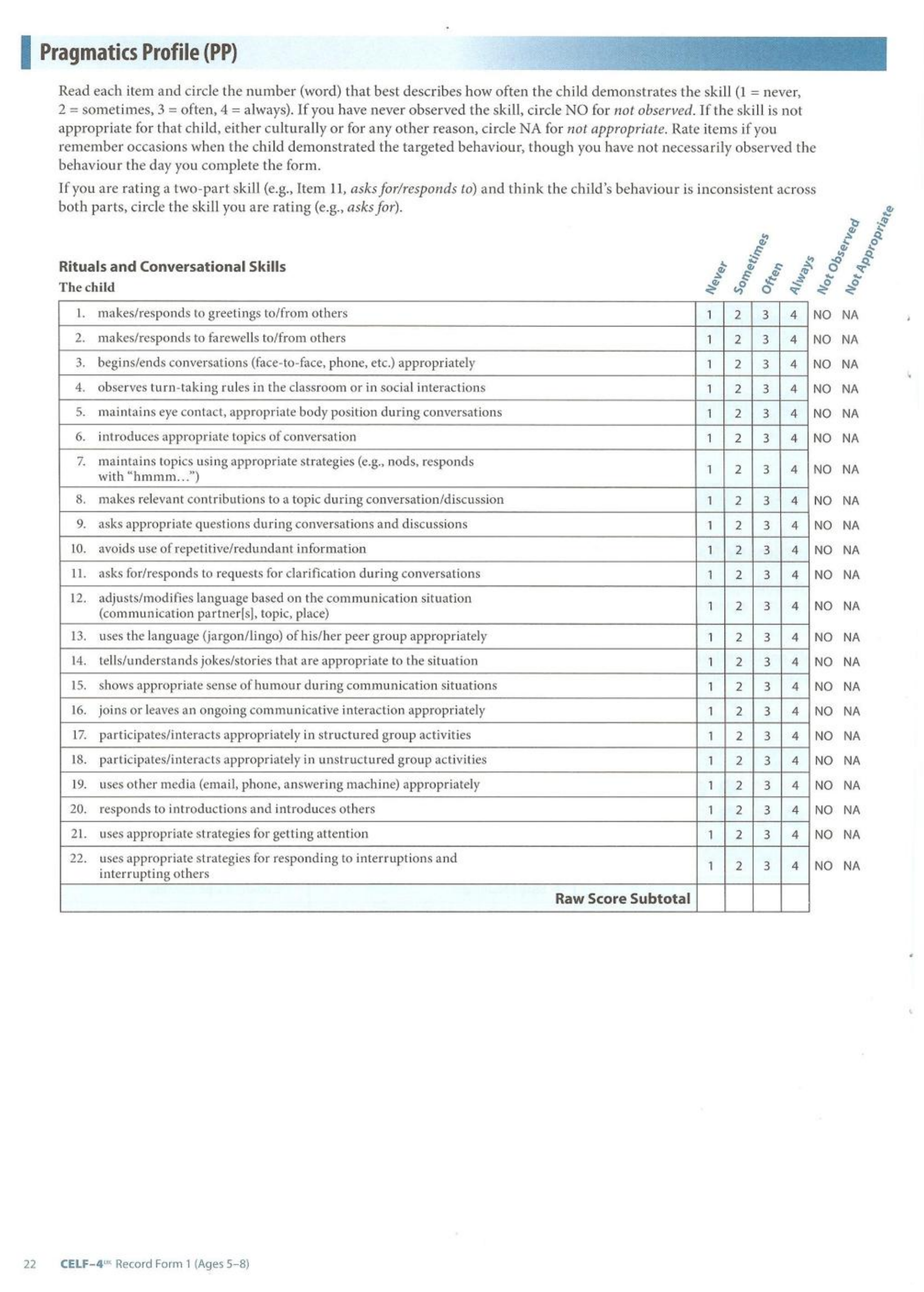
Appendix B

Flowchart for the Pilot Study



Appendix C

Pragmatic Profile Questionnaire



Pragmatics Profile (PP)

Read each item and circle the number (word) that best describes how often the child demonstrates the skill (1 = never, 2 = sometimes, 3 = often, 4 = always). If you have never observed the skill, circle NO for *not observed*. If the skill is not appropriate for that child, either culturally or for any other reason, circle NA for *not appropriate*. Rate items if you remember occasions when the child demonstrated the targeted behaviour, though you have not necessarily observed the behaviour the day you complete the form.

