Behavioural and Electrophysiological Audibility of Speech Sounds in Noise by Normal Hearing Infants

Rachel Stafford

Master of Clinical Audiology

(MCAud)

Research Project

Audiology Section

Department of Linguistics

Faculty of Human Sciences

Macquarie University

2011

Supervised by Dr. Bram Van Dun

National Acoustics Laboratories

Formatted for submission to the *International Journal of Audiology*

Abstract

Objective: To investigate the audibility of the speech sounds /m/ and /t/ behaviourally and cortically in noise by normal hearing infants. **Method:** Eleven normal hearing infants aged 7 to 35 months were assessed behaviourally using visual reinforcement orientation audiometry. Minimum response levels in a background of 55 dB SPL ILTASS noise were obtained for the speech sounds /m/ and /t/. Speech-evoked auditory potentials were then measured using HEARLab™ at 5, 15, and 25 dB SL for each speech sound in the same background noise. A total of 6 conditions were objectively assessed for each subject. **Results:** The minimum response levels for /m/ and /t/ were 55.5 and 38.6 dB SPL, respectively. Significant relationships were found between sensation levels and P-N amplitude, Cortical Power, and *p*-values. CAEP sensitivities revealed that the 50% sensitivity point is around 17.5 dB SPL and there are missing corticals in normal hearing infants in noise. **Conclusions:** Results largely reflected those of older children and adult as predicted. There is potential for using normally hearing infants in noise to simulate hearing losses, instead of hearing-impaired infants however further investigation is required.

Keywords: Infant; Cortical auditory evoked potentional; Noise

Abbreviations

CAEP	Cortical auditory evoked potential	HI	Hearing-impaired
MRL	Minimum response level	NH	Normal hearing
SL	Sensation level	SNR	Signal to noise ratio
VROA	Visual reinforcement orientation audiometry		

Introducing cortical auditory evoked potentials

DEFINITIONS AND MATURATIONAL EFFECTS

Cortical auditory evoked potentials (CAEPs) represent summed neural activity in the auditory cortex in response to sound (Purdy et al, 2004). The CAEP in adults consists of a positive peak (P1) around 50 msec followed by a negative deflection (N1) around 100 msec and another positive peak (P2) around 200 msec (Hall, 2007). This response is 'obligatory' because it is evoked by the presence of sound stimuli, unlike 'discriminative' cortical potentials that require a change in stimulus (Purdy et al, 2004). Presence of the P1-N1-P2 complex indicates that the stimulus has been detected at the level of the auditory cortex (Martin, Tremblay & Stapells, 2007). There are maturation effects on the P1-N1-P2 complex generators (auditory and association areas). Namely, because the N1 component does not begin to emerge until after age three the speech-evoked cortical response in newborn infants is dominated by a large P1 component around 200 to 300 msec, which occurs earlier with increasing age (Golding, Dillon, Seymour, Purdy & Katch, 2006; Hall, 2007; Ponton, Don, Eggermont, Waring & Masuda, 1996; Ponton, Eggermont, Kwong & Don, 2000).

APPLICATIONS OF CORTICAL RESPONSES

In adults, obligatory cortical responses are useful for objective threshold estimation in those thought to have non-organic hearing loss (Rickards & De Vidi, 1995). CAEPs also have uses as an electrophysiological index of auditory system development (i.e. maturation effects) and to show benefits from cochlear implantation, amplification, and auditory training (Cone-Wesson & Wunderlich, 2003). Using CAEPs for the evaluation of amplification is particularly relevant for the infant population, given that subjective responses to amplification are not as readily accessible as they are in their adult counterparts. This application of CAEPs came about with the implementation of universal newborn hearing screening, where subsequently more hearing aids were being fitted early in life, and the need to develop methods suitable for hearing aid verification in infants became apparent (Dillon, 2005; Purdy et al, 2004). It has become clear that CAEPs are most suitable for assessing detection of speech sounds in an infant population when compared to other electrophysiological responses for a number of reasons, specifically; they can use longer stimuli that allow for hearing aid processing; responses are larger hence require fewer repetitions (which is a valuable feature when dealing with a behaviourally unpredictable population such as infants); responses originate from neurons nearer to the end of the auditory system hence represent detection at the cortical level and are more likely to correlate with speech perception; responses can be measured in awake infants, which is practicable as they get older and are awake more often; and finally, CAEPs can be measured for speech sounds (Dillon, 2005; Purdy et al, 2004; Souza & Tremblay, 2006). Particularly these last three reasons support the use of CAEPs for the purpose of learning more about the infant auditory system. The current study uses CAEPs to investigate infant speech in noise detection. The results will give insights into how normal hearing (NH) infants detect speech, and hence begins to process speech sounds in a noisy, thus realistic environment. Another population that the results will potentially provide insight into is hearing-impaired (HI) infants; this is based on the premise that since the addition of noise has been used in other age groups simulate hearing loss to some degree, it can be applied to the infant population also.

HEARLab™ (Frye Electronics, Tygard, OR, USA) is a system that is used clinically to evaluate infants' hearing instruments by measuring speech-evoked cortical responses. The HEARLab™ setup has been adapted to both include the component of background noise, and a wider range of stimulus presentation levels than is typically available. Given that the presence of speech-evoked cortical responses indicates that speech stimuli have been detected, cortical responses in the presence of noise should reflect that speech stimuli have been detected in noise (Hyde, 1997).

Background on behavioural speech testing

RATIONALE FOR STUDYING SPEECH IN NOISE IN INFANTS

It is relevant to study the effects of noise on speech detectability as this information increases our understanding of how normal auditory systems process speech in a realistic, noisy environment (Nozza & Wilson, 1984). Speech perception both in quiet and noise has been studied extensively in adults using both behavioural and objective (CAEP) methods, likely because listening in noise is one of the most common complaints expressed by HI individuals. Infant literature however, particularly in the presence of noise is limited. Naturally, this disparity is likely due to the relative ease in testing adults compared to infants, specifically, adults have the speech and language abilities required for behavioural speech testing, and are more compliant with electrophysiology testing.

A parental survey by Barker and Newman (2004) found that infants are frequently in noisy environments. We also know that infants have significantly poorer thresholds in noise compared to adults when using puretone, speech and narrowband noise stimuli (Nozza, Wagner & Crandell, 1988; Nozza & Wilson, 1984; Schneider, Trehub, Morrongiello & Thorpe, 1989; Trehub, Bull & Schneider 1981). There are even significant differences between speech detection thresholds for preschoolers and infants (Nozza et al, 1988).
To illustrate the significance of these findings Trehub, Bull and Schneider (1981) found that infants require speech to be greater than ten times as intense as adults in order to be detected. Presumably, such adverse listening environments could interfere with a NH child's acquisition of speech, language, and listening skills (Mills, 1975; Trehub, Bull & Schneider, 1981). Consider then the effects of noise on listening, and hence speech and language development for those children who are already 'at risk', that is, those children with HI

and/or auditory processing disorders, whose’ deficits become most apparent in noise. Clearly it is valuable therefore to further include infants in the literature on speech in noise detection.

