Developmental Psychoacoustics: From Gestation through to Early Infancy

A dissertation submitted in partial fulfilment of the requirements for a B.Sc. (Hons.) degree of Music Technology at Queens University Belfast.

May, 2008

Student: John Harding

Student Number: 12754064

Supervisor: Paul Stapleton

Sonic Arts Research Centre

School of Music and Sonic Art

Abstract

The present study aims to overview the development of the human auditory perceptual capacity beginning in the gestational period and leading up to early infancy. Initial focus is placed upon the characterisation of the foetal sound environment which leads onto consideration of the related auditory responses of the foetus in such an environment. The considerations include characterisation of the stimulus and response and both testing methodologies and relative contextual information which are critiqued as it pertains to auditory perception. This leads to further understanding foetal reaction to sound. The transmission characteristics of stimuli are assessed as are relative contextual information such as cognitive development. The identification of factors responsible for developmental changes is a primary aim and aids in the study of age related changes in sensitivity to sound. Further studies of neonates and infants are included and critiqued giving a functional overview of the psychoacoustic development of the human during the period leading up to early infancy. Techniques employed to determine absolute and masked thresholds in Infancy are outlined and comparisons made, where applicable, between infant perceptual capacity and that of an adult. Finally the relationship between related contextual fields is assessed and suggestions for future improvements made, particularly between the fields of developmental psychoacoustics and paediatric audiology.

Table of Contents

Acknowledgements

Several people have made this dissertation possible. Firstly I would like to thank all the lecturing staff at the School of Music and Sonic Art, Queens University Belfast, for their help and support. Special thanks to my supervisor Paul Stapleton for his invaluable advice and guidance.

Thanks to both Jean and John Hunter for their genuine interest, encouragement and support during my time at University, my brothers Timothy and Jamie, my sister Susan and my insane nieces Ríchael and Lucy for inspiring research into child development.

Grateful acknowledgements are made to all individuals and organisations and dedicated researchers whose copyright materials are related to in the dissertation research.

Finally a very big thank you must go to Megan Hunter, for her patients, love and insight, and for maintaining my sanity whilst completing this dissertation.

I would like to dedicate this dissertation to all those mentioned above.

Introduction

Introduction

The purpose of the present study is to asses the auditory development of the human, from a psycho acoustical standpoint, beginning in the gestation period and continuing through to early infancy. Developmental psychoacoustics deals with the application of psychophysical methods to the study of auditory development (Werner, at el. 1992).

Complex sounds can be decomposed into sets of sine waves, infants' ability to perceive complex sounds will be limited by their sensitivity to sounds of different frequencies. Therefore, complete characterisation of auditory development depends on knowledge of age related changes in sensitivity to sound and other basic operating characteristics of the auditory system (Schneider and Trehub, 1980). As sensitivity to sound changes with age a technique to determine absolute and masked thresholds is necessary, with the minimal requirement for such a technique being sensitivity, efficiency of administration and applicability over a wide age range. Identification of factors responsible for developmental changes is necessary to aid the study of age related changes in sensitivity to sound. A variety of complex sounds dominate the auditory environment therefore, any attempt to understand auditory perception must explain abilities to detect, identify, and gather information from them. Likewise, developmental psychoacoustics must address these issues (Clarkson and Clifton, 1985).

In this computer generation, which permits production, control and measurement of complex signals there is a massive increase in interest in perception of complex acoustic signals. Researchers are beginning to understand the nature of complex auditory processing in adults, but knowledge of this processing in infants lags far behind.

Aims and Objectives

The primary aim of this study is to collate a wide range of relevant reading, in relation to a breadth of relative but currently unconnected contextual fields, and to reconcile the findings through critical analysis within a considered framework. This methodology will yield substantial evidence to allow professional comment. The study will include an extensive literature review with exploration of the thinking in the relative fields of study and make further comment on the implications of such for those interested in the area of developmental psychoacoustics, in addition to others seeking to use such information for early work in auditory development.

Throughout this study I will attempt to answer the question relative to the infant: "do they hear what I hear?" and, in addition, will attempt to explore the degree of commonality and shared learning between the fields of paediatric audiology and developmental psychoacoustics, amongst others. The process of combining the findings from the various contextual fields of research in a logical manner should hopefully indicate their relevance leading ultimately to an increased dialogue between the various fields. The important questions to be answered over the course of this work are:

1) What perceptual capacities are available to both the infant and the foetus and how do these capacities develop?

2) What are the procedures for testing the perceptual capacities of the foetus and infant?

3) What other relative information is important to consider when assessing perceptual development?

4) Are the current procedures for testing perceptual capacities flawed, if so in what way?

Layout

To begin the present study will assess the reaction of the foetus to auditory stimuli, if any, and the time frame in which the foetus obtains an ability to react. Sokolov (1963) Found that infant psychophysical methods could be based on head turning in response to sound. According to Werner, et al. (1992) psychoacoustical performance of infants and children is generally not mature. Many reports of age-related differences in psychoacoustical performance have been published leading to doubts about the degree to which such measures reflect the optimal sensory capacities of infants and children began to be voiced. The interpretation of age effects in psychoacoustic performance is a major unresolved issue in the field today and there are also a variety of ways to interpret psychoacoustic data on the immature listener. It is these issues that this study will explore and hopefully build up a picture of the pro's and con's of each method of testing hearing in humans. It will go on to assess the reactions of the newborn, or neonate, to stimuli and the relevant testing procedures for such a study. This will include critique of a variety of literature, and will conclude with both critique of current test methodology and an evaluation of all findings.

Chapter 1 Foetal Experience and Reaction to Sound

There is evidence to suggest that the human foetus is sensitive to sound as early as the second trimester of gestation. It is ironic that while the most commonly used method in assessing infants' psychoacoustical skills was developed by paediatric audiologists as a clinical measure of hearing, developmental psychoacoustics has had very little contact with paediatric audiology, either in terms of further methodological developments or in the substance of our discoveries concerning normally hearing infants and children. (Werner, et al., 1992).

1.1 The Foetal Sound Environment: stimulus and response.

It is only since the 1920's that studies have begun to investigate human foetal responsiveness to sound. Significant scientific advance since this time, in the areas such as ultra-sonic imaging of foetal behaviour, has helped to extend the research in foetal reaction to sound. In addition to the data obtained from human subjects scientific data obtained from animal studies provides information that can not be ethically obtained from human studies.

The first recordings of the human uterus were obtained by Bench (1968) whereby rubber encased microphones, referred to as hydrophones, which were inserted into the cervix and used to measure sound pressure levels for externally generated noises. The result showed a very noisy womb with measurements in the range of 76dB to 96dB SPL with only low-frequency sound being transmitted by the amniotic fluid. However, more recent studies employing hydrophones which have been modified to the impedance of the amniotic fluid have shown results to the contrary: that the womb is a relatively quite place. In a study by Hunse et al. (1990) a hydrophone was positioned inside the cervix of a series of pregnant patients and used to measure the sound pressure levels produced by a loudspeaker located at a distance of one meter externally, and directed towards the abdomen. The level of the uterine recorded sound were compared with the levels detected using a standard microphone positioned between the loudspeaker and abdomen. The results of this study show that certain sounds are already present within the uterus and originate from various maternal sources including respiratory and cardiovascular activity. These sounds provide a noise floor above which level externally generated sounds can be measured (Gerhardt and Abrams, 1996). The results of Hunse et al. show that the spectral characteristics of in uteri measured sound consist of predominantly low-frequency components. The study records measures at 100Hz reaching a sound pressure level of 90dB and also shows that; as frequency increases, spectral energy decreases. In a similar study by Behzquen et al. (1992) hydrophone measurements were taken at the human foetal neck, results of this study showed sound pressure levels of 60dB at a frequency of 100Hz, and a reduction in sound pressure level in the region of 15dB for frequencies above 250Hz.

The spectral characteristics of the externally produced sound that penetrates the uterus in humans have been shown to be very similar to those recorded in pregnant sheep. In a study by Peters et al. (1993) hydrophones were positioned in multiple locations of the sheep abdomen and broadband noise delivered externally at a level of 90 dB SPL. The spectral characteristics of each recording were assessed with relation to an external microphone positioned 10cm external to the subject ewe. The results of the individual hydrophone measurements in this study showed, in general, that low-frequency information in the region of 250Hz and below, received approximately 12dB of amplification in the ventral part of the abdomen, mid-frequency information from 250Hz to 2,000Hz however were attenuated by up to 20dB although mid to high-frequency information, above 3000Hz were attenuated to a lesser degree. According to Gerhardt and Abrams (1996) this general filtering pattern has also been observed in human studies and that the abdomen could be considered as a low-pass filter with high-frequency information rejected at a rate of approximately 6dB per octave.

1.2 Intelligibility of speech in the uterus

I have considered how sound may be filtered and distorted as it propagates through the biological material to the foetal environment and it is important to further consider the intelligibility of speech in the uterus as this evaluation may offer a path to furthering our understanding of fetal acoustic development. In various case studies regarding speech stimuli processing pregnant ewe are used as the transmission characteristics of sound in this animal have shown to be similar to that of humans during pregnancy (Querleu et al. 1988).

