BEHAVIOURAL PITCH PERCEPTION & BRAINSTEM ENCODING OF ODD AND EVEN HARMONICS

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CERTIFICATE

This is to certify that this dissertation entitled "**Behavioural pitch perception & brainstem encoding of odd and even harmonics**" is a bonafide work submitted in part fulfillment for the degree of Master of Science (Audiology) of the student with Registration No. 11AUD006. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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CERTIFICATE

This is to certify that this dissertation entitled "**Behavioural pitch perception & brainstem encoding of odd and even harmonics**" has been prepared under my supervision and guidance. It is also certified that this has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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DECLARATION

This dissertation entitled "**Behavioural pitch perception & brainstem encoding of odd and even harmonics**" is the result of my own study under the guidance of Dr. Vijay Kumar Narne, Lecturer in Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier in any other University for the award of any Diploma or Degree.

Mysore

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Dedicated to
Thatha &
Mama- the two
most
inspirational
people in my
life !!!!!!

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Chapter 1

INTRODUCTION

Pitch, the psychophysical correlate of frequency is one of the three important attributes that can be used to describe a sound. Extracting the pitch from a complex signal forms a vital function of the auditory system since pitch plays an important role in perceiving the prosody of speech, aids in speaker identification, helps in segregating the competing sounds that share a common fundamental frequency (Bregman, 1990; Darwin & Carlyon, 1995) and in the perception of lexical contrasts of tonal languages (e.g. Manipuri & Mandarin). This essential characteristic of a sound, pitch, can be assessed behaviourally using pitch matching tasks. Research shows a good correspondance between the behaviourally perceived pitch and the spectrum of the electrophysiological measure, Frequency Following Response (FFR) (Smith, Marsh, Greenberg & Brown, 1978; Greenberg, Marsh, Brown, & Smith, 1987; Galbraith, 1994; Galbraith & Doan, 1995; Krishnan 2002, 2007; Krishnan, Xu, Gandour & Cariani, 2004, 2005; Skoe & Kraus, 2010; Krishnan & Plack, 2011). The current study focuses on validating this relation between behaviourally perceived pitch and the pitch obtained from FFR for a given stimulus.

FFR is a scalp-recorded, tiny electrical response consisting of periodic peaks whose periodicity (intervals between two major peaks) corresponds to the period of the stimulus frequency (Moushegian, Rupert, & Stillman, 1973). These responses are claimed to be phase locked to the individual cycles of the stimulus waveform &/or the envelope of the periodic stimulus (Krishnan, 2007). The onset latency of the FFR indicates that it originates from the structures in the higher brainstem. In this regard, Smith, Marsh, and Brown (1975) concluded that the Inferior Colliculus is the primary neural generator for the FFR & there is no significant contribution from the brain-stem nuclei caudal to the Inferior Colliculus.

The FFR elicited at the level of the brainstem reflects synchronous phase locked neural activity elicited by sounds containing sustained acoustic features such as sinusoidal tones, harmonically complex vowels, and musical notes. Hence, it has been popularized as a tool to study the sub-cortical representation of speech in normal hearing individuals (Johnson, Trent, Nicol, & Kraus, 2005), musicians (Kraus, Skoe, Parbery-Clark, & Ashley, 2009) and clinical population (Wible, Nicol & Kraus, 2004; Russo, Bradlow, Skoe, Trommer, Nicol, Zecker, & Kraus, 2008; Russo, Nicol, Trommer, Zecker, & Kraus, 2009). Further, it has also been used as an objective tool to study the sub-cortical encoding of the pitch of many types of tonal complexes (Smith, Marsh, Greenberg, & Brown, 1978; Greenberg, Marsh, Brown, & Smith, 1987; Galbraith, 1994; Galbraith & Doan, 1995; Skoe & Kraus, 2010; Krishnan & Plack, 2011), and also voice pitch in the auditory brainstem (Krishnan, 2002, 2007; Krishnan, Xu, Gandour, & Cariani, 2004, 2005).

Studies which made use of FFR to investigate the pitch processing at the brainstem level were taken up on the basis of the behavioural pitch estimation experiments which showed the perception of the fundamental frequency of a complex signal even when the complex was devoid of the fundamental (Seebeck, 1843; Schouten, 1940; Licklider, 1954; Bernstein & Oxenham, 2003). This finding indicated that the envelope periodicity of the stimulus waveform provided sufficient cues for the pitch to be perceived. This in turn made researchers curious to find out whether this finding would hold good even in the case of FFR, which is thought to encode the envelope periodicity of a signal. Smith et al. (1978) were among the first to demonstrate this phenomenon by recording FFR to a complex tone with 'missing fundamental'. They found that the frequency spectrum of the response contained a component at its missing fundamental (F_0). Hence, the electro-physiologically recorded FFR correlated with the behavioural results under these stimulus conditions, wherein the periodicity of the complex stimulus correlates with the perceived pitch.

Although the above electrophysiological studies have suggested that pitch is encoded at the level of the brainstem (FFR), other physiological studies (Palmer & Winter, 1992) and functional neuroimaging reports (Hall, Johnsrude, Haggard, Palmer, Akeroyd, & Summerfield, 2002; Griffiths, Uppenkamp, Johnsrude, Josephs, & Patterson, 2001; Wessinger, Van Meter, Tian, Pekar, & Rauschecker, 2001) suggest that the processing of temporal regularity begins in the brainstem, but pitch extraction is completed in Heschl's gyrus and Planum temporale of primary auditory cortex (Rademacher, Caviness, Steinmetz, & Galaburda, 1993; Rademacher, Morosan, Schormann, Schleicher, Werner, Freund, & Zilles, 2001; Hackett, Preuss, & Kaas, 2001). In presence of these contradictory evidences, stating that FFR reflects pitch perception arouses debate. Hall (1979), Chambers, Feth, & Burns (1986), and Gockel, Carlyon, Mehta, and Plack. (2011) used stimuli whose pitch was different from its periodicity and reported that FFR was not a true representation of pitch perception. Hence, it may be proposed that even though FFR is said to code the periodicity of a signal (Marsh, Brown, & Smith, 1975; Smith et al., 1975; Glaser, Suter, Dasheiff, & Goldberg, 1976), this doesn't correlate with the pitch estimated by the listener subjectively especially under some particular stimulus paradigms (Hall, 1979; Chambers et al, 1986; Gockel et al., 2011).

1.1 Need for the study

There exists conflicting evidence in literature regarding the use of FFR as a tool to assess pitch coding. Smith et al. (1978) were among the first researchers to report a good correspondence between the perceived pitch and periodicity coded by the FFR in a complex signal. Several other researchers have investigated the representation of pitch of complex tones in the auditory brainstem using FFR elicited by various speech and non-speech stimuli and have claimed that the peaks in FFR spectrum correlate with the perceived pitch (Greenberg et al., 1987; Galbraith, 1994; Galbraith & Doan, 1995; Krishnan, 2002, 2007; Krishnan et al., 2004, 2005; Wong, Skoe, Russo, Dees, & Kraus, 2007; Skoe & Kraus, 2010). Hence, these studies conclude that pitch is coded at the level of brainstem and can be assessed using FFR.

Contrary to the above view, Krishnan and Plack (2011) and Gockel et al. (2011) obtained similar temporal pattern of neural activity at the auditory nerve level and at the level of the Inferior Colliculus (as found in the FFR) using auditory nerve models. Hence, they suggest that the brainstem doesn't extract pitch information; rather, it only "preserves" the temporal pattern of neural activity, necessary to encode pitch, which was observed at the auditory nerve level itself. Similarly, by using stimuli whose periodicity differed from the behaviourally evoked pitch, Hall (1979), Chambers et al. (1986) and Gockel et al. (2011) concluded that the periodicity coded by the FFR doesn't correlate with the pitch sensation elicited by the same stimulus behaviourally. Thus, these results also suggest that the FFR obtained at the level of the brainstem reflects a "preservation" of the different temporal envelope of the neural responses occurring at earlier stages of processing, but does not reflect pitch processing per se. Hence, investigations on the relationship between the scalp-recorded FFR and pitch perceived by the subject show contrasting evidence.