If you are rating a two-part skill (e.g., Item 11, *asks for/responds to*) and think the child's behaviour is inconsistent across both parts, circle the skill you are rating (e.g., *asks for*).

Rituals and Conversational Skills

The child

		Never	Sometimes	Often	Always	Not Observed	Not Appropriate
1.	makes/responds to greetings to/from others	1	2	3	4	NO	NA
2.	makes/responds to farewells to/from others	1	2	3	4	NO	NA
3.	begins/ends conversations (face-to-face, phone, etc.) appropriately	1	2	3	4	NO	NA
4.	observes turn-taking rules in the classroom or in social interactions	1	2	3	4	NO	NA
5.	maintains eye contact, appropriate body position during conversations	1	2	3	4	NO	NA
6.	introduces appropriate topics of conversation	1	2	3	4	NO	NA
7.	maintains topics using appropriate strategies (e.g., nods, responds with "hmmm…")	1	2	3	4	NO	NA
8.	makes relevant contributions to a topic during conversation/discussion	1	2	3	4	NO	NA
9.	asks appropriate questions during conversations and discussions	1	2	3	4	NO	NA
10.	avoids use of repetitive/redundant information	1	2	3	4	NO	NA
11.	asks for/responds to requests for clarification during conversations	1	2	3	4	NO	NA
12.	adjusts/modifies language based on the communication situation (communication partner[s], topic, place)	1	2	3	4	NO	NA
13.	uses the language (jargon/lingo) of his/her peer group appropriately	1	2	3	4	NO	NA
14.	tells/understands jokes/stories that are appropriate to the situation	1	2	3	4	NO	NA
15.	shows appropriate sense of humour during communication situations	1	2	3	4	NO	NA
16.	joins or leaves an ongoing communicative interaction appropriately	1	2	3	4	NO	NA
17.	participates/interacts appropriately in structured group activities	1	2	3	4	NO	NA
18.	participates/interacts appropriately in unstructured group activities	1	2	3	4	NO	NA
19.	uses other media (email, phone, answering machine) appropriately	1	2	3	4	NO	NA
20.	responds to introductions and introduces others	1	2	3	4	NO	NA
21.	uses appropriate strategies for getting attention	1	2	3	4	NO	NA
22.	uses appropriate strategies for responding to interruptions and interrupting others	1	2	3	4	NO	NA
	Raw Score Subtotal						