In a study by Griffith et al. (1994) the intelligibility of speech stimuli recorded in utero was assessed. In this study a series of speech stimuli were presented to a ewe through a side located loudspeaker. The presented stimuli were simultaneously recorded with a hydrophone, located at the foetal neck in utero and with an external microphone located 15cm from the flank of the subject. The resulting recordings were displayed to a panel of 102 untrained judges and intelligibility of such perceptually assessed. The results of this study show that male vocalisations were perceived to be more intelligible than a female vocalisations when recorded from within the uterus, but not so when recorded in the air. These results could be accounted for somewhat due to the differences in fundamental frequencies between male and female voice. According to (Prochazka, 1998) the fundamental frequency of the voice of an adult male is in the region of 125Hz whilst that of a female is in the region of 220Hz. As discussed earlier Gerhardt and Abrams (1996) demonstrated that the low-pass filtering characteristics of the abdomen and related biological material begin to take effect at approximately 200Hz, which could account, on some level, for the difference in intelligibility between the vocalisations of the two sexes.

Although the results of this study reflect the propagation of spectral energy relative to speech within the uterus, and indeed the subsequent transmission of such energy toward the foetal outer ear, they do not necessarily reflect the perception of speech by the foetus. In order to accurately reflect this perception it is important to firstly define the transmission pathway to the foetal inner ear.

In a study by Smith et al. (2003) intelligibility of sentences of speech recorded from the uterus of a near-term pregnant ewe were assessed. Sentences were presented to the ewe at 95 and 105 dB SPL and sequential reference recordings, with both a hydrophone and cochlear microphonic (CM) with electrodes were made. [According to Sohmer, H. and Pratt, (1976) the CM is an electrical potential generated in the hair cells of the Corti in response to acoustic stimulation, recordings of the cochlear microphonic potential are made with surface electrodes]. The resulting recordings were randomized and presented to a group of thirty untrained listeners in order to judge the intelligibility of sentences processed through the ewe and foetal inner ear. Intelligibility scores reached 99% for air and uterus conditions. These intelligibility figures dropped to 73% for cochlear microphonic recordings external to the uterus and dropped further to 41% for cochlear microphonic recordings in utero. These results indicated that the filtering characteristics of the tissues and fluids of the maternal abdomen did not affect sentence intelligibility significantly, but rather the filtering characteristics of the foetal inner ear resulted in much poorer intelligibility.

In a comparison study by Gerhardt et al. (1992) cochlear microphonic recordings were taken from near-term foetal and newborn sheep in order to evaluate the extent of foetal isolation from sounds presented external to the ewe. The ewe and foetus were anesthetised and electrodes surgically located in the round window membrane within the inner ear of the foetal sheep. The foetal head was returned to the uterus and surgically closed. Following full recovery the ewe was presented with third-octave-band noises (centred at octave intervals and ranging from 125Hz to 2.0 kHz) delivered through a loudspeaker 1.8 m from one side of the pregnant ewe with sequential reference recordings taken ex utero with a microphone and in utero with a hydrophone previously situated at the foetal neck. Following the recording of cochlear amplitudes the foetus was anesthetised and delivered through an abdominal incision. Following a 24 hour rest period, necessary to allow draining of amniotic fluid from the middle ear, recordings were repeated in the same sound field from the newborn lamb. An index of foetal sound isolation was calculated as the difference between the sound pressure levels that were necessary to evoke equal cochlear microphonic amplitudes from the foetus and from the newborn lamb. The degree of foetal isolation to external sounds was shown to be frequency dependant; 11.1 dB for 125Hz, 19.8 dB for 250Hz, 35.3 dB for 500Hz, 38.2 dB for 1.0 kHz, and 45.0 dB for 2.0 kHz.

As has been discussed, the propagation of acoustic stimuli in the foetal environment is subject to frequency dependant attenuation as a function of the characteristics of the biological material associated with the abdomen which surrounds the foetal head. This results in a signal which, although related to the original, spectrally differs from the source stimulus. The propagation of stimuli through the biological material of the abdomen, such as the abdominal wall and amniotic fluid, is also dependant on the acoustic impedance of that medium. The acoustic impedance of amniotic fluid is greater than that of air; according to Arulkumaran et al. (1992), sound intensity and sound vibration are about 4000 times, or 36dB, less in amniotic fluid, compared to that produced in air. From these figures one could assume that the level of uterus projected stimulus should be in the order of 36dB greater to elicit a similar response to that of airborne stimulus from the newborn. This was shown not to be the case for low-frequency stimuli of 500Hz and below (Gerhardt et al. 1992). It is also important to consider the route in which acoustic energy takes before reaching foetal inner ear.

1.3 Transmission of stimuli to the foetal inner ear: bone conduction.

Sound transmission to the inner ear of the postnatal subject takes the route through the outer and middle ear system. However, according to Gerhardt and Abrams (1996) the route of transmission of ex utero stimuli to the foetal inner ear in utero is likely to be less efficient due to dampening of the mechanics of the middle ear caused by the presence of amniotic fluid which fills the external canal and middle ear cavity. There is currently no consensus on this issue although some interesting studies have been presented on both sides. In a study by Querleu et al., (1988) it is suggested that the impedance of the amniotic fluid is closely matched to that of the fluid within the inner ear, and therefore sound is transmitted to the cochlear receptors in an efficient manner. However, more recent studies seem to suggest that ex utero stimuli can reach the foetal inner ear from pathways additional to the ear canal and middle ear system.

In a study by Gerhardt et al. (1996b) an experiment was devised to compare the effectiveness of two routes of transmission of sound in utero; the traditional route of ear canal and middle ear system to foetal inner ear *vs* bone conduction route to such. According to the author, foetal sheep were selected as test subjects in this case due to a close similarity in both; auditory sensitivity and abdominal filtering characteristics in comparison to those of human subjects; moreover this type of research would be considered unethical in human subjects. The methodology of this study involved the surgical implantation of cochlear microphonics (CMs) to nine near-term foetal sheep under anaesthesia to allow subsequent recordings to be made from one round window (RW) of foetal sheep in utero. Stimulus were delivered to the ewe at intensity levels capable of producing a CM response (average of 100dB) by loudspeaker located 1 meter from the flank as tone bursts centred at 500Hz, 1kHz and 2kHz. The following CM recordings were obtained under three separate conditions; (1).The foetus was positioned such that the loudspeaker was closest to the left ear and the foetal head left uncovered, abdomen closed with clamps. These recordings function as reference conditions. (2).The foetal head was entirely covered with a neoprene hood and secured with a drawstring around the foetal neck. (3).The foetal head was fitted with a neoprene hood which was modified to allow exposure of the left Pinna and ear canal. As before this hood was secured with a drawstring around the foetal neck.

The results of this study show that when the foetal head is shielded with sound-attenuating material, even in the condition whereby the Pinna and ear canal remain uncovered, the level of stimuli necessary to evoke a response must be higher that the stimuli level necessary to evoke a response in the reference condition of bare foetal head. These results suggest that acoustic energy in utero is transferred to the foetal inner ear significantly via bone conduction. According to Gerhardt et al. (1996b) acoustic energy delivered to the human inner ear through bone conduction, regardless of location, results in the perception of the subject that the stimulus is at equal level at both ears. Since the psycho-acoustic ability to localize sound source origin is reliant upon, amongst others, Interaural Intensity Difference, or IID, (Howard and Angus, 2001) it can be assumed that the foetus in likely to be unable to localize sound.

1.4 Foetal cognitive development

Any study regarding the perceptual development of the foetus would not be complete without some degree of consideration of the brain and cognitive development during this period and its relation to foetal behaviour. As is later discussed, the behaviour of the foetus at any particular instance is partially reflective of the brainstem functions available at that time. These brainstem functions are produced in the absence of cognitive processing functions, such as emotions, reasoning and understanding. These functions instead mediate from the forebrain which is much later to be developed. The forebrain and its relative functions remain relatively un-developed until birth and gradually become more functionally mature over the course of the first postnatal months and years. (Sroufe, 1996).

The progression of foetal behaviour, which begins with spontaneous foetal movements and progresses to a preference for maternal voice, seem to reflect the maturation of the brainstem functions (Joseph, 2000). The brainstem of the foetus is initially fashioned around the 32^{nd} day of the gestation period and continues to develop until around the 7^{th} month of gestation (Duckett, 1995).

The brainstem is an extremely complex structure, consisting of a variety of nuclei and subdivisions which collectively allow for a series of sensory and reflex motor functions such as heart rate, breathing, limb, head, and eye movements as well as visual and acoustic perception (Joseph, 2000). The brainstem is responsible for the reflex reactions to a variety of stimuli and is itself incapable of cognitive functions as previously mentioned. (Sroufe, 1996).

According to deVries et al (1985) the human foetus is able to spontaneously move both the head and extremities as early as the 9^{th} week of gestation. In this study of 12 healthy women the developmental course of specific foetal movement patterns was investigated in the first half of gestation, using real-time ultrasound. The study found a gradual increase in occurrence of breathing movements, head rotations, jaw openings, sucking and swallowing as the foetus aged.

According to Joseph (2000) during the 6th-7th week period of gestation the human brainstem matures to produce the medulla, pons and midbrain. The functions of the medulla, which mediates arousal, heart rate and breathing, appear prior to those of the pons, which later mediates both body movements and vestibular and vibro-acoustic perception. According to Joseph, (2000) the development of the pons does not reach an advanced level until the 28th week of gestation and consequently many of the functions associated with its development do not appear until after this period. However some functions appear in advance of others, in a seemingly irregular fashion (Sroufe, 1996).