SPEECH RECEPTION, SPEECH DETECTION, AND MINIMUM RESPONSE LEVELS

Speech reception thresholds (SRTs) are the minimum hearing level for speech at which an individual can recognize 50% of the speech material (American Speech-Language-Hearing Association [ASHA], 1988). While knowledge of infants’ speech recognition ability would be useful in determining functional ability, it is not possible to determine since language and vocabulary are still emerging in infants. The speech-evoked cortical responses that we are measuring are believed to represent detection of a speech stimulus at a cortical level. The behavioural correlate of this is the speech detection threshold (SDT), that is, the minimum hearing level that an individual can just discern the presence of a speech stimulus 50% of the time (ASHA, 1988; Diefendorf, 2009). However, during the behavioural test visual reinforcement orientation audiometry (VROA), NH infants tend to respond 10 to 15 dB suprathreshold; hence we obtain a minimum response level (MRL) instead of a SDT (Widen & O’Grady, 2002). Ironically, the MRL is likely closer to what their SRT would hypothetically be. While our study is aiming to determine infants’ audibility of speech in noise, it is important to keep our behavioural paradigm’s limitation in assessing audibility in mind, and again when comparing to cortically generated waveforms, which actually represent detection.

Behavioural detection-in-noise in infants

To my knowledge there have not been any studies that investigate both behavioural and electrophysiological audibility of speech noise in infants. There are however a number of studies that have behaviourally assessed the masked thresholds of infants using a variety of stimuli, including speech (Nozza, Wagner & Crandell, 1988; Nozza & Wilson, 1984; Schneider et al, 1989; Trehub, Bull & Schneider, 1981).

Trehu, Bull and Schneider (1981) sought to ascertain the effects of a broadband masker on the detection of the repeated phrase “hi there”. Their large sample of infants between 6 and 24 months was grouped according to age and there was an adult control group. Their procedure is a modified version of the conditioned orientation reflex (COR), which requires signals to be presented from one of two loudspeakers, located either side of the infant (Suzuki & Ogiba, 1961). White noise was continuously played from both speakers. They found that masked thresholds were comparable across all infant groups for both masking levels, indicating that it may not necessary to isolate younger and older infants for data interpretation. They also found that adult thresholds were 10-12 dB lower than those of infants. The authors advised that future studies use stimuli with more specific frequency content so that it is clear what part of the signal is detected, and to determine whether there is an interaction between signal frequency and effect of masking, as is seen in threshold work in quiet (Schneider, Trehub & Bull, 1980; Trehub, Schneider & Endman, 1980).

Schneider et al (1989) used the same procedure to examine the developmental course of narrow band noise detection of in noise. Comparison between masked thresholds for infants, preschoolers, children and young adults revealed that thresholds declined exponentially as a function of age indicating that there are developmental changes for masked thresholds, consistent with adult-infant differences of the previous study. The authors raised the notion that the COR paradigm technically assesses localization rather than pure detection, and that their thresholds may differ. To determine this they compared detection and localization performance and found that thresholds were similar, allowing us to interpret that developmental changes shown in this study reflect changes in detection thresholds.

Nozza and Wilson (1984) compared puretone detection thresholds in younger (mean 6.5 mo) and older (mean 12.5 mo) infants, and adults both in quiet and noise with the intention of estimating frequency sensitivity and selectivity. White noise was continuously delivered in the right earphone and the stimulus in the left. There were no significant differences between the two infant age groups, consistent with the notion by Trehub, Bull and Schneider (1981) that younger and older infants can be grouped together. Nozza and Wilson (1984) also concluded that infants had significantly higher thresholds than adults in both the quiet and noisy conditions, supporting the idea that the same level of background noise will more adversely affect speech audibility for infants than it would for adults (Trehub, Bull & Schneider, 1981).

Nozza, Wagner and Crandell (1988) investigated developmental change in the binaural masker level difference by comparing the speech token /ba/ and band-passed (300 to 3000 Hz) random noise in and directly out of phase, across small groups of infants, preschoolers, and young adults. Results were consistent with aforementioned studies; they found a significant difference in sensitivity between the infant and adult groups. The authors suggested that infants' limited ability to listen in noise should heighten our awareness that they require a greater signal-to-noise ratio (SNR) than older children and adults require.

While these studies differ in their procedures, stimuli chosen, and masking noise the finding that infants have higher auditory thresholds than adults in the presence of noise is consistent.

Cortical processing of speech-in-noise in adults and children

A number of studies have examined the effects of of background noise on the neural encoding of speech at the level of the cortex. These studies have focused on adults and children, but to my knowledge, not infants thus far (Anderson, Chandrasekaran, Yi & Kraus, 2010; Martin, Sigal, Kurtzberg & Stapells, 1997; Whiting, Martin & Stapells, 1998). Older subject groups make it possible to examine the effects of noise on speech perception as well as detection. Perception is more meaningful in terms of applicability to the real world as it involves higher processing of speech; it is thus a limitation of our study that for reasons mentioned earlier we will focus essentially on detection. Some speech in noise studies also investigate the relationship between behavioural and electrophysiological measures. While our measures will differ to those used for speech perception, our aim is the same; to determine whether infants' ability to detect speech in noise is related to their electrophysiologic responses in noise.

Studies show that the effects of background noise on audibility and cortical processing of speech are detrimental. Martin et al (1997) investigated the effects of decreased audibility of /ba/ and /da/ speech stimuli produced by high-pass masking noise on obligatory and discriminative cortical potentials in a small group of adults. Results show that as the cutoff frequency was lowered, that is, as audibility decreased, the obligatory N1 response amplitude decreased and latency increased. For the later, discriminatory (N2, P3) responses the effect of masking was even greater. The relationship between behavioral indices of discrimination and the later discriminatory cortical responses was relatively strong and as expected, weak for N1, which provides information on audibility, not discrimination of speech stimuli.

Whiting, Martin and Stapells (1998) similarly investigated the effects of broadband noise masking on the cortical event-related potentials N1, N2, and P3 to the speech sounds /ba/ and/da/ in adults. As the SNR decreases, waveform component latencies increases and amplitudes decreased. Consistent with the previous study, the findings from this study showed a pattern that when behavioural measures indicated that the stimuli were not discriminable N1 was present while N2 and P3 were absent. This is consistent with N1 being an obligatory response (Martin et al, 1997).