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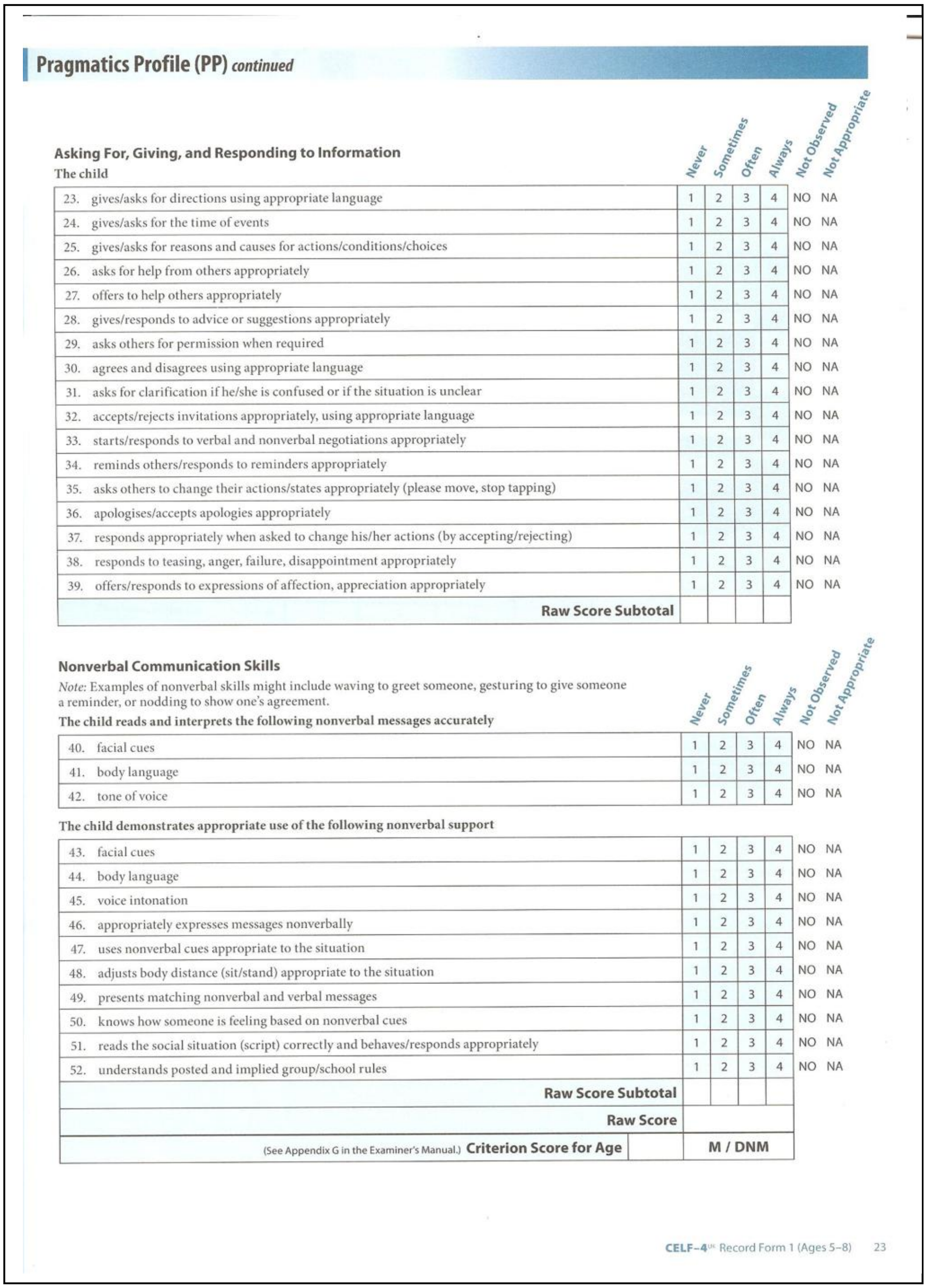
Pragmatic Profile Questionnaire (Continued)



Pragmatics Profile (PP) *continued*

Asking For, Giving, and Responding to Information

The child

	Never	Sometimes	Often	Always	Not Observed	Not Appropriate
23. gives/asks for directions using appropriate language	1	2	3	4	NO	NA
24. gives/asks for the time of events	1	2	3	4	NO	NA
25. gives/asks for reasons and causes for actions/conditions/choices	1	2	3	4	NO	NA
26. asks for help from others appropriately	1	2	3	4	NO	NA
27. offers to help others appropriately	1	2	3	4	NO	NA
28. gives/responds to advice or suggestions appropriately	1	2	3	4	NO	NA
29. asks others for permission when required	1	2	3	4	NO	NA
30. agrees and disagrees using appropriate language	1	2	3	4	NO	NA
31. asks for clarification if he/she is confused or if the situation is unclear	1	2	3	4	NO	NA
32. accepts/rejects invitations appropriately, using appropriate language	1	2	3	4	NO	NA
33. starts/responds to verbal and nonverbal negotiations appropriately	1	2	3	4	NO	NA
34. reminds others/responds to reminders appropriately	1	2	3	4	NO	NA
35. asks others to change their actions/states appropriately (please move, stop tapping)	1	2	3	4	NO	NA
36. apologises/accepts apologies appropriately	1	2	3	4	NO	NA
37. responds appropriately when asked to change his/her actions (by accepting/rejecting)	1	2	3	4	NO	NA
38. responds to teasing, anger, failure, disappointment appropriately	1	2	3	4	NO	NA
39. offers/responds to expressions of affection, appreciation appropriately	1	2	3	4	NO	NA
Raw Score Subtotal						

Nonverbal Communication Skills

Note: Examples of nonverbal skills might include waving to greet someone, gesturing to give someone a reminder, or nodding to show one's agreement.