The implications of the findings of Joseph (2000) may have significant impact when considering the results of foetal studies which test foetal reaction to stimuli, particularly during the period prior to the 28th week of gestation. The results of such studies could, as a result, be considered unreliable.

1.5 Responses of the near-term foetus to stimuli.

The foetus reaches full term between 37 – 42 weeks of gestational age and by this time significant responses, in the form of foetal heart rate accelerations and decelerations, to both acoustic and vibro-acoustic stimuli can be measured. Studies regarding the maturation of foetal responses, as are covered in some detail throughout this document, increase our understanding of the factors which may influence auditory development. As we shall see the maturity of the responses to stimuli appear to run parallel to the functional development of the foetal brainstem.

Birnholtz and Benacerraf (1983) demonstrated that blink-startle responses to vibro-acoustic stimulation can be elicited in the foetus between 24 and 25 weeks of gestational age and were present consistently after 28 weeks. Although this study fails to take into account spontaneous foetal movement which occurs during this period (Joseph, 2000), others have managed to confirm and extend upon these findings.

According to Groome et al. (2000) the study of foetal heart-rate responses, elicited from acoustic stimuli, allows us to assess foetal auditory perception.

In a study by DeCasper et al. (1994) twenty-eight women, 32nd week of gestational pregnancy, were separated into two groups. Group one were taught a rhyme entitled *La Poulette* while group two were taught a rhyme entitled *Le Petit Crapaud*. Both groups were instructed to recite their rhyme aloud three times in succession, daily over the period of 33rd to 37th week of gestation. Each individual recorded the date and time of each recitation as evidence. During the testing phase recordings of each rhyme, spoken by a female graduate student, were presented to the subjects over ex uterine located loudspeaker located 20cm above the abdomen at intrauterine level of 60dB which, according to the author, approximates the level of maternal speech. Each subject wore earphones playing continuous melodic guitar passages whose intensity was set to a level which masked the perception of the presented stimuli. This masking was intended to prevent the influence of foetal reactions due to the subjects' reaction to the stimuli. During stimuli presentation foetal heart rate responses were measured via Doppler-cardiotocograph and monitored in real-time via an audio-video display system. The results of this study show that foetal heart rate decreased in response to target stimuli that they were presented with in the previous 4 weeks but did not change in response to control stimuli with which they were unfamiliar, indicating that foetal reaction to stimuli were influenced by previous exposure to the stimuli. This reduction in heart rate was within the range of 1-5 beats per minute which, according to Groome et al. (2000) is generally interpreted as an attentional response. It may well be that foetal reaction changes in response to constant stimuli and its assessment may be dependant or enhanced by an examination over time using target stimuli.

In a similar study by Kruegar et al. (2004) two groups of women in their 27th week of pregnancy were recruited, aged from 20-36, and randomly assigned to two groups. Group one began reciting a nursery rhyme 6 times daily in the gestation period from 28th to 34th week. Group two began reciting the same passage from week 32 to 34. During weekly test sessions foetal cardiac reactions to an unfamiliar recording of the same passage were noted. For group one significant difference was found at 34 weeks, and, differences approaching significance at 33 weeks while no difference was found at week 32. For group two a significant decrease was found at week 34, while at week 33 a significant increase was found. No significant difference was noted at week 32. By week 34 of gestation both groups displayed significant responses to stimuli regardless of the length of time the rhymes were read to the foetuses. This suggests an attentional response of the foetus to sound beginning during this period.

Chapter 2 Studies of Neonates and Infants

2.1 Neonatal Studies

Hernandez, et al. (2006) conducted a study into the instrumental and vocal music effects on EEG and EKG in neonates of depressed and non-depressed mothers. The study assessed EEG asymmetry and heart rate responses to instrumental music with and without a vocal component. Infants from depressed mothers were expected to be less attentive to the vocal music. The music score was a version of "Dream a little dream" and was played on a Lennox sound stereo am/fm cassette recorder and filtered to a small headphone placed inside a cushioned head cradle. Volume was maintained and checked for each infant. After a 2 minute baseline quiet period each infant was presented with an instrument only or the instrument plus vocal segments for 2 minutes. Infants of depressed mothers exhibited a different response to sensory stimuli than infants born to non-depressed mothers. Heart rate decelerated in both groups of infants immediately when music began thus suggesting they were attentive to music. The question arises of how much cognizance of the findings is implied in paediatric audiology. Morrongiello and Clifton (1984) believe that heart deceleration in response to a stimulus is considered an index of infant attention. The infants of depressed mothers showed a greater lag time in heart rate deceleration suggesting slower responding by this group. This group of infants also showed greater heart rate variability following music onset thus suggesting they may have difficulty modulating arousal. Negative affects of EEG response to vocal music, were found for all infants which may relate to a greater difficulty processing voices, especially singing voices at this stage. Further study may look at mothers singing voice as opposed to a stranger's voice. There were 53 infants in the study; 27 from non-depressed mothers and 26 from depressed mothers. This is a small sample size with uneven numbers in each group which did not allow examination of gender differences of music type. Depression had a genuine base line measure as it was scored on the centre for epidemiological depression scale and a diagnostic structural and clinical interview was also performed. The average age of the infants was 16 days old and 52% of the infants were male. The average age of the depressed mothers was 24 and the non-depressed mother was 28. This age discrepancy could also affect the findings as the depressed mothers had an average age four years younger than their counterparts. The depressed mothers were also of a lower socioeconomic status which could be a factor in their depression. In summary, the findings of this study support the view that newborns attend to music stimuli evident by heart rate changes. Instrumental and vocal music have different effects on infants of depressed versus non-depressed mothers. Infants of depressed mothers show approach behaviours to instrumental music.

Nakata and Trehub (2004) found that infants from 4-7 weeks of age, if not before are highly responsive to the richly intoned sounds of infant directed speech, preferring those to the more muted tones of adult directed speech. Infant directed speech has a heightened pitch, exaggerated pitch contours and slow tempo. Similar to Nakata and Trehub's results; O'Neill et al (2001) found that infants exhibit a greater attention to higher rather than lower pitched renditions of the same song by the same singer. Infants favour consonant, music like harmonic music used in nursery rhymes over dissonant music as in certain types of jazz music. (Trainor and Heinmiller, 1998). Thus suggesting infants are sensitive to critical features of music.

In a study by Jones (2005) the possibility that infants respond to any arousal sensory stimuli with an irregular movement of the mouth and tongue in particular was explored. The author suggests that this is important information to pursue as both imitation and exploration are agents of cognitive development which begin in infancy. According to the author oral exploration is prominent in the first few months and teaches the infant about his or her capabilities. In this study four week old infants were presented with a pattern of stimulation and no stimulation alternating every 20 seconds. This is a common procedure of experiments of infant imitations (Meltzoff & Moore, 1983). Twenty infants, ten of which were male, aged 25-35 days completed the experiment. Tongue protrusions were noted when the infants tongue moved inside the line of the lower lip. Results of this study showed that significantly more protrusions occurred during silent periods between musical sections, while the music itself did not increase tongue protrusions. Thus suggesting that disengagement from stimuli is difficult for the infant.

2.2 Determining Absolute and Masked Thresholds in Infancy

Werner and Rubel, (1993) state that in order to study the development of any auditory system we must firstly determine how basic operating characteristics change over time and the ultimate effect of these changes. They go on to say that the specification of these changes is a primary goal of developmental psychoacoustics. Developmental

Psychoacoustic study is plagued with issues such as developing techniques to determine absolute and masked thresholds of infants and the identification of factors which contribute to these developmental changes. The authors go on to say that the interpretation of age effects in psycho acoustical performance is a major issue, and one on which there is currently no consensus.

Visual reinforcement of the orienting response to a sound is the preferred method for use with infants (VRA: visual reinforcement audiometry) in most developmental studies of basic auditory processes. This technique uses a visual reinforcer, usually a mechanically activated toy, following the head turning component of an orienting response to sound. The head turning response can be elicited reliably by five or six months of age (Chun, Pawsat and Forester, 1960). Reinforcement can maintain it at high levels for thirty to forty trials within a single session (Moore, Thompson and Thompson, 1975).

According to Werner and Rubel, (1993) two versions of technique are commonly employed to determine absolute and masked thresholds of infants:

2.2.1 Technique One: Go/No-go

Go/No-go signal detection: in this version of VRA the infant sits on parents lap with a single loudspeaker located to one side. The stimulus is presented over the loudspeaker for a limited duration when the infant is facing directly ahead. An infant response in the form of a head turn (go response) in response to the presented stimulus is noted as a hit, a head turn with no-signal is a false alarm, while a no-turn on signal is considered a no-go. In this technique adaptive procedures are used and infants who produce consistent no-go responses are typically eliminated from the trials. The subsequent calculation of infant threshold levels are taken from the data obtained from the go-response hits alone. According to Moore et al. (1975) the go/no-go technique of determining infant threshold levels is not ideal from a signal-detection theory perspective as it is assumed that on no-signal or noise trials there is residual random activity in the auditory system that gives rise to a distribution of events along a decision axis, referred to as the noise (N) distribution. On signal trials, the signal is added to background noise, thus providing a boost in activity on that trial. This distribution of activity on signal trials is referred to as the signal-plus-noise (SN) distribution. (Werner and Rubel, 1993).