A child study also examined the effect of noise on objective and behavioural speech perception in noise measures (Anderson et al, 2010). Thirty-two children (aged 8 to 13) were assessed behaviourally using the Hearing in Noise Test (HINT). Obligatory cortical responses were then measured. Children were split into two groups (top and bottom) according to their performance on the HINT. Results found that adding noise significantly reduced the P1 component in both groups and the bottom group had greater N2 amplitudes than the top group.

Cortical evoked responses to speech sounds in noise have also been investigated in children with learning problems and control groups, summarised as follows (Cunningham, Nicol, Zecker, Badlow & Kraus, 2001; Russo, Zecker, Trommer, Chen & Kraus, 2009; Warrior, Johnson, Hayes, Nicol & Kraus, 2004; Wible, Nicol & Kraus, 2002).

Cunningham et al (2001) sought to determine whether speech perception deficits seen in some learning impaired children are associated with abnormal cortical encoding of speech. Behavioural and speech perception measures were studied in learning impaired children and 9 NH children (aged 10 to 13). They found that broadband noise causes a reduction in speech-evoked cortical response amplitudes P1-N1 and P1'-N1' for both NH and learning-impaired children; P1 and N1 were virtually abolished in noise. No significant latency adjustments were present when compared to quiet conditions, unlike those seen in the adult studies.

Wible, Nicol and Kraus (2002) also investigated children with learning impairments' speech-evoked cortical responses in noise. Behavioural speech discrimination and cortical potentials were studied in learning impaired children and 12 NH children (aged 9 to 12). The addition of noise resulted in amplitude reduction and increased response latencies, as seen in the two adult studies reviewed.

Warrior et al (2004) also looked at thirty-two children (aged 8 to 13) with learning impairments' speech-evoked cortical responses in noise with the aim of contributing to the understanding of the physiological mechanisms behind poor speech perception in these children. The finding of this study are consistent with the findings by Cunningham et al (2001) that in children, adding continuous broadband white noise significantly diminishes the size of the cortical response, but does not affect the timing of morphological features of that waveform.

Finally, Russo et al (2009) evaluated speech-evoked cortical responses in background noise in 11 typically developing children (aged 7 to 13) and children with autism spectrum disorders. In the noise condition amplitudes were reduced as expected and P1' latency was increased.

To summarize, all the cortical studies reviewed found decreases in obligatory cortical responses with the addition of noise, however effects on latency were mixed. Four studies (2 adult, 2 child) showed increases in latency with the additions of noise (Martin et al, 1997; Russo et al, 2009; Whiting, Martin & Stapells, 1998; Wible, Nicol & Kraus, 2002) while two child studies showed no effect on latency (Cunningham et al, 2001; Warrior et al, 2004). One study did not address effects on latency (Anderson et al, 2010). Studies vary considerable in stimulus and masker type and delivery method. Billings, Bennett, Moli and Leek (2011) advise that the interpretation of cortical responses in noise needs careful consideration of these variables.

The infant studies outlined earlier provide a guide for which to base our speech detection in noise paradigm on, likewise the procedures used in the objective adult and child studies are adapted to determine infants' speech in noise audibility.

Aims and hypotheses

The aim of this study is to investigate the audibility of the speech sounds /m/ and /t/ behaviourally and cortically in noise by NH infants.

- It is predicted that since speech-evoked cortical responses in noise can be measured in older children and adults that this will also be the case for infants.
- It is also predicted that if the SNR is improved (that is, by presenting at higher SLs) that this will be reflected by an increase in infants' speech-evoked cortical response amplitude, as is consistently seen when assessing older children and adults.
- Since behavioural and cortical speech in noise measures correlate in older children and adults, it is hypothesised that our behaviourally determined MRLs and speech-evoked cortical responses in noise, in infants, will correlate also.

- It is hypothesised that amplitudes and detection sensitivities of cortical responses for NH infants in noise will reflect those of HI infants (in quiet), since the addition of noise simulates a hearing loss, hence subjecting them to associated recruitment problems (Moore, 2003).
- Finally, in HI infants the incidence of ‘missing corticals’, that is, the absence of CAEPs well above behavioural threhsold, is about 25%. HI adults have a lower incidence of 7%. It has been questioned whether the absence is caused by them being just children, or the hearing loss (Van Dun, Carter & Dillon, in preparation). It is predicted that under noisy conditions the absence of CAEPs seen in HI infants is also seen in NH infants.

Methods

Subjects

Twelve infants and young children deemed developmentally suitable for behavioural VROA assessment participated in the study. Due to time constraints hearing was not assessed however all subjects passed their newborn hearing screening and no parental concerns were expressed regarding their hearing. Subjects were recruited from colleagues and friends of the researchers. Non-colleagues were paid a gratuity of AU$20 for their time. The Australian Hearing Human Research Ethics Committee and the Macquarie University Human Research Ethics Committee approved the study.

Stimuli and masker

The speech stimuli used were /m/ and /t/ of 30 msec duration each. The speech sounds /m/ and /t/ have spectral emphases in the low- and high-frequency regions respectively (see

Figure 1) and thus have the potential of providing information about the audibility of speech sounds in different frequency regions (Golding et al, 2006).

The masker used throughout the study was international long-term average speech spectrum (ILTASS) noise (see spectra in Figure 1). It was presented continuously at 55 dB A to represent a moderate level of background noise, commencing prior to the subject entering the room to avoid bringing unnecessary attention to the sound. The use of speech-weighted noise is intended to more closely represent background noise compared to the variations on white noise used in prior studies.

Both the stimuli and masker are presented from the same direction in the free field throughout the study. Free field delivery is intended to more accurately represent a regular listening environment than the headphone-delivered design used in other studies.

The stimulus was delivered via a CD player (behavioural testing) or the HEARLab™ system (cortical testing). Stimulus calibration was carried out at the beginning of each test day using a Brüel & Kjaer Type 2230 sound level meter for behavioural testing and using the HEARLab™ system's free field calibration function for cortical testing. Masking noise was delivered via a CD player for behavioural testing and Adobe Audition™ (Adobe, San Jose, CA) for cortical testing. Loudspeakers for each room were spectrally equalised.

Procedure

Parents of subjects gave informed consent. There were two parts of the assessment. The behavioural component sought to determine the MRLs in noise for /m/ and /t/. Afterwards, speech-evoked cortical responses were recorded at 5, 15, and 25 dB above the behavioural determined MRLs for each speech sound, providing a total of 6 conditions for each subject. Stimulus presentations were based on a predefined counterbalanced order. Otoscopy and screening tympanometry were performed on both ears to exclude the presence of excessive cerumen and monitor middle ear function respectively.