The child reads and interprets the following nonverbal messages accurately

	Never	Sometimes	Often	Always	Not Observed	Not Appropriate
40. facial cues	1	2	3	4	NO	NA
41. body language	1	2	3	4	NO	NA
42. tone of voice	1	2	3	4	NO	NA

The child demonstrates appropriate use of the following nonverbal support

43. facial cues	1	2	3	4	NO	NA
44. body language	1	2	3	4	NO	NA
45. voice intonation	1	2	3	4	NO	NA
46. appropriately expresses messages nonverbally	1	2	3	4	NO	NA
47. uses nonverbal cues appropriate to the situation	1	2	3	4	NO	NA
48. adjusts body distance (sit/stand) appropriate to the situation	1	2	3	4	NO	NA
49. presents matching nonverbal and verbal messages	1	2	3	4	NO	NA
50. knows how someone is feeling based on nonverbal cues	1	2	3	4	NO	NA
51. reads the social situation (script) correctly and behaves/responds appropriately	1	2	3	4	NO	NA
52. understands posted and implied group/school rules	1	2	3	4	NO	NA
Raw Score Subtotal						
Raw Score						
(See Appendix G in the Examiner's Manual.) **Criterion Score for Age**		**M / DNM**				

CELF–4UK Record Form 1 (Ages 5–8) 23

Appendix D

CHILDREN'S AUDITORY PROCESSING PERFORMANCE SCALE

Child's Name_____________________________ Age (Years_____Months_____)
Date____

Name of person completing questionnaire Relationship:
Parent/Teacher/Other____

PLEASE READ INSTRUCTIONS CAREFULLY

Answer all questions by comparing this child to other children of similar age and background. Do not answer the questions based only on the difficulty of the listening condition. For example, all 8-year-old children, to a certain extent, may not hear and understand when listening in a noisy room. That is, this would be a difficult listening condition for all children. However, some children may have more difficulty in this listening condition than others. You must judge whether or not this child has MORE difficulty than other children in each listening condition cited. Please make your judgment using the following response choices: (**CIRCLE** a number for each item.)

RESPONSE CHOICES:

LESS DIFFICULTY	+1
SAME AMOUNT OF DIFFICULTY	0
SLIGHTLY MORE DIFFICULTY	-1
MORE DIFFICULTY	-2
CONSIDERABLY MORE DIFFICULTY	-3
SIGNIFICANTLY MORE DIFFICULTY	-4
CANNOT FUNCTION AT ALL	-5

Listening Condition - *NOISE:*

If listening in a room where there is background noise such as a TV set, music, others talking, children playing, etc., this child has difficulty hearing and understanding (compared with other children of similar age and background).

1. When paying attention. . . . .+1 0 -1 -2 -3 -4 -5
2. When being asked a question. . . . .+1 0 -1 -2 -3 -4 -5
3. When being given simple instructions. . . . . +1 0 -1 -2 -3 -4 -5
4. When being given complicated, multiple, instructions . . +1 0 -1 -2 -3 -4 -5
5. When not paying attention. . . . .+1 0 -1 -2 -3 -4 -5
6. When involved with other activities, i.e., coloring,
   reading, etc.. . . . .+1 0 -1 -2 -3 -4 -5
7. When listening with a group of children. . . . . +1 0 -1 -2 -3 -4 -5

Listening Condition - *QUIET:*

If listening in a quiet room (others may be present, but are being quiet), this child has difficulty hearing and understanding (compared with other children).