There is a significant issue with the reliability of the Go/No-go technique of determining thresholds as the infant is rewarded for correct turns to presented stimuli while incorrect turns, to either no-signal or incorrect location, are not penalised. This system may result in the infant tending to locate stimulus correctly, as a function of memory of reward, and in order to maximise such. This factor was considered by Sinnott et al. (1983) whereby new methods were devised for maintaining infants under stimulus control during Go/No-go threshold testing through the use of randomly interleaved "probe" and "catch" trials. This study showed that reliable threshold data can be obtained from infants via a modified Go/No-go detection, and identical threshold criteria were applied to infants and adults alike.

2.2.2 Technique Two: 2AFC-L

In the two-alternate, forced-choice localisation task (2AFC-L): stimulus is presented over two independent loudspeakers which are located at both the left and right side of the forwards facing infant. In this technique, similarly to Go/No-go, stimulus is presented for a limited duration only when the infant is forward facing however, in this technique stimulus is presented on every trial, and directed to either the left or right located loudspeaker. In this technique correct responses to stimuli presentation are noted when the infant turns 45◦ towards the producing loudspeaker. In addition to the stimulus presentation, a toy is provided near the stimulus producing speaker for additional visual reinforcement. Incorrect responses result in a short inter-trail delay before next trial (Schneider, et al., 1980).

The 2AFC-L procedure has been shown to have several advantages over the Go/No-go: When the infant responds in the correct manner they are always rewarded (time out periods are given for incorrect responses). This procedure favours unbiased responses of the infant, increasing consistency of the results. Rewards are given for both Left and Right responses as apposed to signal only in the Go/No-go procedure, minimising the boredom that may be present in the infant during no-signal trials in the Go/No-go. (Werner and Rubel, 1993)

Schneider et al. (1991) compared both detection (Go/No-go) and localization (2AFC-L) tasks over high and low frequency signals and found that performance was similar over frequency, and, that performance is similar for both Infants and Adults. This study concluded that “at all ages detection occurs when signal to noise ratio reaches a certain value and the size of the ratio required for detection declines with age and the size of the critical band stays constant throughout ages.”

Although the 2AFC-L technique of determining thresholds in infancy has several advantages over the Go/No-go technique outlined it has the distinct disadvantage that it relies heavily on the localisation ability of the subject. Failure to localise the source of the stimulus presentation in this regard does not necessarily negate its detection. One could speculate that the additional introduction of music might enhance and direct further the infant response.

Chapter 3 Development of Spatial Hearing

Auditory localisation is achieved through the complex neural processing of sound localisation cues. According to Howard and Angus (2001) some of these cues arise due to the structural quality of the head itself, i.e. Interaural Time Difference (ITD), Interaural Intensity Difference (IID) and cues arising from the Pinna. Other cues are a function of the way that sound propagates through the environment before reaching the ear i.e. early reflections arriving from surfaces and or a reduction in sound pressure level over distance. The main question here would be: is an infant sensitive to these cues and if so is an infant able to process the cues to correctly localise a sound source. (Werner and Rubel, 1993)

In a study by Ashmed et al. (1991) the role of Interaural Time Difference in sound localisation by infants was investigated. Infants aged between 16 and 23 weeks were assessed and found to have thresholds between 50 and 75 microseconds with no significant difference over age. These results were extremely low in comparison to what was expected and seem to suggest that ITD is not a limiting factor in this age group.

In a study by Clarkson et al. (1989) the effects of stimulus on head orienting responses of infants was evaluated. The results suggest that localisation is selectively deficient for brief sounds, although sounds of longer duration, even sounds with less energy, reliably produces a head turning response in both infants and neonates. However, higher frequencies above 3 kHz were more effective.

Head orienting has also been shown to reflect memory for sound in the neonates. Swan, et al (1993) exposed newborn infants to speech sounds in 2 sessions separated by a 24hr resting period. Their habituation and recovery to these sounds were assessed by spontaneous head orientating toward the sound's location. Thirty six neonates were assigned to 1 of 3 groups; a no change group that heard the same word both days, a change group that heard a different word each day, and a day two age control group that heard 1 of the 2 words for the first time on day two. Both groups habituated to the sound on day one and recovered head turning after the 24 hour delay, but infants that heard the same word again responded less than the age controls did. In addition, these infants also began turning away from the sounds, unlike the other two groups. Following habituation all groups displayed comparable levels of recovery by turning toward a novel post test stimulus. Neonates appeared to retain memory for a specific sound over a 24hour period when presented with the same sound over both days.

These results tend to suggests that a once attractive auditory stimulus became a less desirable through repetition, even when repetition was spaced over two days. Werner and Rubel (1993) suggest that "the auditory system is functioning well before birth and at birth is remarkably mature compared with visual or motor systems, a concentrated effort to reveal the full range discriminatory powers as well as memory for sounds is warranted". Werner and Rubel also state that newborns tested on head orientating to sound beyond the neonate stage stopped turning around 6-8 weeks of age.

Clifton et al (1984) tested infants aged 2 and 6 months with the precedence effect, an auditory phenomenon involved in the process of sound localisation. Each infant was tested with two types of stimuli: sound from a single loudspeaker and precedence effect sounds produced by the same sound displayed through two loudspeakers, with one output leading the other by 7msec. The older infants' localised precedence effect stimuli as they did single source stimuli, indicating that they perceived this phenomenon as expected. Two month olds turned their heads toward single source sounds, but did not localise precedence effect sounds, suggesting that the more difficult perceptual task had not been activated at this age. In general, head turning towards sound proved far more difficult to elicit in younger infants. A click train was ineffective, but a tape recorded human voice elicited above-chance low-level turning.

These results could be due to developmental changes in terms of rapid growth of the auditory cortex during this period. (Marieb, 1995)

Werner and Babel (1993) believe that this decrease in head turning around 6 – 8 weeks probably has little to do with the infants' sensitivity to internal cues; rather, it may reflect a difficulty in organising auditory space and coordinating this with appropriate motor behaviour.

The results of these studies collectively suggest that neonates reliably orient in the direction of a sound, but the response is somewhat fragile. The head-orienting studies suggest that infants are born with some sensitivity to binaural cues that are important for direction discrimination.

Chapter 4 Auditory Capability amongst Preschool Children

There seems to be considerable evidence that the auditory processing of preschool children is considerably less well developed than those of adults. In a study by Schneider et al. (1989) masked thresholds were obtained from listeners in the age range from 6.5 months to 20.5 year olds. The results strongly suggested that masked thresholds of infants are higher. Whilst in a study by Jenson et al. (1987) the intensity, frequency, and duration discrimination of young children were all shown to be poorer than those of adults. Also, at a young age, there seems to be a reduced ability to resolve both temporal and spectral information. (Werner and Rubel, 1993)

This seems to suggest an overall diminished auditory capability in young children. However, as Werner and Rubel (1993) suggest, it is difficult to determine whether these differences are due to a variation in the infants' auditory system in comparison to that of an adult, or, whether other factors such as memory or attention contribute to the differences measured.

4.1 Auditory Distance Discrimination in Infancy

The process of discriminating auditory distance is a combination of evaluating distance cues and representation of space and an object location within that space. According to Werner and Rubel (1993) Infants of six months of age reliably reach for objects, especially those placed within reach, and are reluctant to reach for objects beyond reach. This behaviour has been utilized by Clifton et al. (1991) in a study in which infants between 26 and 32 weeks of age were presented with sounding objects in the dark at four locations, 30 degrees left and right, within reaching distance (15cm) and out of reach (60cm) at the same orientation. Infant' ability to localize the sound was assessed by measuring reaches of either hand into the space occupied by the objects when within reach. In two experiments infants reached more often into the correct location of the sounding object when placed within reach than when placed beyond reach. In the second experiment the objects were presented at midline in the light and off midline in the dark. Infants reached correctly in the dark and showed no inclination to reach toward the midline position where they had handled the object in the light. By seven months of age infants have at least a dichotomous discrimination of auditory space: within and beyond reach. The implications of these behaviours are discussed in relation to object permanence and cognitive development.

The results of this study seem to suggest that, as of six months, infants have at least a dichotomous discrimination of distance.

4.2 Perception of Pitch in Infancy

According to Werner and Rubel (1993) the field of psychoacoustics has traditionally been emphasised on the processing of pure tones, which form the basis for many existing models of auditory processing. However, in the environment in which we live, such pure tones rarely occur; instead we encounter a variety of complex spectra. Therefore, in order to fully comprehend auditory perception, the ability to process information from complex tones must be understood. Howard and Angus (2001) describe a complex tone as a sound consisting of two of more pure tones, or sinusoids, at different frequencies.

Werner and Rubel (1993) describe pitch as the attribute of sound that allows a listener to judge one sound as higher as or lower than another.

According to Patterson (1969) the fundamental frequency is not necessary for pitch perception. A study by the same author compared the effectiveness of noise in masking changes in both the frequency of a sinusoid and the low pitch of a complex signal. Although, the sinusoid and complex signal conveyed the same pitches, their masking patterns were shown to be quite different. Listeners could not detect a change in the pitch of the sinusoid in the presence of a noise band of similar frequency, but the low pitch of a complex signal did not disappear when the frequency region of the fundamental was masked by a band of noise. Rather a band of noise spanning the higher component frequencies eliminated the perception of pitch of the missing fundamental. These findings strongly suggest the importance of high frequency content in low frequency perception.