Behavioural assessment

MRLs were obtained using the VROA procedure in a sound attenuated test booth with an adjacent test room. The subject was seated in their parent's lap or highchair with the loudspeakers positioned 90º to their right one metre away. One clinician sat opposite the subject, keeping them sufficiently distracted, indicated when to apply a (non) stimulus trial and voted when they observed a response. They were blinded by masking noise applied through headphones. Another clinician presented sounds from the adjacent room and provided a puppet reward when in agreement of the child's response. The infant was conditioned to turn in response to each speech sound. If they could not be conditioned they were excluded from the study. Conditioning occurred at loud levels that did not exceed 80 dB SPL. Each trial was presented at a rate of four times per second for a duration of three seconds, a rate considered sufficient to ensure maintenance of the subject's attention not sufficiently different from the rate used for the cortical testing to be of any consequence. MRLs were obtained following the modified Hughson-Westlake procedure. The procedure was stopped if responses were observed for two out of three ascending stimulus trials and no nonstimulus trials. If either observer voted in response to a nonstimulus trial then the infant's level of distraction will be address and a full set of stimulus and nonstimulus trials repeated.

Cortical assessment

Speech-evoked cortical responses were recorded using the HEARLab™ system in a sound attenuated test booth. The subject was seated in their parent's lap approximately 1.8 metres from the loudspeaker, which was positioned at 0º azimuth. A clinician kept the subject quiet and still using toys and silent movies and monitored electrode placement. Silent movies were chosen rather than the <40 dB SPL utilized in previous studies since the reliability of cortical responses in this condition has not been investigated in infants or children, or in the presence of a masker. We also sought to make the two test environments as similar as possible to allow for comparison. Sites for electrode placement were prepared using a cotton applicator and electrode gel. Single use Ambu Blue Sensor N™ self-adhesive electrodes were placed at Cz (active), M1 (reference) and Fpz (ground) sites. Impedance was monitored throughout testing to ensure it is less than 5 kΩ difference electrodes. For the first two subjects stimulus levels ranged between 0 and 30 dB SL, and at 5, 15, and 25 dB SL for subjects thereafter. Sensation levels are defined as the difference between the cortical stimulus presentation level and the behaviourally determined MRL for the corresponding speech sound. An attenuator was used to overcome the limited number of presentation levels available on HEARLab™. When MRLs exceeded 55 dB SPL cortical recordings were performed at reduced SLs so as not to exceed 80 dB SPL. HEARLab presented stimuli with an interstimulus interval of 1125 msec in blocks of 25. If the acceptance/rejection ratio was poorer than 1:2 the recording was paused and resumed only after the subject had settled. An automatic statistical detection paradigm was used, with the resultant system generated *p*-value determining whether or not a response was present. Testing for a condition concluded after approximately 200 accepted epochs, or if the *p*-value was $p \leq 0.001$.

Data analysis

Data from one subject could not be obtained, as we were unable to condition them for the VROA task. The remaining 11 data sets were analysed offline in MATLAB™ (Mathworks, Natick, MA). Baseline correction was applied to the first 200 msec of the recording window and a 10 Hz low-pass filter was applied. The amplitude of the P component was identified by the software as the largest positivity between 100 to 300 msec, with the P latency being the latency of that peak. Likewise, the amplitude of the N component was determined as being the largest negativity between 200 to 600 msec, occurring after P, with the N latency the latency of that deflection.

P-value detection was calculated by applying a Hotelling's T-squared statistic to a (M x Q)-dataset, with M collected epochs in each recording, and Q bin averages. These Q = 9 bin averages were taken as the means of 9 data bins ranging from 101 to 550 msec, each bin 50 msec wide. Using this statistic, both waveform repeatability over all recorded epochs, and significant difference from zero could be objectively assessed. A resulting *p*-value less than 0.05 suggests that a CAEP response is likely to be present, while a *p*-value equal or greater than 0.05 suggests that there is no evidence that a CAEP response is present.

CAEP power was obtained by subtracting EEG noise power from the power of the averaged waveform. Average waveform power was calculated as the mean of the square of each sampled point in the averaged waveform ranging from 0 to 600 msec. EEG noise power was estimated by calculating the mean value for each sampled point in the epoch, across epochs, and the variance around that mean. These variances were then averaged across all sampled points within the epoch and the square root of the average taken to produce an estimate of the root mean square (rms) noise present during that run.

Results

Data was obtained from five females and seven males, ranging in age between 7 to 35 months, mean 21 months (SD 9.2 months).

Behavioural

In the presence of 55 dB SPL ILTASS noise the /m/ MRL for 11 subjects ranged between 50 and 65 dB SPL, mean 55.5 dB SPL (SD 5.2 dB SPL). The MRL for the /t/ stimulus for 11 subjects ranged between 35 and 45 dB SPL, mean 38.6 dB SPL (SD 4.5 dB SPL). The behaviourally obtained MRLs determined the presentation levels later used in the electrophysiology session. When ILTASS noise is presented at 55 dB SPL, the SNR required to detect /m/ = 0 dB SNR and for /t/ = -15 dB SNR.

Electrophysiology

/m/ CAEP VERSUS /t/ CAEP

No significant differences were found between /m/ and /t/ latency or amplitude characteristics ($p > 0.05$); hence they have been grouped together for subsequent analyses.

SENSATION LEVEL VERSUS CAEP AMPLITUDE

The grand averages of responses to stimuli presented at three sensation level ranges (0 - 10, 15 - 20 and 25 - 30 dB SL) are shown in Figure 2, which shows that cortical response amplitudes increase with SL

Regression analysis on 66 data points found a significant, positive relationship between sensation level and P-N amplitude ($r = 0.52$, $p = 0.000008$) (see Figure 3). There is also a significant positive relationship between SL and both P and N amplitude. Figure 3 also compares the P-N amplitudes of increasing SLs with two other infant speech detection studies. Van Dun, Carter and Dillon (in preparation) assessed HI infants' (aged 8 to 30 mo) detection of /m/ and /t/ while Carter, Golding, Dillon and Seymour (2010) assessed NH infants' in quiet (aged 9 to 15 mo) detection of the same stimuli. The P-N amplitudes of our NH infants in quiet are significantly larger than the NH infants in quiet. There are no significant differences in amplitude between our NH infants in noise and the HI infants.

SENSATION LEVEL VERSUS CAEP LATENCY

No significant relationship was found between SL and either P or N latency (p=>0.05).

SUBJECT AGE VERSUS AMPLITUDE AND LATENCY

When regressing CAEP latency and amplitude characteristics on the subject's age (ranging from 8 to 30 months) using 66 data points between 0 and 30 dB SL, only P latency correlated with age, that is, as age increased, P latency decreased. P latency had a correlation of $r = -0.34$ with age ($p = 0.00005$, intercept = 214 msec, slope = -2.23). No significant relationships were found between age and N latency, P or N amplitude $p>0.05$.

NOISE

The EEG noise amplitudes of 66 data points from 11 infants' have a mean of 27.91 µV (SD 2.6 µV) and median 27.96 µV.