8. When paying attention. . . . .+1 0 -1 -2 -3 -4 -5
9. When being asked a question. . . . .+1 0 -1 -2 -3 -4 -5
10. When being given simple instructions. . . . . +1 0 -1 -2 -3 -4 -5
11. When being given complicated, multiple, instructions . . +1 0 -1 -2 -3 -4 -5
12. When not paying attention. . . . .+1 0 -1 -2 -3 -4 -5
13. When involved with other activities, i.e., coloring,
    reading, etc.. . . . .+1 0 -1 -2 -3 -4 -5
14. When listening with a group of children. . . . . +1 0 -1 -2 -3 -4 -5

Listening Condition - *IDEAL:*

When listening in a quiet room, no distractions, face-to-face, and with good eye contact, this child has difficulty hearing and understanding (compared with other children).

15. When being asked a question. . . . .+1 0 -1 -2 -3 -4 -5
16. When being given simple instructions. . . . . +1 0 -1 -2 -3 -4 -5
17. When being given complicated, multiple, instructions . . +1 0 -1 -2 -3 -4 -5

Listening Condition - *MULTIPLE INPUTS:*

When, in addition to listening, there is also some other form of input (i.e., visual, tactile, etc.), this child has difficulty hearing and understanding (compared with other children).

18. When listening and watching the speaker's face. . . . . . . +1 0 -1 -2 -3 -4 -5
19. When listening and reading material that is also being read out loud by another. . . . .+1 0 -1 -2 -3 -4 -5
20. When listening and watching someone provide an illustration such as a model, drawing, information on the chalkboard, etc.. . . . .+1 0 -1 -2 -3 -4 -5

Listening condition - *AUDITORY MEMORY/SEQUENCING:*

If required to recall spoken information, this child has difficulty (compared with other children).

21. Immediately recalling information such as a word, word spelling, numbers, etc.. . . . .+1 0 -1 -2 -3 -4 -5
22. Immediately recalling simple instructions. . . . .+1 0 -1 -2 -3 -4 -5
23. Immediately recalling multiple instructions. . . . .+1 0 -1 -2 -3 -4 -5
24. Not only recalling information, but also the *order* or *sequence* of the information. . . . .+1 0 -1 -2 -3 -4 -5
25. When delayed recollection (1 hour or more) of words, word spelling, numbers, etc. is required. . . . . +1 0 -1 -2 -3 -4 -5
26. When delayed recollection (1 hour or more) of simple instructions is required. . . . . +1 0 -1 -2 -3 -4 -5
27. When delayed recollection (1 hour or more) of multiple instructions is required. . . . . +1 0 -1 -2 -3 -4 -5
28. When delayed recollection (24 hours or more) is required . . . .+1 0 -1 -2 -3 -4 -5