Hall (1979) compared the FFR spectrum with the behaviourally perceived pitch of amplitude modulated tones with varying envelope periodicities and concluded that FFR is a reflection of envelope periodicity, but not of the pitch of the missing fundamental. However, it is not clear in this study, how the amplitude modulated complex with a 400 Hz periodicity had a pitch that corresponded to 200 Hz. Furthermore, Chambers et al. (1986) used inharmonic complexes to prove that FFR represents the encoding of waveform periodicity but not pitch perception. They found that the peaks in the FFR spectrum were different from the pitch matched by the subjects. However, the behaviourally obtained pitch matches were only slightly (5-15Hz) different from the peaks of the FFR spectrum. Such a small difference is insignificant to conclude that FFR can't be equated to the pitch perceived, since such small variations in pitch matches are inevitable, owing to the difficulty level of the pitch matching task (Schouten et al., 1962; Patterson, 1973; Lundeen & Small, 1983).

The current study aims at re-examining the contradicting evidences on the use of FFR as a reliable measure of behavioural pitch perception utilizing complex tones consisting of a missing fundamental, odd and even harmonics of the complex presented monaurally. Using a protocol comparable to the current study, but in the dichotic condition, Gockel et al. (2011) reported similar findings as Hall (1979) and Chambers et al. (1986). However, they used only even harmonics (two in number) to one ear and only odd harmonics (one in number) to the other. Moreover, they used dichotic presentation for FFR recording, which may require integration at the level of the brainstem. However, such evidence for integration at the level of brainstem is limited (Musiek, 1983b). Thus, it can be argued that FFR didn't correlate with behavioural pitch since there was inadequate integration of the dichotic stimuli at brainstem to obtain an FFR, whereas integration of the dichotic stimulus did occur at cortex to result in behavioural pitch perception.

The odd harmonic complex was used as the critical stimulus in this study, since such a complex doesn't have a pitch of $2F_0$ as expected from the spacing between its harmonic components (like found for the even harmonic complex, which has a pitch corresponding to $2F_0$). Instead, it has a dual periodicity with a pitch that corresponds to 9f0/5 Hz and 9f0/4 Hz (Benade, 1976). Hence, studying the FFR in response to such a stimulus would give us a greater insight into the relationship between FFR & pitch perception.

The primary aim of the present study was to investigate the correlation of FFR with the behaviourally perceived pitch. This was taken up to better understand the theories of pitch perception as well as the neural plasticity of the pitch perception. This can be studied by examining whether a training induced enhancement or clinical condition induced degradation in FFR influences the pitch processing or on a more general note, the temporal representation of sound. Therefore, in the current study, we investigated the electrophysiological and behavioural encoding of pitch of odd and even harmonics. This was carried out by recording FFR while the stimuli were presented monotically and by assessing behavioural pitch perception, which in turn would help us to validate if FFR can be used as an objective tool to study pitch perception.

1.2 Aim

This study aims at assessing if FFR reflects pitch encoding at the level of the auditory brainstem.

1.3 Objectives

1. To study behavioural pitch perception of odd and even harmonics in a complex signal with missing fundamental.

2. To obtain FFR using odd and even harmonics of this complex signal with missing fundamental.

3. To compare the periodicity of these complex stimuli estimated from FFR with the pitch perceived behaviourally.

Chapter 2

REVIEW OF LITERATURE

A particular sound signal is usually said to have three physical dimensions- intensity, frequency, and time/phase (Yost, 2009). The subjective attribute of frequency, like loudness and timbre, is called as pitch. American National Standards Institute (ANSI, 1973) defines pitch as "that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from high to low." The main objective correlate for the pitch of a simple pure tone is its frequency. However, the tone's intensity, duration, and temporal envelope also have significant influence on its pitch (Houtsma, 1995). For a complex tone with many different frequencies, like most naturally occurring sounds, we may hear a single pitch or a cluster of pitches (Houtsma, 1995).

2.1 Significance of pitch

Pitch is an essential element of a sound. It conveys most of the prosodic information in speech and also helps to identify the speaker. In tonal languages (e.g Manipuri & Mandrain), pitch variations alter the meaning of a word. Pitch cues also help in segregation of competing sounds based on similar fundamentals, a phenomenon called auditory scene analysis (Bregman 1990; Darwin and Carlyon 1995). Finally, it also contributes to the melody and harmony in music.

2.2 Overview of the models/theories of pitch perception

Many researchers have put forth models and theories to better understand pitch coding in the auditory system. There are basically two theories- spectral theory and temporal theory. Spectral theory says that the frequency is coded based on the location of the signal on the tonotopic axis. The main proponents of this theory are Goldstein (1973), Terhardt (1974) and Cohen, Grossberg, and Wyse (1995). However these theories cannot explain coding of complex signals with unresolved harmonics, amplitude modulated tones, missing fundamental complexes, etc.

The temporal theory, on the other hand, describes mechanisms in which pitch is extracted from the lowest common inter-spike interval that is phase-locked by the neurons. Usually, the waveforms of complex tones show periodic envelope peaks whether or not low-frequency harmonics are contained in the stimulus. Thus, neural phase locking to the periodicity of the low frequency fundamental (F0) plays an important role in the encoding of the low pitch associated with such complex sounds. Most studies have focused on temporal theory because they provide the best account of the diverse range of pitch phenomena including perception of the 'missing fundamental' (Licklider, 1951; Evans, 1983; Shofner 1991b; Rhode, 1995; Cariani & Delgutte, 1996a; Cariani & Delgutte, 1996b; Meddis & O'Mard, 1997, Cedolin & Delgutte, 2005; Larsen et al., 2008). This interval-based representation can predict the pitch of both resolved and unresolved harmonics (Meddis & Hewitt, 1991; Cariani & Delgutte, 1996a; Cedolin & Delgutte, 2005).

The current version of the temporal approach uses autocorrelation, as was originally proposed by Licklider (1951). Meddis and colleagues (Meddis & Hewitt, 1991; Meddis & O'Mard, 1997) have established the most fully developed versions of autocorrelation to explain the pitch of complex stimuli, and investigators like Slaney and Lyon (1993); Yost, Patterson, and colleagues (e.g., Yost, Patterson, & Sheft, 1996); and Bernstein and Oxenham (2005, 2008), have added modifications to these autocorrelation- like models. In autocorrelation, an original time pattern, $x(t)$, is time shifted (by t) and multiplied times the original pattern, and the products are summed. This integrated product is depicted as a function of the time shift (t,lag) between the original and time-shifted pattern, resulting in the autocorrelation function (Yost, 2009).

There are basically two means of studying the pitch perception in humans - behavioural and electrophysiological and many researchers have attempted to find out the correlation between the two.

2.3 Behavioural pitch estimation

A variety of studies have reported that the pitch of a signal depends on the periodicity of its waveform envelope. This was basically demonstrated using periodic complex sounds with fundamental frequencies (F_0) in the range of 50 to 700 Hz that give rise to low pitches associated with their F_0, even when the signal is devoid of this low frequency energy. This phenomenon was initially described by Seeback (1843) but was popularised by Schouten (1938) who called it the "missing fundamental". He concluded that the periodicity of the "residual" higher harmonics give rise to a pitch that corresponds to the low frequency fundamental. Thus, this phenomenon has also been called as periodicity pitch (deBoer, 1976; Evans, 1978; Moore, 1989), residue pitch, virtual pitch, or low pitch (Schouten, 1940). In 1954, Licklider used similar complexes to demonstrate that even when the low-frequency auditory channels were saturated with low-frequency masking noise, the pitch that was heard was derived from the periodicity of the waveform. The importance of periodicity cues for pitch perception was also demonstrated by Bernstein and Oxenham (2003) using unresolved harmonics. In one of their experiments, unresolved even and odd components of a complex (i.e. above the 15^{th}) were presented dichotically to opposite ears such that peripheral spacing between components was $2F_0$. A pitch corresponding to $2F_0$ was perceived that corresponded to the periodicity of the temporal envelope ($2F_0$).

It is a well-accepted fact that the pitch representation is robust for stimuli which have harmonics in the resolved spectral region and less robust for those which have only unresolved harmonics (Krishnan & Plack, 2011). Moreover, it is commonly seen that the complex tones reveal ambiguous virtual pitches, especially for inharmonic tones, which lack the lower components and also for particular harmonic complexes. This pitch perceived is found to depend on frequency of the lowest component (Fastl & Zwicker, 2007). In this context, Krishnan and Plack (2011) showed that, there was ambiguity in pitch judgments when lowest harmonic of the complex was around 720 Hz. This indistinct pitch can be higher or lower than that perceived by a fundamental of similar frequency. Sometimes, such an ambiguous pitch is perceived when pitch match is possible at 2 frequencies (Fastl & Zwicker, 2007). Pitch ambiguity i.e., the observation of multimodal pitch selections for one tone, has been related to ambiguity or quasi periodicity in the temporal fine structure of the stimulus waveform (de Boer, 1956a,b; Schouten et al., 1962).