SENSATION LEVEL AND SOUND PRESSURE LEVEL VERSUS CAEP POWER

Regression analysis on 66 data points from 11 infants for the speech stimuli /m/ and /t/ indicates a significant, positive relationship between SL and CAEP Power (r = 0.38, p = 0.0015) as seen in Figure 4. CAEP Power is zero at -1.25 dB SL. Figure 4.1 and Figure 4.2

indicate that CAEP Power is zero at 56.2 dB SPL for the speech stimulus /m/ and at 37.1 dB SPL for the speech stimulus /t/, respectively.

SENSATION LEVEL VERSUS P-VALUE

As shown in Figure 5 regression analysis of 66 /m/ and /t/ data points found a significant, negative relationship between SL and *p*-value ($r = -0.4695$, $p = 0.00007$), that is, as SL increases, *p*-value decreases. The regression line hits the p=0.05 criterion line at 11.4 dB SL. Figure 6 is constructed based on Figure 5.

SENSATION LEVEL VERSUS DETECTION SENSITIVITY

Figure 6 displays CAEP sensitivity as a function of SL for three infant populations: NH in noise (our study), NH in quiet, and HI in quiet. Sensitivity was calculated by dividing the number of CAEPs (i.e. p<0.05) by the total number of runs for a particular SL. The 50% sensitivity point for our infants is approximately 17.5 dB SL.

Discussion

The aim of this study was to investigate the audibility of the speech sounds /m/ and /t/ behaviourally and cortically in noise by NH infants. As is seen in older adults and children, the following was predicted:

- Speech-evoked cortical responses in noise would also be measurable in infants;
- Improving SNR (by presenting at higher SLs) would result in increased amplitudes;
- Behavioural and cortical measures using speech stimuli in noise would correlate.

It was also hypothesised that the noisy environment would simulate a hearing loss in our infants, and the associated recruitment. If this is the case, then the amplitudes and detection sensitivities of cortical responses for NH infants in noise would potentially reflect those of

HI infants (in quiet). Finally it was hypothesised that under noisy conditions the absence of CAEPs seen in HI infants is also seen in NH infants.

Behavioural

The MRLs obtained, approximately 55 and 40 dB SPL for /m/ and /t/, respectively, noticeably have 15 dB difference between them. It is possible that a contributing factor is apparent from viewing Figure 1; the ILTASS noise has a reduction in spectral energy at the frequency where /t/ peaks. The more efficient masking of the /m/ stimulus essentially means that our simulated hearing loss is a mild rising one. In a background noise of 55 dB SPL our infants required an SNR = 0 dB in order to minimally respond to, or 'detect' the /m/ stimulus, and an SNR = -15 dB to detect /t/. Seeing as most tests involving noise start from around the age of 6, it would be worthwhile to investigate the SNR required for speech detection in subjects younger than this. It would also be interesting to note whether differently shaped noise would yield a more consistent masking effect to both speech sounds.

Electrophysiology

This study established that as is seen in other age groups, speech-evoked cortical responses in noise can also be measured in NH infants (Anderson et al, 2010; Cunningham et al, 2001; Martin et al, 1997; Russo et al, 2009; Warrior et al., 2004; Whiting, Martin & Stapells, 1998; Wible, Nicol & Kraus, 2002).

Although not one of our aims it was noted that that no amplitude or latency differences were found between the /m/ and /t/ waveforms. This was contrary to Purdy et al (2004) where NH infants *in quiet* yielded larger /t/ amplitudes and increased /m/ latency (when compared to each other). It is entirely possible that our sample size was insufficient to detect a difference, or perhaps the lack of difference could be due to masking noise effect. While these are no more than speculations, it is an area with potential clinical applications in the documentation of auditory processing and hence worthy of further investigation in various populations (Hall, 2007).

Returning to our predictions, it was found that improvements in SNR yielded increases in speech-evoked cortical amplitudes (as seen in Figure 2 and 3). This was consistent with other child and adult studies that found as SNR improved, amplitudes increased (Anderson et al, 2010; Cunningham et al, 2001; Martin et al, 1997; Russo et al, 2009; Warrior et al., 2004; Whiting, Martin & Stapells 1998; Wible, Nicol & Kraus, 2002). It was noticed that P-N amplitude was more strongly correlated with SL than P alone, suggesting the consideration of this variable in future studies of this nature.

It was also hypothesised that speech-evoked cortical potential amplitudes would reflect those of HI infants. The P-N amplitudes in Figure 3 shows that NH infants in were *not* significantly different from those of HI infants assessed by Van Dun, Carter and Dillon (in preparation), in fact they are significantly larger than the amplitudes of NH infants in quiet assessed by Carter et al (2010). Larger amplitudes at low SLs for these groups compared to the NH infants in quiet is reflective of recruitment. These results show that NH infants in noise CAEP amplitudes are characteristic of HI infants'.

Since behavioural and cortical speech in noise measures correlate in older children and adults, it was hypothesised that this would also be the case in our NH infants. Figure 4 demonstrates that it might be possible to calculate CAEP power at different intensities, find the point where the the CAEP Power is equal to zero, and the corresponding SL. Figure 4 shows that this point is -1.25 dB SL, which happens to be very close to 0 SL, i.e., the behavioural MRL. This indicates that the CAEP starts to emerge from about the same point the child starts to react to the sound (in quiet this would be detectable). Figure 4.1 and 4.2 similarly show the point where the the CAEP Power is equal to zero, and the corresponding SPL for the speech sounds /m/ and /t/ respectively. Again, both are very close to their respective MRLs (/m/ point = 56.2 dB SPL; mean 55.45 dBSPL and /t/ point = 37.1 dB SPL; mean 38.63 dB SPL.). These findings support the notion that behavioural and cortical speech in noise measures may also correlate in infants. However, although CAEP power indicates SL is about 0 dB to emerge, it only will be detectable (on average) from about 11 dB SL on (as seen in Figure 5, where p=0.05 at 11.4 dB SL. This is caused by the noise in the recording which obscures the cortical response, and hence entirely dependent on the number of epochs recorded.

Another hypothesis was that detection sensitivities of cortical responses for NH infants in noise would reflect those of HI infants, since we predicted that the addition of noise simulating a hearing loss would be sufficient to evoke similar auditory responses. Figure 6 shows that the 50% sensitivity point for our infants is approximately 17.5 dB SL. This is the point where, if going above this SL, a CAEP is more likely to be detected than not. A comparison between Carter et al (2010), Van Dun, Carter and Dillon (in preparation) and our study revealed that NH infants in quiet detection sensitivities quite closely reflect those of NH infants in quiet, whereas we were expecting to be more closely aligned with the HI infants. In particular, the HI infants had much higher sensitivites at low SLs whereas the other two groups' sensitivities increased more gradually. The possible roles of recruitment and/or inconsistent behavioural responsiveness in HI infants are to be further investigated by Van Dun, Carter and Dillon (in preparation), however if the former is the case then this does not explain why the HI and NH infants in noise had such similar amplitude characteristics (as seen in Figure 3). Perhaps there are additional effects, beside recruitment at play which masking noise does not sufficiently replicate.