In an experiment by Wilson et al. (1976) Seven month old infants were tested using a head-turning experiment in which each infant sat on a parent's knee facing an experimenter. The infant was then entertained with silent toys. Sounds of 500ms in duration were played repeatedly from a loudspeaker located to one side of the infant. Infants' tested quickly learned to turn towards the sound source when a change in pitch occurred, even when harmonically complex tones were used. Also when in harmonic complex tones were presented more than 75% of infants were successful at discriminating these signals. This experiment suggests that infants pitch perception depends on spectral content, similar to adult pitch perception.

Clarkson and Clifton (1985) studied 7 month old infants who were sat on a parents knee opposite the examiner who entertained them with silent toys. Sounds lasting more than 500ms from a background pitch category were played repeatedly at sound pressure levels of 45 to 60 DB. (A), from a loudspeaker located to one side of the infant. The infant learned to turn toward the sound when a change in the pitch of the sounds occurred. If infant turned during change in pitch they were credited with a "hit" and an animated toy was illuminated and activated. The results of this experiment demonstrate that seven month old infants can recognise the constancy of pitch for harmonic tonal complexes having different spectral characteristics and can categorise those sounds consistently with their pitches. Infants can synthesise the low pitch of the missing fundamental.

For adults, the low pitch of inharmonic signals become less salient and more difficult to hear as the frequencies of partial are shifted increasingly away from a harmonic relation (DeBoer, 1976). Seven month olds can synthesise the low pitch of inharmonic tonal complexes (ITC). Only eleven infants successfully categorised the three ITCS which is a small sample size so can this experiment cannot be statistically valid.

Sensitivity is generally assessed using sine wave tones in a range of frequencies (Trehub et al., 1980). It has been shown that the thresholds of infants, like adults, vary with both frequency and band width of the stimulus (Trehub et. al., 1980). The author also suggests that the differences between the thresholds of infants, compared to that of adults, were not significant.

In a study by Trehub et al. (1980) localisation responses to octave-band noises at 200, 400, 1K, 2K, 4K and 10K were obtained from infants 6, 12 and 18 months using the 2AFC-L procedure (noted earlier). A correct response was rewarded by activating an animated on top of the speaker. Intensity of noise was varied during the trials to determine thresholds at each centre frequency. Thresholds for lower frequency were 5-8dB higher in six month old compared to that of older infants, however, there were no significant differences amongst groups at the higher frequencies. Infant thresholds were shown to be 20 – 30dB higher than adult thresholds at lower frequencies. At higher frequencies thresholds for infants were approaching those of adults.

Sperling (1967) believes that the usual decrease in hearing ability with increasing age is due to the loss of muscle tone of the tympanic muscle.

5.1 Mode of stimulus presentation

Trehub et al. (1980) present sounds over loudspeakers in order to avoid the problems associated with the use of earphones i.e. it may be difficult to get an infant to wear headphones without finding them tiresome. However it is difficult, when presenting sound over loudspeakers, to know the intensity of sound available at the subject ear due to varying head position. According to Werner and Rubel (1993) Sound amplitude is measured differently for loudspeaker and earphone presentations, and, when sound-field presentation is used, amplitude is measured at the position of the listener's head. Thus, the amplitude arriving at the head is estimated. Earphones are calibrated using a microphone that is held in a cavity, the volume and resonance of which are approximately those of the external ear. However, because of the infant's outer ear cannel differs in size and shape from that of adults a single amplitude estimate is not entirely accurate, as it would vary over frequency as a function of the resonant properties inherent with the size/shape of the ear canal. (Werner and Rubel, 1993)

In a study by Berg and Smith, (1983) the threshold measurements obtained under both conditions were compared: An adaptive up-down tracking procedure was used in combination with a visually reinforced head turn response to examine auditory sensitivity for 500, 2K and kHz tone bursts in infants 6 to 18 months of age. Six and 10 month old infants were tested with headphone presentation of stimuli, while 10, 14 and 18 month olds were tested in sound field. Infant threshold estimates for both headphone and sound field were within 15dB of adult comparisons for all frequencies and age groups. Six month olds were significantly less sensitive to 8 kHz tone than either of the lower frequency stimuli, but older infants demonstrated approximately equal sensitivity for all three frequencies tested.

The fact that different researchers, using different methods, have obtained similar results seems to indicate that the thresholds noted are meaningful. It also indicates that the physical properties of the infant ear may significantly contribute to the differences between infant and adult detection thresholds.

Chapter 6 Discrepancies between Psychoacoustics and Audiology

The present study focuses upon developmental psychoacoustics from a number of contexts, many of which are traditionally not considered as related. These contexts, as reviewed during previous sections of the present study, include: Anatomical Development, Obstetrics and Gynaecology, Child Development, Genetic Psychology, Experimental Child Psychology, Nervous and Mental Disease, Developmental Psychobiology and Otolaryngology amongst others. As a matter of tradition within the field of developmental psychoacoustics these contexts are often disregarded, or rather, not considered to be correlates. This factor continues to a similar degree in another context; that of paediatric audiology.

According to Werner and Rubel (1993) a fundamental difference between the general fields of psychoacoustics and audiology is evident in their primary foci. Whilst the psychoacoustic focus is the definition of the perceptual capacity of a given populace, the focus of audiology is the definition of the perceptual capacity of any individual from within that populace. Moreover, once the audiologist has recognised the perceptual capacity of the individual, and the degree of deficit thereof, they must endeavour to improve the perceptual capacity of the individual. The existing link between the two contextual fields is in the form of normative data. Normative data is a general term for data provided by the psychoacoustic field which relates to what is considered to be the average perceptual capacity of the populace. This normative data is typically employed by paediatric audiologists during evaluations of individual capacity, whereby evaluations of individual capacity are related to that of the normative data. This process allows the audiologist to arrive at a measure of individual perceptual deficit. In other words: the normative data, provided by psychoacoustic studies, is employed by audiologists in order to evaluate the difference between an individual's perceptual capacity and that of an average individual.

The purpose of this chapter, and indeed a general aim of the present study, is to indicate how data provided by typically isolated contextual fields correlate, and by doing so inform the advance of future interaction. In earlier chapters of the present study the literature outlined originates from a number of unrelated contextual fields, although the reader is not intentionally made aware of the breadth of such. These contexts are generally omitted from studies of developmental psychoacoustics. It is considered that if the reader accepts the information as related, then this is testament to the significance of including such. In this chapter however, it is necessary to indicate the isolation of two fields in particular.

To date there has been extensive application of normative data in the field of audiology, primarily focused in areas such as frequency resolution (e.g. Nelson, 1991), temporal resolution (e.g. Madden and Feth, 1992) and binaural acuity (e.g. Santurette and Dau, 2007). According to Werner and Rubel (1993) during the course of these studies researchers often deal with a number of problematic issues such as sound pressure level of stimulus presentation and large variability of subject sensitivity to such. The recent extension of psychoacoustics into the consideration of the developmental aspects of infant capacity has also created unique problematic issues regarding non-sensory factors such as memory, attention, habituation, and fatigue[1]. In standard developmental psychoacoustic practice the testing criteria is typically arranged in such a way that these factors are reduced through the employment of criteria which dictate, amongst others subject sample size and the testing procedures for such. As we shall see these processes are far from ideal and are overviewed as follows.

6.1 Subject Selection

The majority of the studies referred to in chapter two of the present study; *studies of neonates and infants*, feature surprisingly uniform subject selection criteria. This factor appears to be a significant issue in the field of developmental psychoacoustics and may be due, to a degree, to the bulk of these studies being completed by a relatively small group of researchers, and despite the employment of a wide range of testing procedures the exclusion characteristics of these studies remain very similar. Specific examples of the employment of this type of exclusion criteria include: Schneider, et al., 1989; Schneider et al., 1991; Schneider and Trehub, 1980; Trehub, Schneider, and Endman, 1980; Clarkson, and Clifton, 1985 and Clarkson, Clifton, Swain, and Perris, 1989 amongst others.

The exclusion criteria defined by the developmental psychoacoustics researchers as cited above include: the subject displaying signs of hearing loss, family history of hearing loss, middle ear abnormality and the presence of handicapping conditions

[1] For a full review of these issues please refer to Werner and Rubel (1993)

including preterm birth. It may be deduced that this rather strict selection criteria results in subject samples that do not truly represent the perceptual capacity of the average populace and rather bias toward an 'elite' group of such. This selection process therefore acts to reduce the relevance of the resulting normative data. Further examination of the investigations cited above reveals additional exclusion of subjects who are deemed to be 'fussy', or rather, displaying a tendency to be inattentive or lethargic. Rejection rates for such behaviour can be substantial, reaching 40% in some cases. The subjects which are excluded from such trials are consequently referred to audiologists for evaluation of their perceptual capacity and, since the normative data used by the audiologist in such an evaluation originates from studies of 'elite' individuals, the resulting measures of perceptual capacity and deficit thereof, can be considered as questionable.

6.2 Testing Procedural Variables

There are a number of variables in the application of testing procedure applied during psychoacoustic testing of populace capacity and the clinical audiology testing of individual capacity. These variables are overviewed as follows.