An odd harmonic complex is one such peculiar stimulus due to the quasi-periodicity in the stimulus waveform. Such a stimulus is found to have a pitch that does not correspond to 2 F_0, even though its envelope consists of 'double spaced' harmonics. Instead, it has a dual periodicity, and hence dual pitch wherein none of the frequencies are equal to 2 F_0. The two frequencies at which the pitch is perceived can be derived from the formula 9f0/5 Hz and 9f0/4 Hz (Benade, 1976).

A large number of behavioural studies have examined pitch perception in normal hearing individuals and discovered that a task of pitch estimation is found to be significantly difficult. Hence, a large inter-subject variability has been documented (Schouten et al., 1962; Patterson, 1973; Lundeen & Small, 1983; Chambers et al., 1986). Some factors that may affect the results of pitch estimation tasks are, training in complex tone pitch matching, prior experience, musical training and other individual variables like motivation, and ability to do pitch judgments. Asking a subject to match to the most obvious pitch or both the pitches they perceive will also matter. The response range of frequencies that the author chooses as valid is also a contributing factor (Schouten et al, 1962; Patterson, 1973; Lundeen & Small, 1983).

2.4 The Frequency Following Response (FFR) and its relation to pitch perception

The Frequency Following Response (FFR) reflects sustained synchronous phase-locked activity in a population of neurons that phase-lock to the low rates of waveform periodicity in the stimulus (Marsh et al., 1975; Smith et al., 1975; Glaser et al., 1976). FFR can be elicited by any stimulus that comprises a steady state or sustained portion. Commonly used stimuli are speech (Krishnan, 2002, 2007; Krishnan et al., 2004, 2005) tone bursts (Moushegian, 1973; Glaser et al., 1976) and various other types of complex signals (Galbraith, 1994; Galbraith & Doan, 1995;

Skoe & Kraus, 2010; Krishnan & Plack, 2011). The amplitude is largest for vertex placement and for frequencies below 500 Hz (Moushegian et al., 1973; Marsh et al., 1975; Smith et al., 1975). The threshold for the scalp recorded response is high, between 30-60 dB SL, relative to the behavioural threshold for the stimulus (Moushegian et al., 1973; Marsh et al., 1975; Smith et al., 1975). The scalp recorded FFR can be recorded between 70 Hz and 2000 Hz (Glaser et al, 1976; Moushegian, 1973). This upper limit of obtaining FFR correlates with the upper limit of phase locking by the neurons in the auditory brainstem. It has been observed that the amplitude of FFR decreases with increasing frequency for the tone bursts (Glaser et al., 1976), increasing harmonic number for multi-tone complexes (Greenberg et al., 1987) and synthetic speech stimuli (Krishnan, 2002). This reduction in amplitude may reflect the drop in phase locking when frequency increases.

The neural generators of FFR are found to be the higher brainstem structures. Smith et al., (1975) found that the latency (5.3 ms) of FFR recorded directly from the Inferior Colliculus (IC) was similar to the latency of the scalp recorded potential (5.6 ms). The comparable latency is consistent with the IC being the primary neural generator for the FFR. This hypothesis was further tested by recording FFR bilaterally from IC and Medial Superior Olive (MSO), and from the scalp of a Cat. The authors saw that cryogenic cooling of the IC led to a significant reduction of both the IC and scalp FFR, while FFR recorded from MSO remained at the control amplitude. They concluded that the brain-stem nuclei caudal to the IC don't contribute majorly to the FFR recorded from the scalp, at least in the Cat. Marsh, Brown, and Smith, (1974) propose two distinct pathways from the Cochlear Nucleus (CN) to the IC in the generation of the FFR; a direct pathway to the contralateral IC via the Lateral

Lemniscus (LL), and an ipsilateral pathway via the SOC and the LL. Hence, it has most commonly been reported that the FFR originates from the region of the IC (Sohmer, Pratt & Kinartti, 1977).

FFR is often assumed to reflect the pitch of sounds as perceived by humans. Since the FFR constitutes a relatively pure measure of neural periodicity, it has been used by many researchers to monitor periodic neural activity during perception of pitch of simple & complex tones. The preliminary report on FFR as being a measure of pitch perception using simple sinusoids came from Moushegian et al. in 1973. They recorded FFR from the human scalp using tonal signals between 250 Hz – 2 kHz. This study revealed that each frequency evokes a unique response, in which the pattern of neural discharge is time locked to the temporal structure of the stimulus. They demonstrated that the brainstem response to a 250 Hz tone follows the periodicity of the tone, such that the peaks in the response occur at 4 ms intervals (period = 1/frequency; 1/250 Hz=4ms).

FFR is also claimed to be an electrophysiological correlate of pitch perception in complex tones, especially the missing fundamental. One of the early investigations by Smith et al., (1978) showed that FFR to a missing fundamental complex exhibited majority of its spectral energy at the frequency of the missing fundamental, similar to the pitch perceived during behavioural tasks. However, the frequencies of the four component partials of the complex tone were not significantly represented within the FFR spectrum. The FFR obtained for the missing fundamental, is spectrally similar to, and quite often, larger in amplitude than the FFR wave evoked by a pure tone of the same pitch. Hence, even though the pure-tone and complex tone stimuli have different spectral compositions, the FFR waveforms evoked by each of them contain, predominantly, one frequency that conforms to the perceived pitch of both stimuli. These results support the hypothesis that the pitch of the missing fundamental (residue pitch) is based on the period of a stimulus wave rather than its spectral content. Similar to the behavioural studies, they also demonstrated that narrow-band noise centred at the missing fundamental has no effect on FFR to a complex tone with missing fundamental, but drastically attenuates FFR to a pure tone at that frequency. The masking results further suggest that the pitch of the pure tone is carried by elements most sensitive to low frequencies, whereas, the pitch of the missing fundamental is mediated by elements sensitive to frequencies other than those within the band of the masking noise, probably using the temporal coding mechanism.

In 1979, Greenberg and Marsh recorded the FFR during presentation of multicomponent harmonically related tone bursts. The frequency spectrum and waveform periodicity of FFR to low-order harmonics (harmonic ranks 3-5) were clearly dominated by a frequency corresponding to the "missing fundamental". Comparable to behavioural results, the amount of energy in this frequency band reduced drastically with increasing harmonic rank, becoming negligible for harmonics above the thirteenth. Hence they concluded that the existence of a similarity between psychophysical and FFR measures of pitch raises the possibility that the "transmission code" in the brainstem auditory pathway is also based on the neural periodicity.

Response to such a complex tone, lacking its fundamental, was also investigated by Greenberg, Marsh, Brown and James (1987). They concluded that FFR to complex tones, devoid of its fundamental, is spectrally comparable to that recorded by pure tones of the same frequency. They also found that the FFR waveform to signals containing only odd harmonics of a 122 Hz signal are significantly different from that recorded for stimuli with all the harmonics of a 244 Hz signal. However, spectral analysis for both stimuli revealed a peak at the same frequency that corresponded to the common difference frequency (244Hz). It was found that the waveform for odd harmonics had 3 periodicities (i.e. 3 different time periods based on interval analysis) but still showed a peak only at 244Hz in spectral analysis. Hence, they concluded that by doing spectral analysis (FFT) of the response added waveform; we can get information solely on coding of the envelope of the signal and not about the pseudo-periods (de Boer, 1956). However, FFT of a response subtraction waveform results in a peak away from 244Hz (e.g 280Hz) which matches with the behaviourally obtained pitch. However, on further examination of this data, we observed that according to the periodicity calculated from the waveform and behavioural pitch estimation data, this signal should have a dual pitch of 216 and 296Hz, not at 280Hz as reported by Greenberg et al (1987). Thus, in this study it is unclear how they obtained a response at 280Hz for an odd harmonic complex with fundamental of 122Hz, in the FFR and behavioural data.