Finally, when observing Figure 6 it becomes apparents that none of the infant groups, even 20, 30 dB above their behavioural thresholds have 100% detection sensitivities. This means that missing corticals are not explained by the presence of HI, or the wearing of hearing aids, it is because of age.

Limitations and future research

This study was subject to the statistical limitations that come with a small sample size. Larger sample size and an increased number of test conditions could combat this, however it is important to take into account how fatigue affects CAEPs, particularly when dealing with an infant population. It also cannot be ensure that all of the subjects have normal auditory processing abilities. In fact, it is likely that at least one infant has an auditory processing disorder given the 10% incidence rate, however at this stage it is only possibly to diagnose from around the age of 6. It is possible that because these children perform poorly in noise and we have tested in that condition that they are not representative of the intended population. This ties in with a possible extension of this study, where the current paradigm is adapted by adjusting the noise source 90º away from the speech stimuli. This should facilitate detection of speech sounds in noise and be reflected in cortical responses. This information could be used for the LISN-S test at NAL with a younger population, which looks for auditory processing disorders, specifically, difficulties with spatial auditory processing. Another possible extension includes further investigation of detection sensitivities in other infant population, particularly those with NH to explore cortical absence further. Although no direct clinical implications are proposed from this study it does contribute to the research field; there is some support for the utilisation of NH infants in noise to simulate HI infants. If this is the case, while it would be valuable to be able to more closely control aspects of the 'hearing loss' than is possible with HI infants, it is unlikely that the breadth of hearing deficits can be fully appreciated, and there is further research required for example to explain why noise can simulate some HI results such as P-N amplitude (see Figure 3) and not CAEP detection sensitivities (see Figure 6).

Conclusion

NH infant audibility of the speech sounds /m/ and /t/ was investigated behaviourally and cortically in noise. As was predicted and seen in other population, infants' speech-evoked cortical responses in noise are able to be measured and CAEP amplitudes increase with increasing SNR. There is also the potential that the emergence of CAEPs is correlated with MRLs, that is, that behavioural and cortical speech in noise measures are correlated in infants. It was also established that NH infants in noise, like HI infants are susceptible to 'missing corticals', and that it appears this is due to age, not the hearing loss. Finally, simulating a hearing loss using noise in an infant population showed promising similarities to the HI infants' amplitudes, but there appears to be other contributing factors, given the differences in detection sensitivities.

Acknowledgements

The author would like to thank Bram Van Dun for his supervision audiologist Sharna Raley for her assistance with data collection, and the National Acoustic Laboratories.

Declaration of interest: The authors report no declarations of interest.

Figures

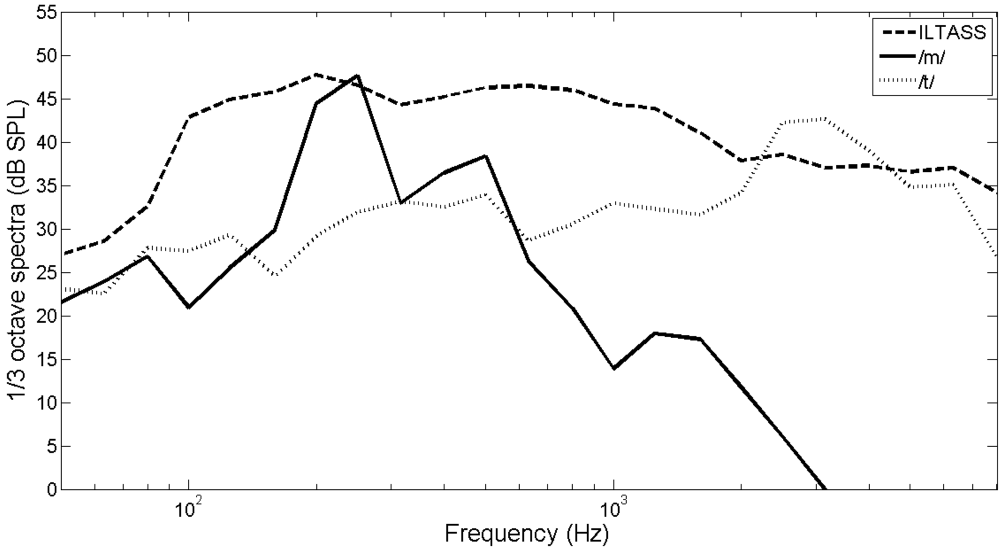

Figure 1. The 3rd-octave power spectra for speech sounds /m/ and /t/ presented at 55 dB SPL, and for International Long-Term Averaged Speech Spectrum (ILTASS) noise presented at 55 dB A.

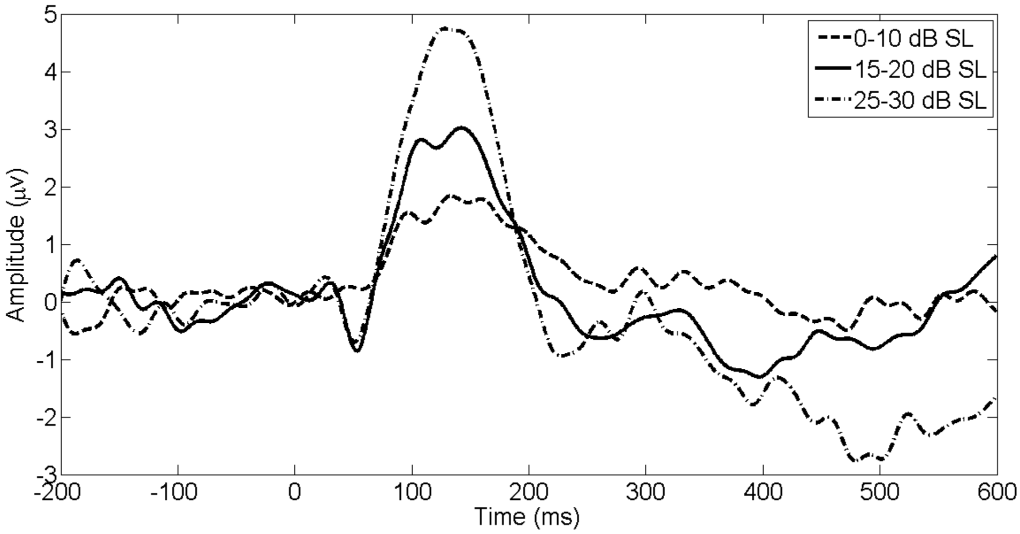

Figure 2. Response waveform grand averages for three different sensation level ranges: 0-10 dB SL, 15-20 dB SL, 25-30 dB SL.