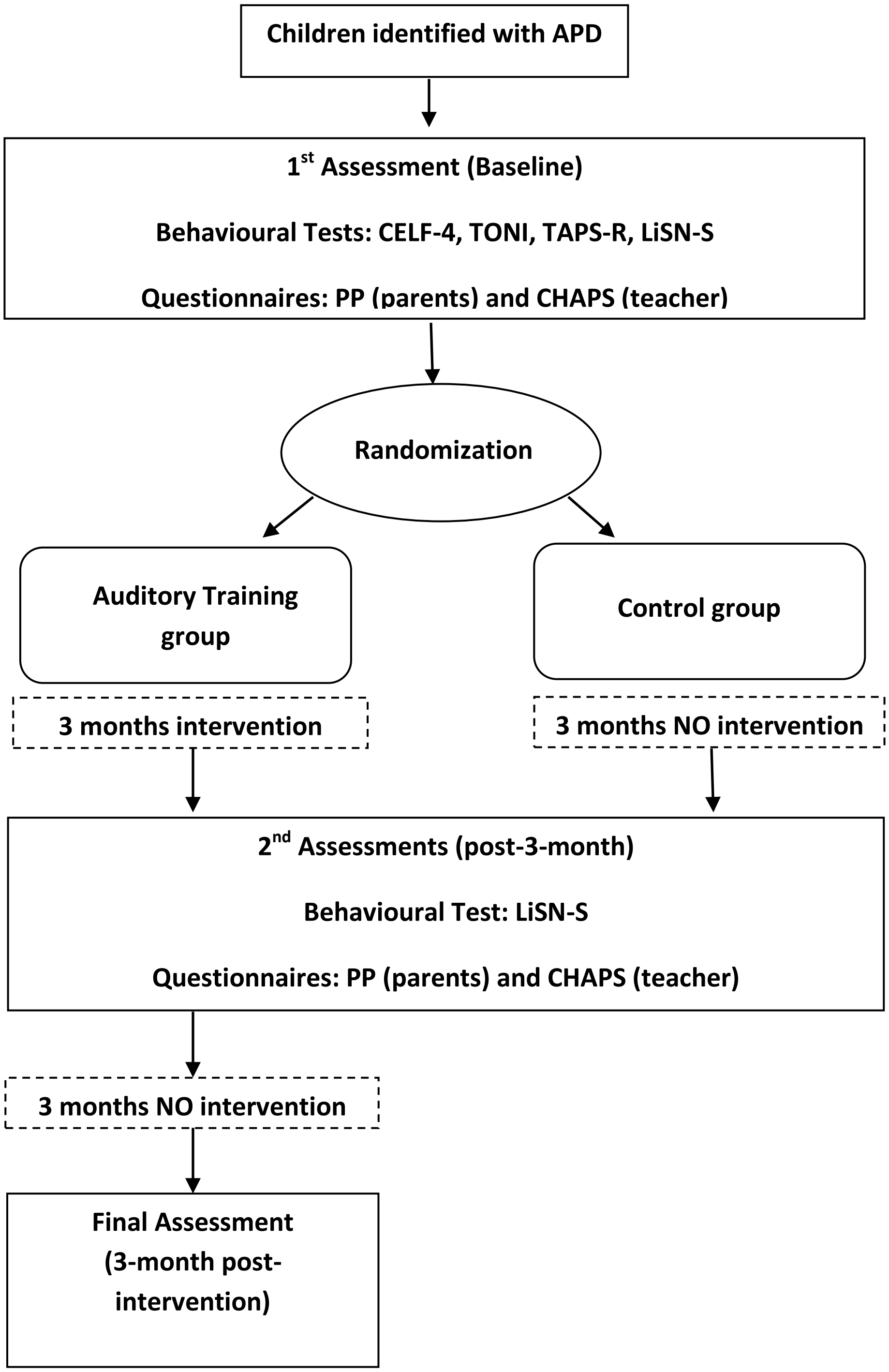
Listening Condition - *AUDITORY ATTENTION SPAN:*

If extended periods of listening are required, this child has difficulty paying attention, that is being attentive to what is being said (compared with other children).

29. When the listening time is less than 5 minutes. . . . . +1 0 -1 -2 -3 -4 -5
30. When the listening time is 5 to 10 minutes. . . . . +1 0 -1 -2 -3 -4 -5
31. When the listening time is over 10 minutes. . . . . +1 0 -1 -2 -3 -4 -5
32. When listening in a quiet room. . . . .+1 0 -1 -2 -3 -4 -5
33. When listening in a noisy room. . . . .+1 0 -1 -2 -3 -4 -5
34. When listening first thing in the morning. . . . . +1 0 -1 -2 -3 -4 -5
35. When listening near the end of the day, before supper time. . . . . +1 0 -1 -2 -3 -4 -5
36. When listening in a room where there are also visual distractions. . . . . +1 0 -1 -2 -3 -4 -5

Appendix E

Flowchart for Study II



Appendix F

Department of Otolaryngology – Head & Neck Surgery

Centre for Hearing Intervention & Language Development

APD History Sheet

Subject's details

Subject Initial	:	Subject Number	:
DOB	:	Date seen	:
Age	:	Gender	: M / F
Race	:	Dominant language	: English / Chinese / Malay / Others:
Handedness	:		
Address	:		