Krishnan and Plack (2011) claimed that the FFR recorded to complex tones codes for pitch. They reported doubling of pitch behaviourally when unresolved harmonics are presented in alternating sine and cosine (F_0 of 90 Hz (ALT90)) phases which are also evident in the FFR spectrum & autocorrelation function. The temporal pattern of phase-locked neural activity obtained from FFR & behavioural pitch estimates shifted from a 90 Hz periodicity to a 180 Hz periodicity when the lowest harmonic in the complex was shifted from a completely resolved spectral region to a completely unresolved spectral region. Thus, FFR results are similar to the behavioural results, suggesting that pitch relevant information preserved in the FFR could serve as an electrophysiological correlate of the behavioural pitch measure. They also conclude that FFR periodicity strength decreases for unresolved harmonics which is consistent with previous behavioural measures. However, the reduction in the FFR response is small in comparison to the behavioural results. From ACF data they conclude that, when the lowest frequency of the harmonics was in the resolved region, the second peak of ACF occurred at a delay corresponding to the period of 90 Hz which was relatively bigger than the first peak (corresponding to a periodicity of 180 Hz). When the lowest frequency of the harmonics was in the unresolved, higher spectral region, the two peaks were either similar in magnitude or the first peak (180Hz) was greater in magnitude than the second peak (90Hz). This shift in the relative prominence of the autocorrelation peaks serves as a neural correlate of the doubling of perceived pitch observed for alternating 90Hz stimuli in behavioural estimates and in previous psychophysical studies (Ritsma & Engel, 1964; Lundeen & Small, 1983). They added that, usually the first peak in the ACF is used to estimate pitch. Hence, the results for ALT stimuli have been interpreted to suggest that pitch extraction based on autocorrelation does not represent the doubling of pitch observed in behavioural experiments, since the first ACF peak for both resolved and unresolved stimuli was found at the same delay. However, the prominence of the second peak, led them to conclude that FFR does correlate with pitch.

Contrary to the above reports, a small number of researchers have argued against the use of FFR as an objective measure of pitch. Hall (1979) was the first to point out that the two stimuli utilized by initial investigators like Smith et al., (1978) had the same waveform envelope periodicity, so the FFR and its spectra corresponded to both the pitch and the waveform envelope. However, it is possible that the FFR only reflected a neural following of the waveform envelope and had no relation to pitch perception. He found that the FFR recorded for the three complex stimuli correlated well with the periodicity of the waveform envelope, but not the perceived pitch. He concluded that the FFR represents the encoding of waveform envelope periodicity but not the perception of the missing fundamental.

The relation between the FFR and the low pitch of complex tones was investigated on four normal hearing adults with extensive musical training, by Chambers et al. (1986). Eleven complex stimuli were synthesized such that frequency content varied but waveform envelope periodicity was constant. This was accomplished by repeatedly shifting the components of a harmonic complex tone upward in frequency by ΔF of 20 Hz, producing a series of six-component inharmonic complex tones with constant inter component spacing of 200 Hz. Pitch-shift functions were derived from pitch matches for these stimuli to a comparison pure tone. The FFRs were recorded for the complex stimuli that were judged most divergent in pitch by each subject and for pure tone signals that were judged equal in pitch to these complex stimuli. Spectral analyses suggested that the spectral content of the FFRs elicited by the complex stimuli did not vary consistently with component frequency. While the pitch shifted in a monotonic fashion with increases in the frequency content of the components of the stimuli, the FFR fundamental frequency remained fairly constant near 200 Hz. The pure tone and complex stimuli elicited matching pitch but evoked FFRs of different fundamental frequency. Chambers et al. (1986) do not suggest that periodicity mechanisms at the brain stem level do not contribute to pitch extraction. Nevertheless, they conclude that the frequency of the FFRs closely approximated the frequency of the stimulus envelope.

A recent exploration by Gockel et al. (2011) used inharmonic complexes (Phase 1), followed by odd and even harmonics (Phase 2) of a complex tone with a 244 Hz fundamental to investigate the relationship between FFR and pitch perception. Using inharmonic complexes in Phase 1, they found that peak of the FFR spectra corresponded to the envelope rate of 244Hz while the pitch matches calculated for these stimuli did not occur at this frequency. By comparing the FFR to response obtained from an auditory nerve model, they concluded that FFR only demonstrates the maintenance of the periodicity coded by the auditory nerve. In phase 2, stimulus presentation conditions that were primarily used were: (1) 2+3+4th harmonic to the left ear; (2) 2+4th harmonic to the left and 3rd to the right. When all components were presented to the same ear, the peak of the magnitude spectrum of the FFR & pitch perceived corresponded to the "missing" F_0. However, for "dichotic" condition (2), the same pitch i.e., that of the missing fundamental (244Hz) was perceived but the peak of FFR spectrum was obtained at 448Hz. The ACF of the FFR obtained in this study for dichotic presentation of the harmonics was dissimilar to that obtained for monaural presentation, and the FFR obtained to this dichotic condition did not reflect the pitch perceived. The results indicate that the neural responses reflected in the FFR preserve monaural temporal information that may be important for pitch, but do not directly represent the pitch of dichotic stimuli. Overall, they concluded that the FFR reflects a low-pass-filtered "preservation" of the envelope periodicity reflected in the neural responses occurring at lower stages of processing, but does not reflect pitch processing.

As seen from literature, there are contradictory views about whether or not FFR is a true reflection of pitch processing. Some researchers claim that FFR recorded at the level of brainstem replicates the pitch perceived by the listener, while others suggest that it doesn’t correlate with behavioural pitch estimates. Hence, it is necessary to investigate the relation between FFR and pitch perception to validate whether or not FFR can be used as a tool to study pitch encoding.

Chapter 3

METHOD

To address the aims of the current study, two experiments were conducted. In Experiment 1, Frequency Following Responses (FFR) was recorded for complex signals and in Experiment 2, behavioral estimation of the pitch of these complex signals was examined.

3.1 Participants

11 normal hearing individuals in the age range of 17-26 years were included in the study. All participants included for the study had pure tone thresholds of ≤ 15dBHL for air condition stimuli between 250Hz to 8000Hz and bone conduction stimuli between 250Hz and 4000Hz. Their middle ear function was ensured to be normal, as indicated by an ‘A’ type tympanogram and presence of ipsi-lateral acoustic reflexes at 500Hz, 1kHz, 2kHz on immitance evaluation. They had no history of speech and language disorder, neurologic disorder or any cognitive deficits. Prior consent was taken from the participants for the study.

3.2 Experiment 1: Recording of the frequency following response

3.2.1 Stimuli

A total of 3 harmonic complexes each having a total duration of 80 ms with 5 ms raised cosine onset and offset ramp, with a starting phase of 0 degrees were synthesized using Matlab 7.8.0 (R2009a) software. Stimulus 1 (S1) consisted of odd and even harmonics of the complex tone with a missing fundamental of 224Hz (i.e

448, 672,896,1120,1344,1568, 1792 & 2016Hz). Stimulus 2(S2) consisted of only first four even harmonics of a stimulus with a fundamental of 224Hz (i.e. 448, 896, 1344, & 1792Hz). Stimulus 3 (S3) consisted of only first four odd harmonics of a stimulus with a fundamental of 224Hz (i.e. 672, 1120, 1568, & 2016Hz). Waveforms and the corresponding spectra of these three stimuli are shown in Figure 3.1.