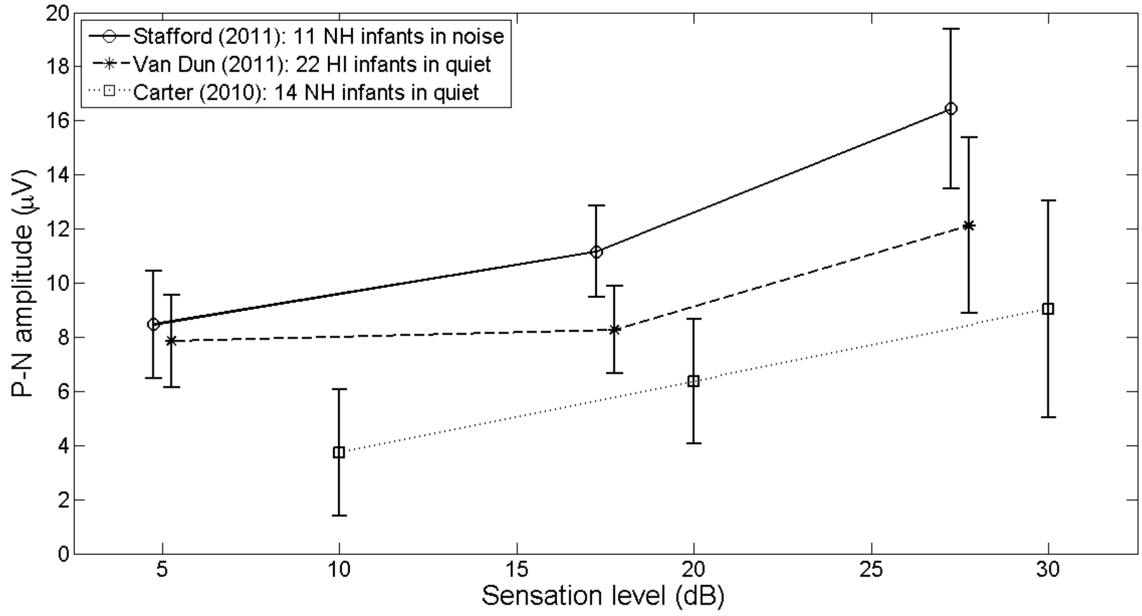

Figure 3. CAEP Positive-to-Negative (P-N) amplitudes from three studies as a function of SL ranges: 0-10 dB SL, 15-20 dB SL, 25-30 dB SL. Error bars denote 95% confidence intervals. A comparison is made between our infants and two other infant speech detection studies, also using /m/ and /t/ stimuli. Van Dun, Carter & Dillon (in preparation) evaluated hearing-impaired infants in quiet (aged 8 to 30 mo) while Carter, Golding, Dillon & Seymour (2010) evaluated normal hearing infants in quiet (aged 9 to 15 mo).

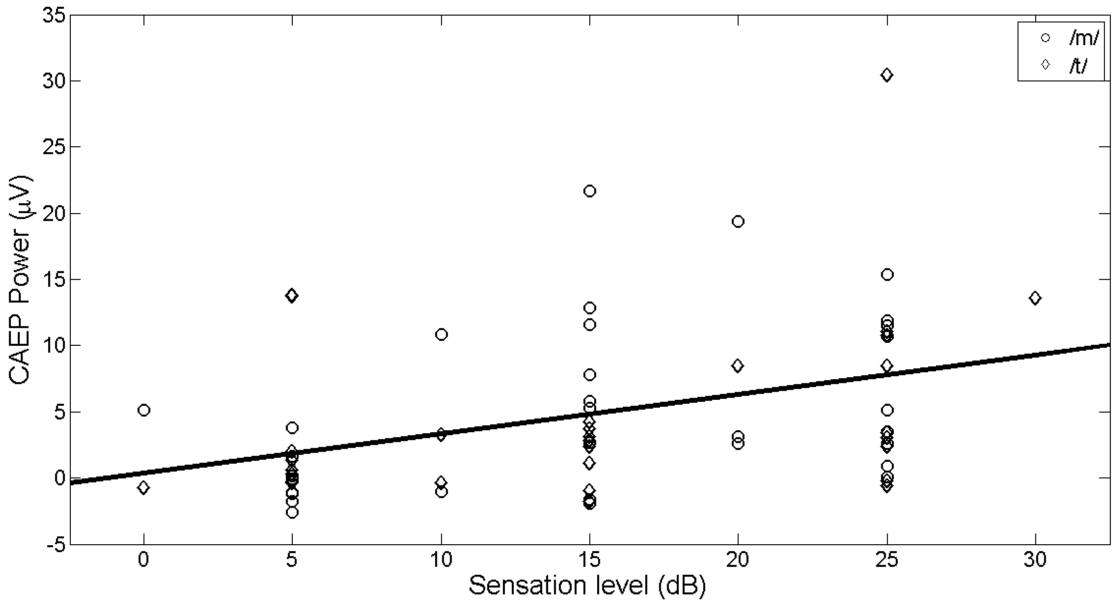

Figure 4. Scatterplot of 66 data points form 11 infants, displaying CAEP Power as a function of SL for the speech stimuli /m/ and/t/.

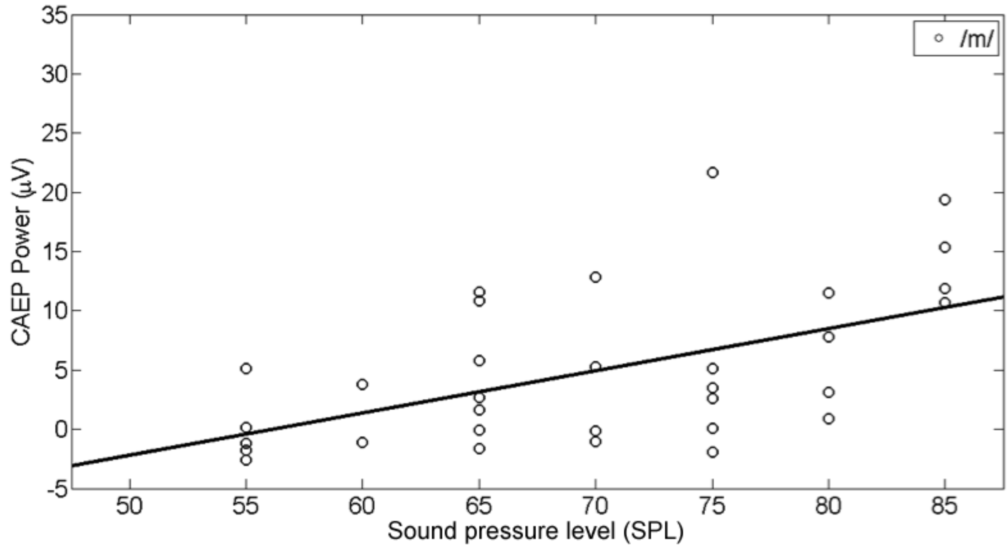

Figure 4.1. Scatterplot of 33 data points from 11 infants, displaying CAEP Power as a function of SPL for the speech stimulus /m/.