6.2.1 Training

The majority of the studies referred to in chapter two of the present study; *studies of neonates and infants*, feature a period of training prior to the commencement of the study. Despite the employment of a wide range of testing procedures over the breath of these works, cited in *6.1 Subject Selection*, the process of training individual subjects remains a consistent feature of this type of study. Regardless of the particular psychoacoustic capacity being measured, or indeed the audiology deficit being assessed, the subjects are presented with target stimuli prior to testing to allow stimulus presentation threshold to be set. The threshold of the stimulus presentation is subsequently set to a level which is deemed to be comfortably loud from the tester perspective and the subjects are trained with relation to such. This process allows the tester to assess individual response to the testing condition and to further identify whether a subject is selected or rejected from the study. Ignoring momentarily the fact that this process leads towards normative data of the ‘elite’ populace as detailed previously, this training process presents a further issue when employed for audiology testing.

According to Werner and Rubel (1993), when a subject is suspected of having perceptual capacity deficit, click-evoked auditory brainstem response (ABR) testing is typically first to be performed. This process involves the presentation of stimuli to the subject; typically consisting of 0.1 ms audible clicks of alternating polarity, through head-phones and subsequent recording of subject responses from positions on the scalp via subcutaneous electrodes (Şevik et al., 2008). The results of the ABR testing are subsequently compared to normative data during behavioural testing. As a result of the ABR testing the audiologist has some indication of the threshold level required for stimulus presentation during the subsequent behavioural testing. Since individual perceptual capacity of the subjects concerned by audiology varies exponentially, so too does the stimulus presentation threshold, and where individual capacity is particularly reduced, stimulus presentation threshold may deviate significantly from that used during the psychoacoustic studies from which the normative data originates. This acts to reduce the relevance of the resulting audiology measures further.

6.2.2 False-Alarm Rates

The majority of the developmental psychoacoustic studies referred to in chapter two feature additional exclusion criteria dictated by what are termed; false-alarm rates. The majority of modern psychoacoustic studies employ the go/no-go task for assessing infant capacity, as discussed in chapter two. In these cases adaptive procedures are employed to determine false-alarm rates of the individual subject. Any subject who indicates a propensity to respond during no-signal trials are eliminated from the study, so too are those subjects who fail to respond correctly during periods of stimulus presentation. In each case, any subject who is determined as having a high false-alarm rate is excluded. According to Werner and Rubel (1993) however, during audiology studies false-alarm rates must be dealt with, and are done so qualitatively, through notation of behavioural pattern. Since psychoacoustic studies omit subjects displaying high false-alarm rates, no normative data of this behaviour exists, and it is therefore generally interpreted by the audiologist as function of perceptual capacity deficit. It is clear that this presents an issue; since normative data resulting from psychoacoustic trials omits those subjects that produce significant false-alarm rates, and the audiologist must deal with these qualitatively, no accurate quantitative measures can be made. Moreover, no comparison to the average false-alarm rate of the populace can be achieved. Finally there is also a strong likelihood that the training procedures employed to achieve stimulus threshold levels prior to the commencement of the study, as detailed previously, may affect the subject false-alarm rate through subject habituation to test stimuli.

Chapter 7 Discussion

The findings of the present study have relevance to the following fields; perceptual development, speech perception, auditory nervous system development, psychoacoustics and paediatric audiology (Werner, et al., 1992). Thus the following results of the present study have influence over a vast area of contextual fields. The following is an overview of the collective findings of the present study.

The early scientific assessments of the foetal environment showed it to be a noisy environment (Bench, 1968). However more recent studies, featuring updated and impedance matched hydrophone technology, have shown results to the contrary: that the uterus is a relatively quiet environment (Hunse et al., 1990). The results of the more recent studies produce normative data of the level of sounds which are already present in the foetal environment which in turn dictates a noise floor, above which level any externally generated stimuli can be measured. Successive studies employing such normative data (Gerhardt and Abrams, 1996) provide a clear picture of the characteristics of the foetal environment which includes the abdomen and related biological material. This biological material was subsequently shown to have a low-pass filtering characteristic; with high frequency information rejected at a rate of approximately 6dB per octave (Behzquen et al., 1992). These results have been further reinforced in animal studies (Peters et al., 1993; Querleu et al. 1988).

The intelligibility of speech in the foetal environment has been assessed (Grifith et al., 1994), as an evaluation of such may offer a path to further understanding foetal acoustic development. The results of such studies indicate that male vocalisations are perceived as being more intelligible in the uterus; however these results could be accounted for somewhat due to the differences between fundamental frequency of male and female vocalisations (Prochazka, 1998), and filtering characteristics of the uterus and related biological material reducing the spectral energy of female vocalisations to a greater degree than that of the male. Although these studies reflect the propagation of spectral energy through the uterus and toward the foetal outer ear they do not clearly reflect the transmission to the foetal inner ear, and the subsequent foetal perception of speech. Studies which employ Cochlear Microphonic (CM) technology to complete recordings from within the foetal inner ear, (Smith et al., 2003; Gerhardt et al., 1992), suggest that the filtering characteristics of the tissues and fluids of the maternal abdomen do not significantly affect sentence intelligibility in the uterus; however the filtering characteristics of the foetal inner ear resulted in much poorer intelligibility.

Since the propagation of acoustic stimuli in the foetal environment is dependant upon the acoustic impedance of the transmission medium (Hunse et al., 1990; Gerhardt and Abrams, 1996; Behzquen et al.1992; Peters et al., 1993), and since the impedance of the amniotic fluid differs from that of air by approximately 36dB (Arulkumaran et al., 1992) it was assumed that studies of foetal reaction in this environment should require an increase of stimulus presentation in the order of 36dB, matching the impedance of amniotic fluid, in order to illicit a foetal response. However this was shown not to be the case for low-frequency stimuli of 500Hz and below (Gerhardt et al., 1992). The traditional middle ear route of sound transmission to the foetal inner ear in utero was assumed (Querleu et al., 1988), however, more recent studies have shown that acoustic stimuli reaches the foetal inner ear significantly via bone conduction (Gerhardt et al., 1996b). The results of this study state that acoustic energy delivered to the inner ear via bone conduction is perceived at an equal level in each ear, regardless of location of the original stimuli. Moreover, since perception of localisation is dependant on Interaural Intensity Difference, or IID (Howard and Angus, 2001), then it is assumed that the foetus is likely to be unable to localise sound.

Studies regarding perceptual development are further related to cognitive development of the foetus and the behaviour of the foetus at any particular instance has been shown to be partially reflective of the brainstem functions which are produced in absence of cognitive functions such as emotion, reasoning and understanding (Sroufe, 1996). These functions mediate from the forebrain which is much later to be developed. The results of foetal response studies have been shown to feature parallel advances to those outlined in cognitive development studies, with responses being reliably achieved from approximately the 28th week of gestation, a period in which the foetal brainstem reaches an advanced level (Joseph, 2000). Additional studies have shown that a blink-startle response to both acoustic and vibro-acoustic stimuli can be consistently elicited in the foetus during this period (Birnholtz and Benacerraf, 1983). Although the results fail to consider spontaneous foetal movements which occur during this period other have managed to extend upon the findings (Groome et al. 2000).

The measurement of foetal heart rate responses elicited from acoustic stimuli allows us to assess foetal auditory perception (Groome et al. 2000). The results from extended time frame studies of foetal reaction indicate that foetal reaction to stimuli can be influenced by previous exposure to such (DeCasper et al. 1994; Kruegar et al. 2004). The results in both cases suggest an attentional response of the foetus beginning during the 33rd week of gestation.

In more recent studies, concerning the neonate, reactions have assessed with both EEG and EKG technology (Hermandez et al., 2006). In this study heart rate responses to both instrumental and vocal music were assessed in neonates from both depressed and non-depressed mothers. Although the subject sample selection in this case was questionable the results of this study showed that infants of depressed mothers exhibited a less significant reaction to both types of stimuli however; a general preference for music containing vocalisations was evident.

Studies suggest that infants from 4-7 weeks of age, if not before, are highly responsive to infant directed speech, preferring those to the adult directed speech (Nakata and Trehub, 2004). The infant during this period has also been shown to exhibit a greater attention to higher rather than lower pitched renditions of the same song (O'Neill et al., 2001). Infants favour consonance over dissonance (Trainor and Heinmiller, 1998) suggesting infants are sensitive to critical features of music and, infants respond to a lack of sensory stimuli with an irregular movement of the mouth and tongue (Jones, 2005) suggesting that disengagement from stimuli is difficult for the infant (Meltzoff and Moore, 1983).

During the neonate and infant period techniques to determine absolute and masked thresholds of infants and the identification of factors which contribute to these developmental changes are important (Werner and Rubel, 1993). Visual Reinforcement of the orienting response to sound is the preferred method of testing infant perceptual capacity and can reliably elicit a head turning response in infants from 5 months of age (Chun, Pawsat and Forester, 1960). This testing methodology employs a visual reinforcing object which has been shown to maintain response levels from thirty to forty trials within as single session (Moore, Thompson and Thompson, 1975). The Go/No-go signal detection version of Visual Reinforcement is the most frequently employed technique in determining infant threshold levels, although this procedure is plagued with issues and far from ideal (Moore et al., 1975).

Studies have shown that at all ages detection occurs when signal to noise ratio reaches a certain value and the size of the ratio required for detection declines with age and the size of the critical band stays constant throughout ages. However, up until three years of age the resonances inherent with the outer ear vary in comparison to that of an adult which may account somewhat for any differences measured.