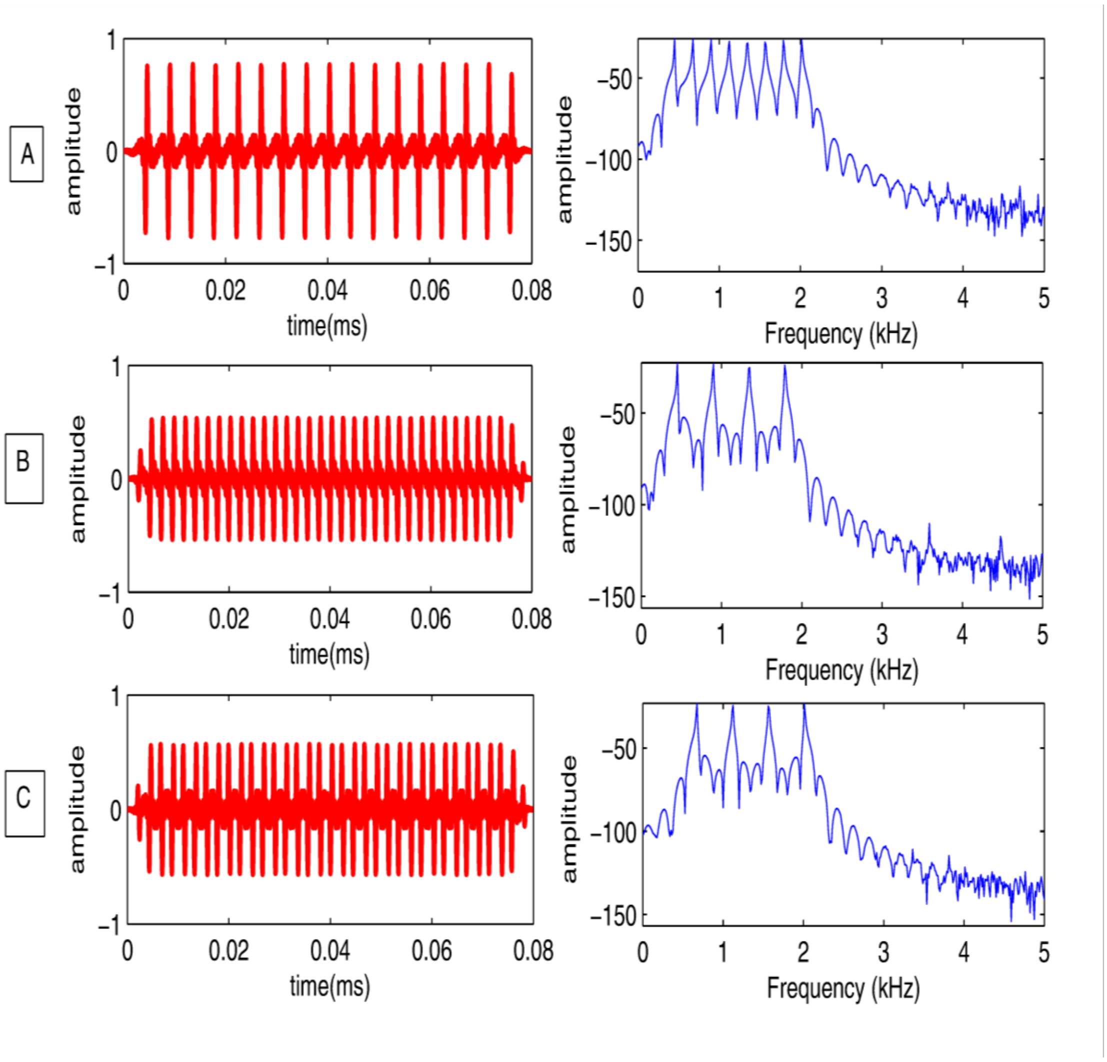


Figure 3.1: Shows the waveform and spectrum of the three harmonic complexes used for FFR recording. Panel (A) shows the waveform of Stimulus 1(S1) on the right and its spectrum on the left. Similarly, Panel B & C depicts the waveform and spectrum for stimulus 2 (S2) and Stimulus 3 (S3) respectively.

3.2.2 Procedure:

Participants were comfortably seated on a reclining chair. Patient preparation was done by using a skin abrasive paste to clean electrode sites and conduction gel to adhere the electrodes on the scalp. Individual electrode impedance was ≤5kΩ and inter-electrode impedance was ≤2kΩ. Subjects were instructed to sit calmly or sleep in order to avoid myogenic artifacts.

For stimulus presentation and data recording, Intelligent Hearing Systems (IHS) Smart EP (version 4.2.0) with Advanced Research Module was used. Based on random selection, 5 subjects within each group were tested in the right ear and 5 subjects in the left ear, to rule out ear effects. The order of presentation of stimuli was randomized to avoid order effect. Stimuli were presented monoaurally through ER-3A inserts and calibrated to be presented at 70dBSPL. Stimuli were presented at a rate of 7.1/s in alternating polarity to reduce stimulus artifact. A minimum of two replicable repetitions of 3000 sweeps each was obtained for each recording. The response was recorded for an epoch of 100ms; with a 10ms pre and post stimulus acquisition. The EEG was amplified 1 lakh times and filtered between 100-3000Hz. Recordings were obtained from Cz, referenced to the tip of the nose while ground was placed at Fpz.

3.3 Experiment 2: Behavioral estimation of pitch

Following the FFR recording, the behavioural experiment was carried out. Pitch matching of the harmonic complexes was carried using psycon 2.18 software (Kwon, 2012).

3.3.1 Stimuli

Subjects were tested with same stimuli during the behavioural task as those used for their respective FFR recording. The stimuli utilized for Experiment 2 were similar to those used for Experiment 1 in every way, except that they were of a longer duration, i.e 500ms to aid in pitch matching.

3.3.2 Procedure:

Subjects were seated comfortably in an air conditioned, sound treated room. Stimuli were generated and played at a comfortable level via Sennheiser HDA-200 headphones using psycon (version 2.18) software. To estimate behavioural pitch of the above stimuli, subjects were instructed to perform a pitch matching task at a comfortable loudness level, using method of adjustment. This was performed using 2 signals, a reference signal and a comparison signal. The reference signal (S1,S2 and S3) were kept constant while the comparison tone consisted of pure tone stimuli whose frequencies could be adjusted by the patient. The subjects were instructed to estimate the pitch of the complex signal by matching it with the varying pure tone.

Owing to the difficulty in pitch matching of complex tones as reported in literature and demonstrated by subjects taken up for this study, a 10-15min training in pitch matching of complex tones was carried out prior to starting this experiment.

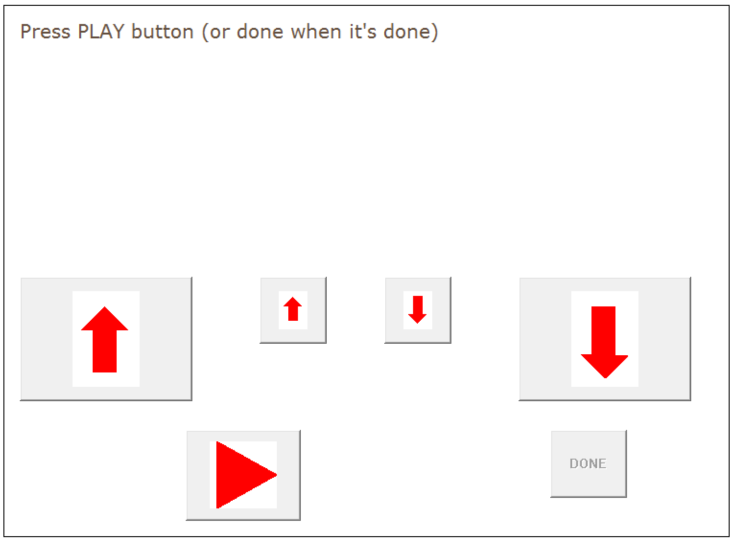


Figure 3.2: Screenshot of the psycon window used by subjects for the behavioral pitch matching task using method of adjustment. Upward arrows were used to increase frequency of the pure tone (comparison tone) while downward arrows were used to decrease its frequency. Large arrows and small arrows were employed to change frequency in 10Hz & 2Hz steps respectively.

The starting frequency of the pure tone that was used as the comparison tone was ~300Hz for stimulus 1 and ~400Hz for stimulus 2 and 3. A screenshot of the window displayed in the psycon software for pitch matching using the method of adjustment is shown in Figure 3.2. The frequency of this pure tone could be decreased or increased by the subject in large steps of 10Hz or small steps of 2Hz each, until the pitch of the complex signal and pure tone was judged to be same by the subjects. When subjects reported such a pitch match, the frequency of the pure tone that correspond to the pitch sensation associated with the complex stimuli was noted. To account for order effect, the sequence of presentation of stimuli was randomized. For each stimulus, pitch matching was performed thrice, and the average of the three trials was taken as the matched pitch.

Chapter 4

RESULTS & DISCUSSION

The aim of the present study was to evaluate the relation between periodicity coded by the FFR and the pitch perceived behaviourally. For this purpose, FFR was obtained on 11 individuals for three stimuli. Stimulus 1 consisted of a complex signal with missing fundamental (S1), Stimulus 2 was a complex signal with only even harmonics (S2), and a stimulus3 was a complex signal with only odd harmonics (S3). The fundamental frequency used to obtain these harmonic complexes was 224Hz. Following FFR acquisition, behavioural pitch estimation was also carried out on the listeners using the same stimuli used for FFR recording. The data collected in both experiments was tabulated and subjected to the following analysis:

- The resultant FFR waveforms were subjected to spectral analysis by carrying out Discrete Fourier Transformation (DFT) & an autocorrelation function (ACF) using MATLAB 7.8.0(R2009a) software. In addition, an autocorrelogram (ACG) was plotted to derive the correlation at every instant of time. The ACG is derived using custom made MATLAB program similar that described by Krishnan et al. (2010). This can be related to the pitch strength obtained in the FFR over time.