Parents /Guardian's details

Education level	: (Father) Postgraduate / Graduate / Diploma / 'O' level / Others (Mother) Postgraduate / Graduate / Diploma / 'O' level / Others
Main caregiver	: Parents / Grandparents / Nanny / Domestic helper / Others

Is there any family history of language, learning and reading difficulties

☐ Yes ☐ No

If yes, please describe:____

Previous or current diagnoses:	**Date of diagnosis:**
☐ Auditory processing disorder	………………………………………………
☐ Language disorder or language delay	………………………………………………
☐ Dyslexia	………………………………………………

☐ Dyspraxia ………………………………………………

☐ Motor / sensory integration difficulties ………………………………………………

☐ Visual-spatial processing difficulties ………………………………………………

☐ Autism ………………………………………………

☐ Global developmental delay ………………………………………………

☐ ADHD / ADD (Under medication? Yes / No) ………………………………………………

Previous or ongoing therapies:			**Start date**	**End date**	**Frequency**
Previous	Current	(tick '√' the box)			
☐	☐	Speech & Language therapy	……………….	……………….	……………….
☐	☐	Reading therapy	……………….	………………	……………….
☐	☐	Occupational therapy	……………….	………………	……………….
☐	☐	Music therapy	……………….	………………	……………….
☐	☐	CBAT: FFW/ Earobics /Somonas AIT / REVAMP	……………….	………………	……………….

Educational setting:

- Government mainstream / Private mainstream / International school / Special school / Home schooling
- Name of the school: ……………………………………………………………………………………………
- **Classroom:** big /medium / small Number of children in the classroom: ……

  High ceiling / echoing / near a main road / open plan

  Traditional classroom / group arrangement
- **Where seated:** Front / middle / back / nearer to the teacher / next to a window
- **Teacher:** soft spoken / foreign accent / dialect / rapid speech / faces away / stands in front / walks around
- **Teaching methods:** Visual material / gestures / overheads / powerpoint / handouts / prior home work / audio tapes / videos / computer
- **Best subjects at school:** ……………………………………………………………………………………
- **Most difficult subjects at school:** ………………………………………………………………………

I. Child’s perception of problems:

a) Hearing in noise: no problem / difficult to hear / not sure
b) Hearing in quiet: no problem / difficult to hear / not sure
c) Hearing teacher: no problem / difficult to hear / not sure
d) Hear the parents at home: no problem / difficult to hear / not sure
e) Hear friends at playground: no problem / difficult to hear / not sure
f) Not able to tolerate loud sounds: yes / no / not sure
g) Other (please describe): ……………………………………………………………………………………

II. Parents perception of child’s problems:

a) Easy to get your child’s attention by calling name? yes / sometimes / no
b) Your child is easily distracted by noises? yes / sometimes / no
c) Your child can only pay attention to one speaker at a time? yes / sometimes / no
d) Your child has problems in understanding when two people speak at the same time? yes / sometimes / no
e) Your child easily misunderstands things said in a noise environment? yes / sometimes / no
f) Your child has difficulty telling where sounds are coming from? yes / sometimes / no
g) Your child shows better understanding of language within small groups or face-to-face talks than within larger groups? yes / sometimes / no
h) When given oral instruction, your child observes the reactions of other children and copy them? yes / sometimes / no
i) Your child is reserved towards unfamiliar people with foreign accent? yes / sometimes / no
j) Your child shows lack of understanding when people speak fast? yes / sometimes / no
k) Your child has difficulties in repeating all of a text that he/she has heard? yes / sometimes / no
l) Your child uses short sentences when he/she speaks? yes / sometimes / no
m) Your child mumbles or speaks indistinctly? yes / sometimes / no
n) Your child is not good at memorizing song lyrics or poem? yes / sometimes / no
o) Does your child clap to the wrong rhythm when listening to music? yes / sometimes / no
p) Does your child sing or hum a wrong melody when repeating a piece of music? yes / sometimes / no

Questions (a) to (k) are related to understanding of speech in demanding conditions
Questions (l) to (n) are related to speech and language abilities of the child
Questions (o) to (q) are related to reproducing musical cues