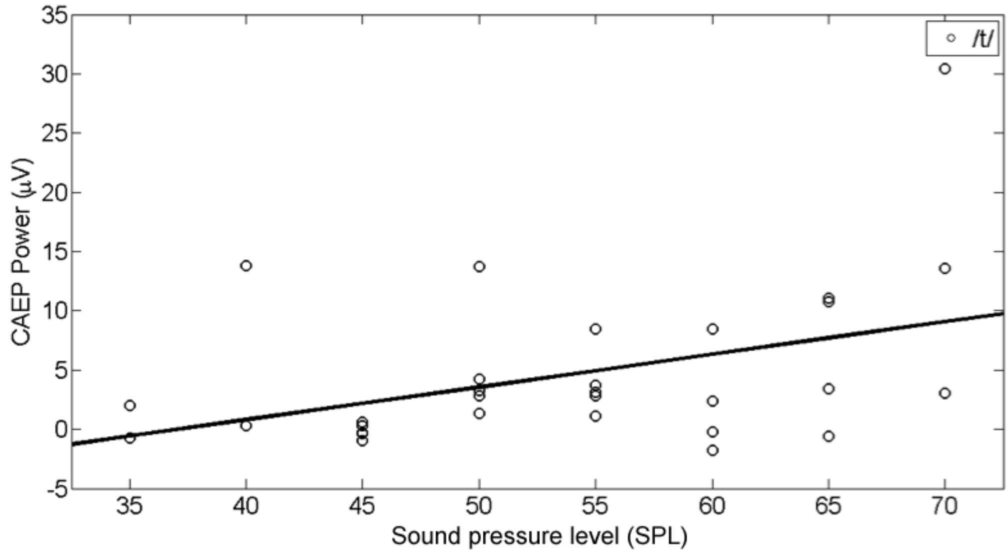

Figure 4.2. Scatterplot of 33 data points from 11 infants, displaying CAEP Power as a function of SPL for the speech stimulus /t/.

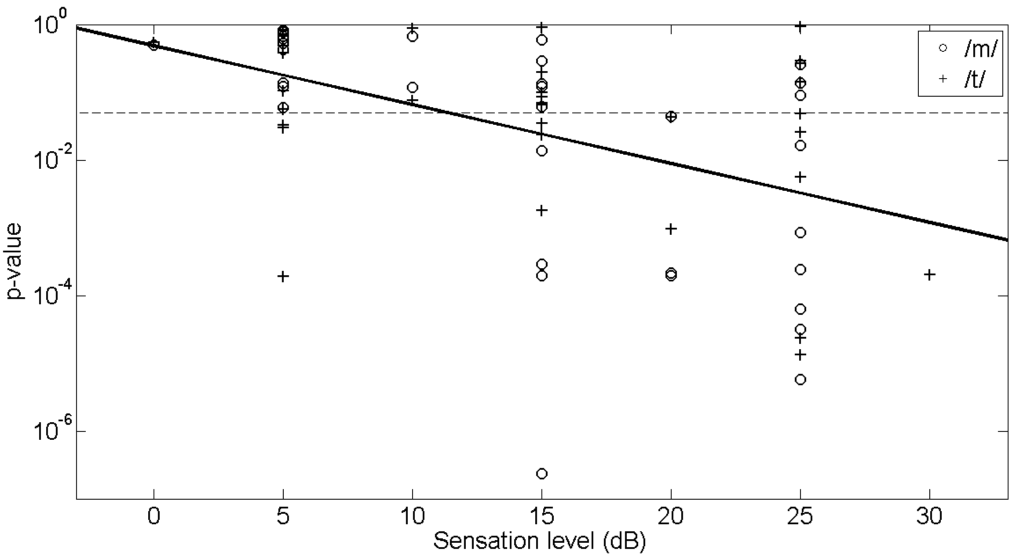

Figure 5. Scatterplot of 66 data points from 11 infants, displaying *p*-value versus sensation level for speech stimuli /m/ and /t/. The dashed horizontal line represents a $p = 0.05$ criterion used to determine whether a response could be accepted as present.

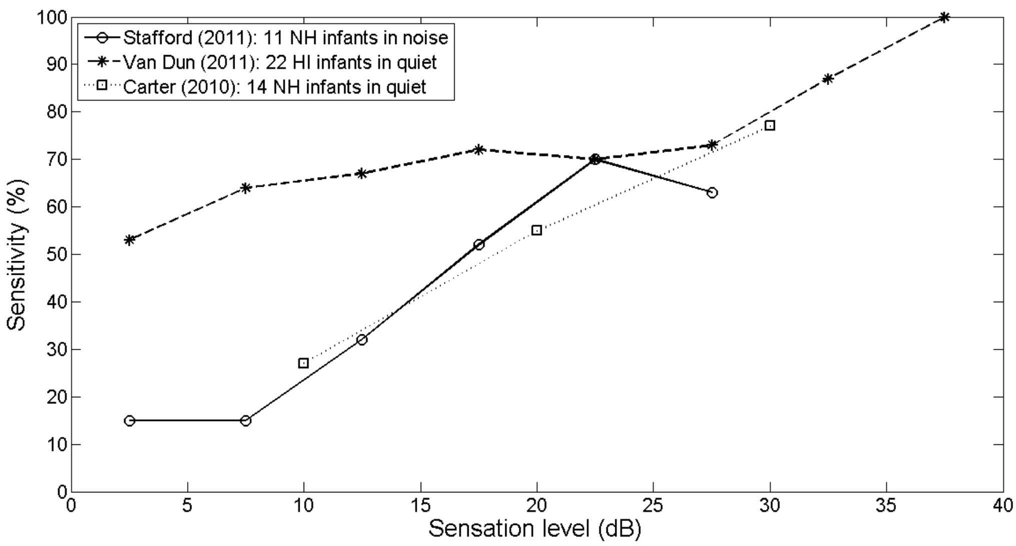

Figure 6. Sensitivities from three studies as a function of SL: A comparison is made between our infants and two other infant speech detection studies, also using /m/ and /t/ stimuli. Van Dun, Carter & Dillon (in preparation) evaluated hearing-impaired infants in quiet (aged 8 to 30 mo) while Carter, Golding, Dillon & Seymour (2010) evaluated normal hearing infants in quiet (aged 9 to 15 mo).

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