- The mean and standard deviation (SD) of the pitch estimated by the listeners was calculated from the 3 trials of pitch matching carried out for each of the three stimuli. Using this data, the mean pitch estimated by the entire subject group for stimulus 1, 2 & 3 was determined.

- The frequency extracted by spectral analysis and auto-correlation for the FFR was then compared to the pitch perceived by the subject behaviorally.

4.1 Responses obtained to stimulus 1 (S1):

A good replicable FFR was observed in all listeners, except one (P10). The obtained FFR was subjected to spectral analysis using DFT and autocorrelation for estimating fundamental frequency. The group mean added waveform[1], spectral analysis and autocorrelation for S1 is shown in the Figure 4.1. Spectral analysis showed the first major peak at 224Hz with an amplitude of 0.116µV and the next prominent peaks at frequencies corresponding to the harmonics of 224 Hz which are 448Hz (0.065µV) and 672Hz (0.023µV). These results are further supported by the autocorrelation function, which also corresponds to a frequency of 224Hz [*lag = 4.465ms; Frequency (Hz) =1/lag(s)*] with a strong correlation (r=0.8). At the frequency predicted by the FFR and ACF i.e 224Hz, the autocorrelogram shows a strong correlation (r=0.8), indicating a strong pitch strength across time. Thus, FFR codes the missing fundamental, as 224 Hz, which is represented in the envelope of the stimulus in spite of being absent in the stimulus. Many of the previous investigators (Smith et al., 1978; Greenberg & Marsh, 1979; Greenberg et al., 1986) have demonstrated that FFR represents the missing fundamental by encoding the envelope periodicity of the stimulus.

In the behavioural experiment, the pure-tone that matched the pitch of S1 was on average 234.60Hz with a standard deviation of ±11.05Hz, for which the expected pitch was at a frequency of 224 Hz (i.e its fundamental frequency). Figure 4.2 depicts the frequencies of the pure-tones at which each listener matched the pitch. The difference between matched pure-tone frequency and expected pitch is within *10 Hz*

[1] Added waveform indicates that the data recorded in rarefaction and condensation polarity were added.

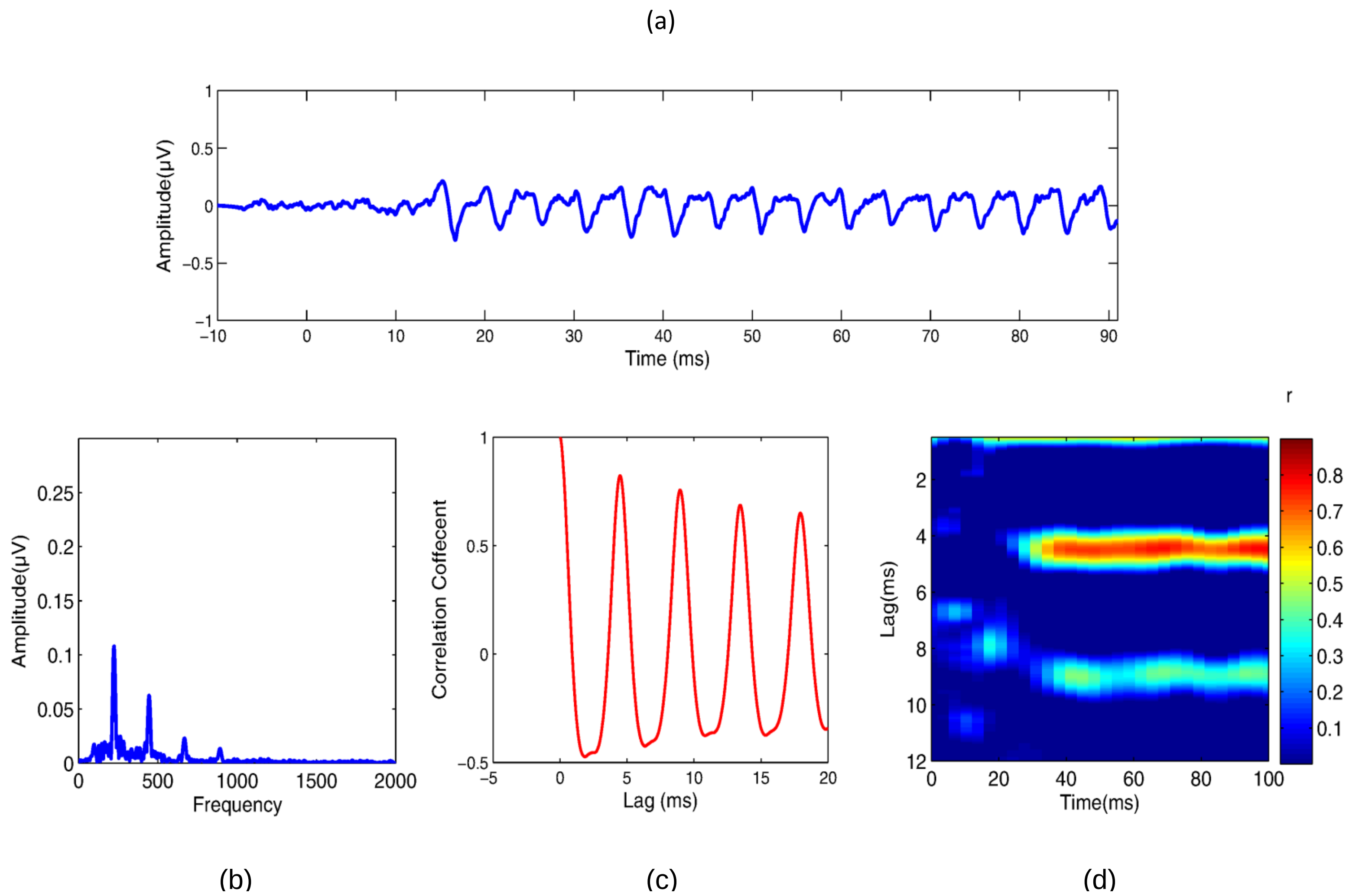


Figure 4.1: Results of spectral analysis for S1. (a) The group mean added waveform (the first10ms represents the pre-stimulus baseline) (b) the DFT of this waveform (c) ACF for this waveform (d) auto-correlogram obtained from this waveform. It can be noted from this figure that all the measures predict the same frequency of 224Hz, i.e the fundamental.

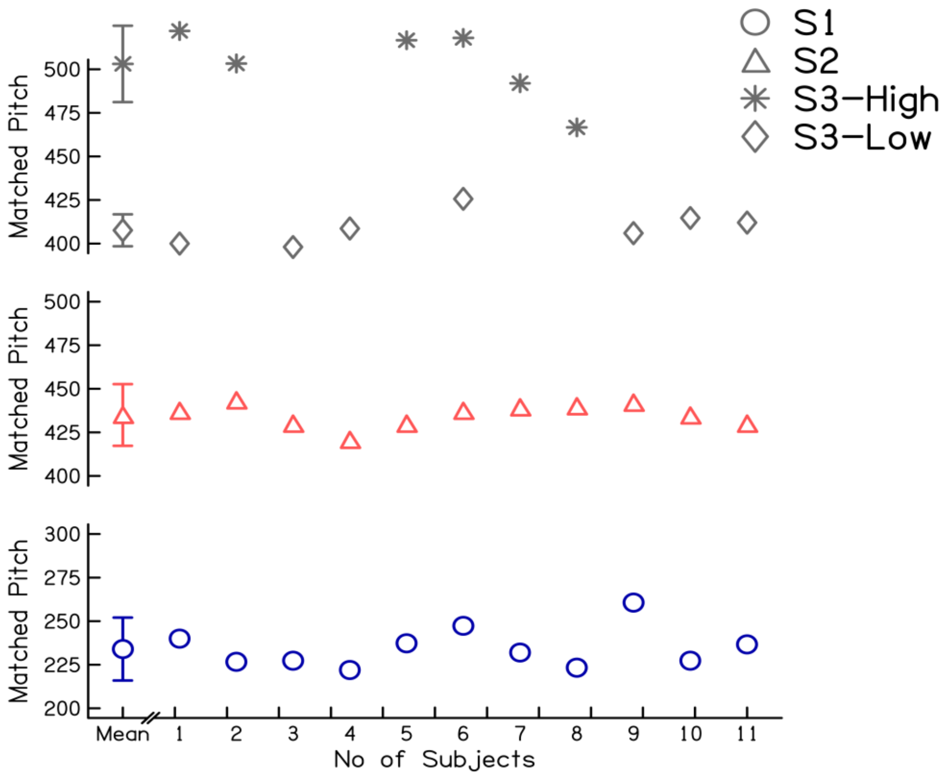


Figure 4.2: Graph depicting matched pitch by each subject and mean matched pitch for S1, S2, S3. The abscissa represents individual subjects and ordinate represents frequency of the pure tone at which pitch match was obtained. Each data point denotes the frequency at which pitch match was obtained. Key of symbols used for each stimulus is shown on right top corner. It can be noticed that subject 1 & 6 demonstrate dual pitch matches for S3.