Infants aged from 16 to 23 weeks were found to have extremely low thresholds for Interaural Time Difference (Ashmed et al., 1991); results of which suggest that sound localisation is not a limiting factor in infancy. Head orienting responses of infants and neonates was evaluated and the results suggest that localisation is selectively deficient for brief sounds, although sounds of longer duration, even sounds with less energy, reliably produces a head turning response (Clarkson et al., 1989). Head orienting has also been shown to reflect memory for sound in the neonates (Swan et al., 1993) with results that suggest auditory stimulus becomes less attractive to the infant through repetition, even when presentation was spaced over a two day period. Tests show that subsequent to the first two months of infancy, the precedence effect can be utilised to localise sound, and, these results may relate to the development of the auditory cortex during this period (Clifton et al. 1984).

It has been shown that the signal to noise thresholds of infants, like adults, vary with both frequency and band width of the stimulus (Schneider et al., 1989), although, the intensity, frequency, and duration discrimination of infants were all shown to be poorer than those of adults (Jenson et al. 1987). Also, at a young age, there seems to be a reduced ability to resolve both temporal and spectral information (Werner and Rubel, 1993). As of six months, infants have at least a dichotomous discrimination of distance (Clifton et al. 1991). Furthermore: an infants' perception of pitch is dependent on spectral content of the presented stimuli, similar to adult pitch perception (Wilson et al., 1976). Thresholds of infant sensitivity have also been shown to vary over both bandwidth and frequency of the stimulus and the differences between infant and adult thresholds have been shown not to be significant (Trehub et al. 1980; Berg and Smith, 1983).

The present study focuses of developmental psychoacoustics from a number of contexts many of which are traditionally not considered as correlates. This factor is wide ranging throughout the field but significantly apparent between the fields of developmental psychoacoustics and paediatric audiology. The normative data provided by studies of developmental psychoacoustics is subsequently employed by paediatric audiology and functions collectively as baseline measures from which individual perceptual capacity deficit can be measured. The present study has identified several areas of concern relating to the testing methodologies employed during developmental psychoacoustics studies, which are in turn amplified during paediatric audiology studies through use of such normative data. These issues are discussed in some depth in chapter six of the present study and are outlined as follows.

The recent extension of psychoacoustics into consideration of the developmental aspects of infant capacity has brought about new problematic issues regarding non-sensory factors of the subject such as memory, attention, habituation, and fatigue (Werner and Rubel, 1993). A result of this is that the developmental psychoacoustic testing criteria are arranged in such a way that these factors are reduced through the application of strict subject selection and testing procedures. The subject selection criteria exclude those who are deemed to be fussy, lethargic or inattentive. In addition a subject who is deemed to produce significant false responses, collectively termed false-alarm rates, is excluded from taking any further part in the trail. These selection processes, amongst others such as training of subjects prior to the study, generally result in normative data which is biased toward an 'elite' range of the population. Moreover, since this normative data is subsequently employed by paediatric audiologists in studies of individual perceptual capacity, any inaccuracies in normative data is continued and amplified through this contextual field resulting in perceptual capacity measures which can be considered as flawed.

Conclusion

The present study gives detailed account of the development of human auditory perception from a psycho acoustical standpoint beginning in the gestation period and progressing through to early infancy. The present study, through the collation of information from a breadth of contexts, identifies additional factors which may affect development which is necessary to aid the study of age related changes in sensitivity to sound. Relevant testing methodologies employed during the evaluation of human auditory perception are outlined and critiqued to inspire professional comment and to aid in future advances in the field. The present study attempts to answer the question relative to the infant: do they hear what I hear? Furthermore the present study has explored the degree of commonality and shared learning between the fields of paediatric audiology and developmental psychoacoustics, amongst others which should encourage increased dialog in future.

The determination of the perceptual capacities available to both the infant and the foetus are deemed to be important, as are the developmental aspects of these capacities. This aim is met with extensive literature review of both directly and indirectly related contextual fields and the collation of such in a logical and progressive manner. A further aim of the present study is to define the testing procedures for testing the perceptual capacities of the foetus and infant. This aim is also met through literature review with particular focus upon the testing methodologies employed. In addition relative information from contextual fields external to developmental psychoacoustics, such as cognitive development for example, are considered as important factors when assessing perceptual development. Finally inaccuracies in the current procedures for testing perceptual capacities are identified through critical analysis and comparison of the relevant literature.

It is difficult to generalise between the average infant and adult perceptual capacity however, this study reveals that in the early scientific experiments into the fetal environment are flawed although more recent studies provide a clearer picture of the characteristics of the foetal environment. The intelligibility of speech in the foetal environment is assessed and male vocalisations are perceived as being more intelligible in the uterus, although the characteristics of the maternal abdomen do not significantly affect sentence intelligibility in the uterus. Furthermore sound transmission reaches the foetal inner ear significantly via bone conduction which suggests that the foetus is unable to localise sound. The results of foetal response studies have been shown to feature parallel advances to those of cognitive development studies, with responses being reliably achieved from approximately the 28th week of gestation. Additional studies suggest an attention response of the foetus beginning during the 33rd week of gestation.

The infant is shown to feature a general preference for music containing vocalisations and have also been shown to favour consonance over dissonance, furthermore; infants of depressed mothers are shown to exhibit less significant reactions to stimuli. Studies suggest that infants from 4-7 weeks of age are highly responsive to infant directed speech, preferring those to the adult directed speech and infants respond to a lack of sensory stimuli with movement of the mouth and tongue. This suggests that disengagement from stimuli is difficult for the infant. Concerning the methodologies employed for infant testing; Visual Reinforcement is the most frequently employed technique in determining infant threshold levels, although this procedure is plagued with issues and far from ideal. Infants aged from 16 to 23 weeks were found to have extremely low thresholds for Interaural Time Difference a feature of auditory localisation. These results may relate to the development of the auditory cortex during this period. It has been shown that the signal to noise thresholds of infants is similar to those of an adult although the intensity, frequency, and duration discrimination are poorer. The infant perception is similar to adult pitch perception and the differences between infant and adult thresholds have been shown not to be significant.

One of the more significant findings to emerge from this study is the identification of several areas inaccuracies in testing methodologies employed during developmental psychoacoustics studies. These inaccuracies are in turn amplified during paediatric audiology studies through use of the normative data produced by developmental psychoacoustics. A general result of the current methodologies is normative data which is biased toward an ‘elite’ range of the population.

In order for a true measure of infant perceptual capacity to be attained the developmental psychoacoustic field must increase dialog between the additional contextual fields included in this study. Moreover, future studies should utilize modified testing methodology to reduce bias toward a measure of the elite populace. Only then can we truly understand the average capacity of the populace. This will not only advance our understanding of the perceptual capacity of the average individual but also increase the relevance of measures of individual perceptual capacity deficit.

References

Allen, P., Wightman, F., Kistler, D., and Dolan, T. (1989) *Frequency resolution in children.* Journal of Speech and Hearing Research. Volume 32, 317 – 322.

Arulkumaran, S., Talbert, D., Hsu, T. S., Chua, S. Anandakumar, C., Ratnam, S. S.(1992) *In-utero sound levels when vibroacoustic stimulation is applied to the maternal abdomen: an assessment of the possibility of cochlea damage in the fetus*. Journal of Obstetrics and Gynaecology, Volume 99 (1), 43–45.

Ashmed, D. H., Davis, D. L., Whalen, T., Odom, R. D. (1991) *Sound localisation and sensitivity to Interaural Time Differences in Human Infants*. Journal of Child Development. Vol. 62, 1211 – 1226.

Behzquen, S., Gagnon, R. and Hunse, C. (1992) *The Fetal Sound Environment during Vibroacoustic Stimulation in Labour: Effect on Heart Rate Response*. Journal of Gynecology & Obstetrics, Volume 75, 500 – 555.

Bench, J. (1968) *Sound transmission to the human foetus through the maternal abdominal wall*. Journal of Genetic Psychology.

Berg, K. M., and Smith, M. C., (1983) *Behavioural thresholds for tones during infancy*. Journal of Experimental Child Psychology. Vol. 35, 409 – 425.

Birnholtz, J., Benacerraf, B. (1983). *The development of human fetal hearing*. Journal of Science.

Chun, Pawsat, and Foster 1960. *Sound localisation in infancy*. Journal of Nervous & Mental Disease. Vol. 130, 472-473.

Clarkson, M. G., Clifton, R. K., (1985) *Infant Pitch Perception: Evidence For Responding to Pitch Categories and the Missing Fundamental*. Journal of the Acoustical Society of America. Vol.77, 1521-1528.

Clarkson, M. G., Clifton, R. K., Swain, I. U., Perris, E. E., (1989) *Stimulus duration and repetition rate influence newborns' head orientating towards sound*. Department of Psychology, University of Massachusetts, Amherst.

Clifton, R.K., Morrongiello, B.A., Kulig, J.W., Dowd, J.M. (1981) *Newborns' Orientation Toward Sound: Possible Implications for Cortical Development.* Child Development, Vol.52, 833-838.