across listeners. This small difference is not considered as a considerable difference as it is a well-accepted fact that there are inherent difficulties in a behavioural pitch matching task for complex tones even in normal hearing individuals. There are many factors that affect the pitch matching ability, like musical experience, training, instructions, etc (Schouten et al., 1962; Patterson, 1973; Lundeen & Small,1983; Chambers et al.,1986). In this study subjects were non-musicians and had only 15 min of training was given prior to the pitch matching task, which may be the probable reason for the large SD in this test. Thus, it is evident that results of the current study for S1 are in agreement with earlier evidence on perception of the missing fundamental (Seeback, 1843; Schouten, 1938; de Boer, 1979; Evans, 1978; Moore, 1989). Considering the results of the present study and previous studies, we can conclude that the behavioural pitch matches was obtained around the frequency of the missing fundamental.

Table 4.1: *Comparison of the frequency derived from FFR with the frequency of the pure tone matched in the behavioural task for S1.*

S1	***FFR data (Hz)***	***Behavioural mean (Hz)***
P1	224.7	240
P2	224.6	226.66
P3	224.6	227.33
P4	224.6	222
P5	224.6	237.33
P6	224.6	247.33
P7	224.6	232
P8	224.7	223.33
P9	224.5	260.66
P10	NR*	227.33
P11	224.6	236.66
Mean	224	234.6
SD	-	11.05

* Reliable FFR recording could not be obtained on P10

The periodicity predicted by the FFR data and frequency of the matched pure-tones are presented in Table 4.1. From the table it can be noted that behaviourally matched tone varied by approximately by 10Hz from the periodicity estimated in FFR. This small variation is expected in the pitch matching task (Schouten et al., 1962; Patterson, 1973; Lundeen & Small, 1983; Chambers et al., 1986). Hence the pitch of S1 estimated behaviourally can be considered as approximately similar to that obtained from FFR data. This close correspondence between the pitch of S1 estimated behaviourally and that obtained objectively from FFR is in accordance with many previous studies (Smith et al 1978, Greenberg & Marsh 1979; Greenberg et al. 1986). Further, temporal theories of pitch perception which claim that the lowest common interspike interval is calculated to be the fundamental frequency of the signal (Licklider, 1951; Evans, 1983; Shofner, 1991b, Rhode, 1995, Cariani & Delgutte, 1996a; Cariani & Delgutte, 1996b; Cedolin & Delgutte, 2005; Larsen et al., 2008) also support these findings.

4.2 Responses obtained to stimulus (S2):

For S2, a reliable FFR was obtained in all the 11 listeners, other than P2. The grand averaged data for the added waveforms was then subjected to DFT and autocorrelation to estimate the periodicity. The analysis revealed a large peak at 448Hz, which was followed by its harmonic at 896Hz with amplitude of 0.655µV & 0.025µV respectively. The first peak corresponds well to the periodicity of 448Hz which is predicted by the auto-correlation for the FFR waveform [*lag of 2.232ms (Frequency (Hz) =1/lag(s))*] with a moderate correlation of r=0.6. This can be clearly observed in Figure 4.3. The auto-correlogram also depicts a strong correlation (r=0.8) at 448Hz, indicative of good strong pitch salience across time. The estimated periodicity of the FFR waveform (448Hz) is found to be similar to the stimulus periodicity (448Hz). Many of the previous investigators have also reported similar results (Moushegian et al., 1973; Hall, 1979, Smith et al., 1978; Greenberg & Marsh 1979; Greenberg et al., 1986; Chambers et al., 1986 ; Krishnan, 2007 & Gockel et al

2011). Thus results of the present and previous investigations supports the notion that stimulus periodicity is well represented in the FFR.

In the behavioural pitch matching task, listeners matched the pitch to a mean frequency of 435 Hz with a SD of ±6.73Hz. Frequencies matched by the individual subjects are shown in the form of data points in Figure 4.2. As discussed in section 4.1, the behavioural data has a large SD owning to the complexity of the pitch matching task (Schouten et al., 1962; Patterson, 1973; Lundeen & Small, 1983; Chambers et al., 1986).

Table 4.2: *Comparison of the frequency extracted from FFR with the frequency of the pure tone matched in the behavioural task for S2.*

S2	***FFR data (Hz)***	***Behavioural mean (Hz)***
P1	448.2	437.33
P2	NR*	443.33
P3	448.2	430
P4	448.2	420.66
P5	448.2	430
P6	448.2	437.33
P7	448.2	439.33
P8	448.2	440
P9	448.2	442
P10	448.2	434.66
P11	448.3	430
Mean	448	434.96
SD	-	6.73

* Reliable FFR recording could not be obtained on P2

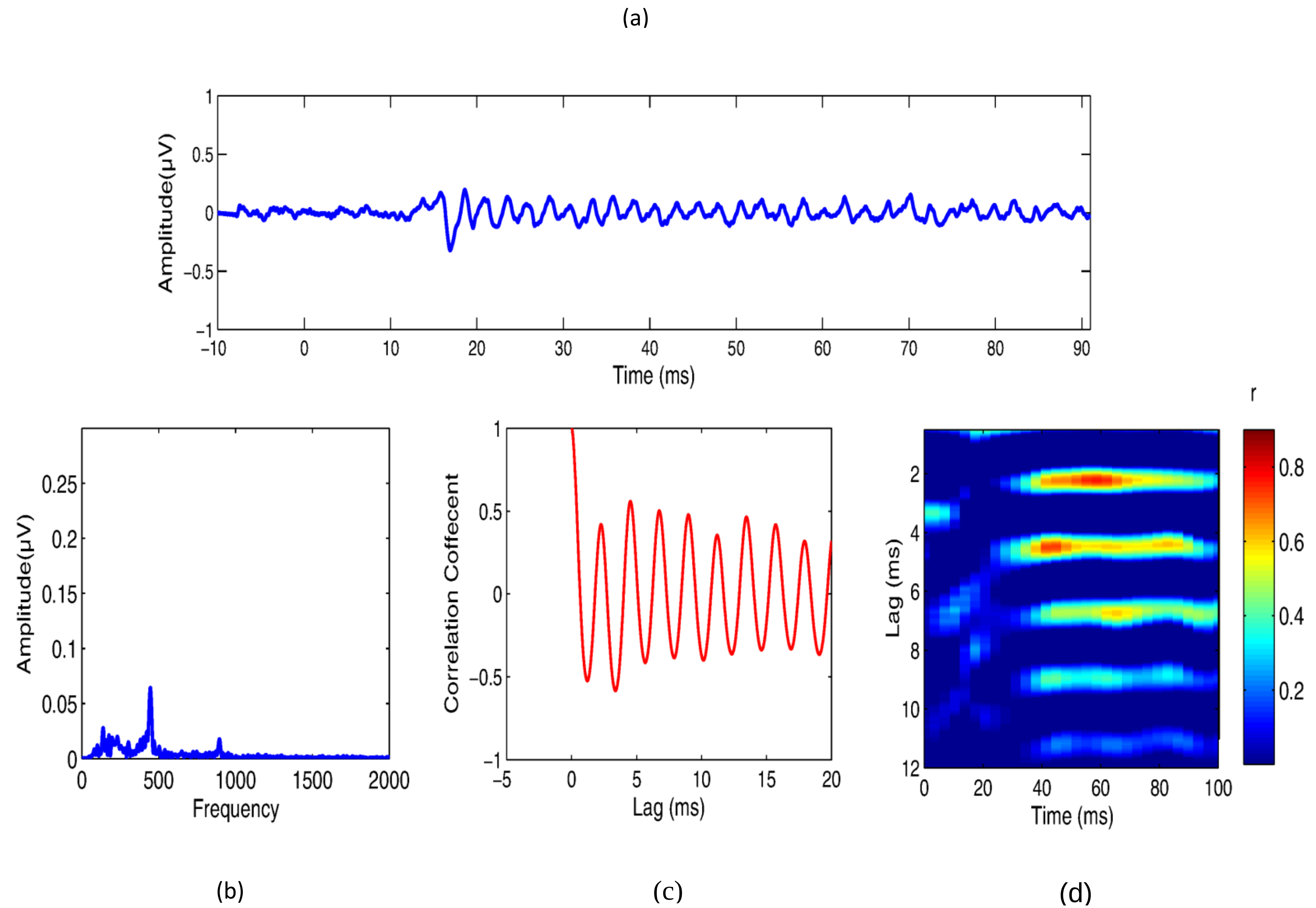


Figure 4.3: Results of spectral analysis for S2. (a) The group mean added waveform (the first10ms represents the pre-stimulus baseline) (b) the DFT of this waveform (c) ACF for this waveform (d) auto-correlogram obtained from this waveform. All these measures indicate that the frequency coded by the FFR was 448Hz.