Clifton, R., Perris, E., and Bullinger, A. (1991) *Infants' Perception of Auditory Space*. Developmental Psychology. Vol. 27, 187-197

Clifton, R. K., Morrongiello, B. A., Dowd, J. M. (1984) *A Developmental Look at an Auditory Illusion; The Precedence Effect.* Developmental Psychobiology. Volume 17, 519-536.

DeBoer, E. (1976). *On the Residue and Auditory Pitch Perception*. In W.D. Keidel and W.D. Neff (eds) *Handbook of Sensory Physiology*. Berlin. Springer Publishing. 479-583.

DeCasper, A., Lecanuet, J.-P., Busnel, M.-C., Granier-Deferre, C., Maugeais, R. (1994) *Fetal reactions to recurrent maternal speech*. Journal of Infant Behaviour and Development.

De Vries, J. P., Visser, G. H. A., and Prechtl, H. F. R. (1985) *The emergence of fetal behaviour*. II Quantative Aspects. Journal of Early Human Development, Volume12, 99 – 120.

Duckett, S. (eds) (1995) *Paediatric Neuropathology*. USA, Williams and Wilkins.

Gerhardt, K. J. and Abrams, R. M. (1996) *Fetal Hearing: Characterisation of the Stimulus and Response*. Perinatology, Volume 20, 11-20.

Gerhardt, K. J., Huang, X., Arrington, K. E., Meixner, K., Abrams, R. M., and Antonelli, P. J. (1996b) *Fetal sheep in utero hear through bone conduction*. American Journal of Otolaryngology. Volume 17, 374 – 379.

Gerhardt, K. J., Otto, R., Abrams, R. M., Colle, J. J., Burchfiel, D. J. and Peters, A. J. M. (1992) *Cochlear microphonics recorded from fetal and newborn sheep*. The American Journal of Otolaryngology, Volume 13, 226-233.

Griffith, S. K., Brown, W. S. Jr., Gerhardt, K. J., Abrams, R. M. and Morris, R. J. (1994) *The perception of speech sounds recorded within the uterus of a pregnant sheep*. Journal of the Acoustical Society of America, Volume 96, 2055 – 2063.

Groome, L., Mooney, D., Holland, S., Smith, Y., Atterbury, J., Dykmann, R. (2000) *Temporal pattern and spectral complexity as stimulus parameters for eliciting a cardiac orienting reflex in human fetuses*. Journal of Perception and Psychophysics.

Hermandez – Reif, M. Diego, M. and Field, T. (2006) *Instrumental and vocal music effects on EEG and EKG in neonates and non-depressed mothers*. USA, Elsevier, Journal of Infant Behaviour and Development, Volume 29, 518 – 525.

Howard, D. M., Angus, J. A. S. (2001) *Acoustics and Psychoacoustics*, Second Edition. UK, Focal Press.

Hunse, C. Forman, J. and Gagnon, R. (1990) *Human fetal behavioral states after vibratory stimulation*. International Journal of Gynecology & Obstetrics, Volume 33, 282.

Jenson, J. K., Neff, D. L., and Callaghan, B. P. (1987) *Frequency, Intensity, and duration discrimination in young children*. Asha, Volume 29, 88.

Jones, S.-S. (2005). *Exploration of Imitation? The effect of music on 4 – week old infants' tongue protrusions*. Journal of Infant Behaviour and Development.

Joseph, R. (2000) *Fetal Brain Behaviour and Cognitive Development*. USA, Academic Press.

Kruegar, C., Holditch-Davis, D., Quint, S., DeCasper, A. (2004). *Recurring auditory experience in the 28 – to 34 – week fetus*. Journal of Infant Behaviour and Development, Volume 27, 537 – 543.

Kuhl, P. K. (1979) *Speech Perception in Early Infancy: Perceptual Constancy for Spectrally Dissimilar Vowel Categories.* Journal of Acoustical Society of America. Volume 66, 1668-1679.

Madden, J. P., and Feth, L. L. (1992) *Temporal resolution in normal-hearing and hearing-impaired listeners using frequency-modulated stimuli*. Journal of Speech and Hearing Research. Vol. 35, PP. 436-442.

Marieb, E. N. (1995). *Human Anatomy and Physiology*, Third Edition. USA, Benjamin/Cummings Publishing.

Meltzoff, A.-N., Moore, M. K. (1983) *Newborn infants imitate adult facial gestures*. Journal of Child Development.

Miller, C.L., Younger, B.A. and Morse, P.A. (1982). *The Categorisation of Male and Female Voices in Infancy.* Infant Behaviour and Development, Volume 5, 143-149.

Moore, J. M., Thompson, G. and Thompson, M. (1975). *Auditory Localisation of Infants as a Function of Reinforcement Conditions.* Journal of Speech and Hearing Disorders. Volume 40, 612-622.

Morrongiello, B. and Clifton, R. (1984) *Effects of sound frequency on behavioural and cardiac orienting in newborn and five-month-old infants*. Journal of Experimental Child Psychology. Volume 38, 429 - 446.

Muir, D.W., Clifton, R.K. and Clarkson, M.G. (1989). *The Development of Human Auditory Localisation Response: A U-Shaped Function*. Canadian Journal of Psychology, Volume 43, 199 – 216.

Nelson, D. A. (1991) *High-Level Psychophysical Tuning Curves: Forward Masking in Normal-Hearing and Hearing-Impaired Listeners*. Journal of Speech and Hearing Research. Vol. 34, PP. 1233-1249.
Patterson, R.D. (1969) *Noise masking of a change in residue pitch*. Journal of the Acoustical Society of America. Volume 45, 1520-1524.

Pescara-Kovach, L., Fulkerson, A. L., Haaf, R. A. (2000) *Do you hear what I hear? Auditory context, attention and recognition in six month old infants*. USA, Elsevier.

Peters, A. J. M., Gerhardt, K. J., Abrams, R. M., Longmate, J. A. (1993) *Three-dimensional intra-abdominal sound pressures in sheep produced by airborne stimuli.*. Journal of Gynecology & Obstetrics, Volume 169, 1304 – 1315.

Prochazka, A. (eds) (1998) *Signal Analysis and Prediction*. Germany, Birkhauser Publishing.

Querleu, D., Renard, X., Versyp, F., Paris-Delrue, L., and Crepin, G. (1988) *Fetal Hearing*. Journal of Gynecology & Obstetrics, Volume 28, 191 – 212.

Santurette, S., and Dau, T. (2007) *Binaural pitch perception in normal-hearing and hearing-impaired listeners*. Journal of Hearing Research. Vol. 223, PP. 29-47.

Schneider, B. A., Trehub, S. E., (1985) Infant Auditory Psychophysics: An Overview. In G. Gottlieb and N.A. Krasnegor (Eds.), *Measurement of Auditions and Vision During the First Year of Life: A Methodological Overview*. USA, Ablex. PP. 113-126.

Şevik, O., Akdogan, O., Gocmen, E. S., Ozcan, K. M., Yazar, Z., and Dere, H. (2008) *Auditory brainstem response and otoacoustic emissions in Duane retraction syndrome*. International Journal of Pediatric Otorhinolaryngology. Article in Press, Elsevier Science.

Schneider, B. A., Trehub, S. E. and Bull, D. (1980). *High Frequency Sensitivity in Infants*. Science. Volume 207, 447-452.

Schneider, B. A., Trehub, S. E., Morrongiello, B. A., and Thorpe, L. A. (1989) *Developmental changes in masked thresholds*. Journal of the Acoustical Society of America. Volume 86, 1733 – 1741.

Schneider, B. A., Trehub, S. E., and Thorpe, L. A. (1991) *Developmental Perspectives on the localization and detection of auditory signal*. Perception and Psychophysics. Volume 49, 10 – 20.

Sinnott, J. M., Pisoni, D. B. and Aslin, R. N. (1983) *A comparison of pure tone auditory thresholds in human infants and adults*. Journal of Infant Behavior and Development, Volume 6 (1), 3 - 17.

Smith, S. L., Gerhardt, K. J., Griffiths, S. K., Huang, X. and Abrams, R. M. (2003) *Intelligibility of Sentences Recorded from the Uterus of a Pregnant Ewe and from the Fetal Inner Ear***.** Audiology & Neuro-Otology, Volume 8, 347-353.

Sohmer, H. and Pratt, H. (1976) *Recording of the cochlear microphonic potential with surface electrodes*. Journal of Electroencephalography and Clinical Neurophysiology, Volume 49, 253 – 260.

Sroufe, L. A. (1996) *Emotional Development*. USA, Cambridge University Press.

Swan, I. U., Zelazo, P. R. and Clifton, R.K. (1993). *Newborn Infants Memory for Speech Sounds Retained over 24 Hours.* Developmental Psychology. Volume 29, 312-323.

Trainor, L. and Heinmiller, B. (1998). *The development of evaluative responses to music: Infants prefer to listen to consonance over dissonance*. Journal of Infant Behaviour and Development. Volume 21, 77 – 88.

Trehub, S. E., Schneider, B. A., and Endman, M. (1980) *Developmental changes in infants' sensitivity to octave-band noises*. Journal of Experimental Child Psychology. Volume 29, 282-293.

Werner, L. A., Rubel, E. W., (eds) (1993) *Developmental Psychoacoustics*. USA, American Psychological Association.

Wilson, W. R., Moore, J.M., & Thomson, G. (1976) *Auditory thresholds of infants utilizing Visual Reinforcement Audiometry* (VRA). Journal of American Speech and Hearing.