A comparison was made between the frequency extracted by FFR and frequency of the pitch matched pure tones used for behavioural pitch matching and results are displayed in Table 4.2. These results suggest that there is a good correspondence between FFR and behavioural data since they differ only by around 15 Hz, which is acceptable in a pitch matching task (as discussed in section 4.1). The findings with S2 are in support of the temporal theories of pitch perception discussed previously in section 4.1. Hence we can conclude that FFR well preserved the pitch perceived by the listeners for S2.

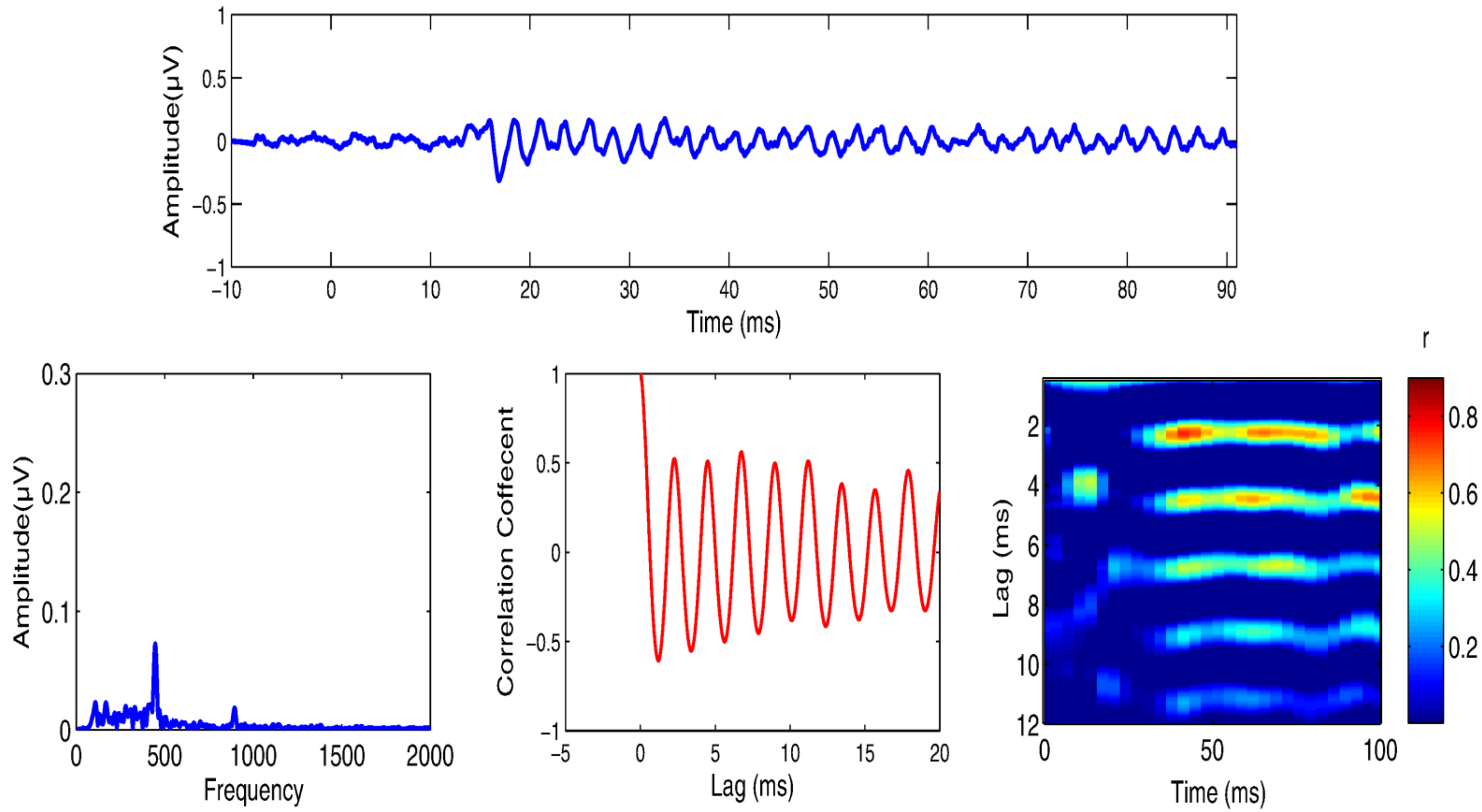
4.3 Responses obtained to Stimulus 3 (S3)

A robust FFR was obtained on 10 out of the 11 listeners for S3. DFT and autocorrelation was carried out on the added grand averaged waveforms for to determine its spectral composition. The group mean added waveform, spectral analysis and autocorrelation for S3 is shown in the Figure 4.4. A prominent peak at 448 Hz ($2F_0$) with amplitude of 0.0877µV was found in the DFT which was followed by its harmonic at 896.4 Hz of 0.0226µV. The ACF demonstrated a moderate correlation of r=0.52 at a frequency of 448 Hz based on a lag of 2.232ms *[Frequency (Hz) =1/lag(s)*]. At this frequency represented in the FFR and ACF (i.e 448Hz), the autocorrelogram also showed a strong pitch salience across time. Thus, the FFR to S3 predicts a frequency of 448Hz which is similar to that obtained from the FFR data for S2, since the frequency difference between the components is the same for the even and odd harmonic stimuli (for even harmonic signal:448-896=896-1344=1344-1792=448; for odd harmonic signal: 672-1120=1120-1568=1568-2016=448Hz).

On close examination of the stimulus waveform, S3 was found to have a dual periodicity of 416 Hz and 526 Hz can be as shown in Figure 4.5. Consequently, in the behavioural task listeners reported pitch matches at pure-tones of two different frequencies. As shown by the individual data points in Figure 4.2, out of 11 listeners, 5 listeners pitch matched S3 to a mean low pitch of 407.67 Hz and SD of ±9.14. On the other hand, 4 listeners matched S3 to a slightly higher frequency of mean 503.11Hz and SD of ±21.042. Two listeners (P1 and P6) were able to perceive a dual pitch and hence matched S3 to a lower frequency (mean: 412.5Hz) and a higher frequency (mean: 520Hz). There is a close correspondence between the pitch matched by the listeners in the current study and that reported by Benade (1976), who suggested that the dual pitch for such an odd harmonic complex was found at a frequency of $9F_0/5$ and $9F_0/4$. Such reports of multiple pitches in a signal have been attributed to the quasi-periodicity in the temporal fine structure of the stimulus waveform (de Boer, 1956a,b; Schouten et al., 1962).

On comparison of the FFR and pitch matching data for S3 it was seen that there was a considerable variability between the frequency represented in the FFR and frequency at which pitch match was achieved. FFR predicted only one periodicity and this differed by approximately 50Hz from the behavioural match. This comparison of FFR versus behavioural data is shown in Table 4.3.

(a)



(b) (c) (d)

Figure 4.4: Results of spectral analysis for S3. (a) The group mean added waveform (the first10ms represents the pre-stimulus baseline) (b) the DFT of this waveform (c) ACF for this waveform (d) auto-correlogram obtained from this waveform. All these measures indicate that the frequency coded by the FFR was 448Hz.

Table 4.3: *Comparison of the frequency extracted from FFR with the frequency of the pure tone matched in the behavioural task for S3.*

S3	***FFR data (Hz)***	***Behavioural mean-Low (Hz)***	***Behavioural mean-High (Hz)***
P1	NR*	400	522
P2	448.2		503.33
P3	448.2	398	
P4	448.2	408.67	
P5	448.2		516.67
P6	448.2	425	518
P7	448.2		492
P8	448.2		466.67
P9	448.2	406.67	
P10	448.2	414	
P11	448.3	412.66	
Mean	448	407.67	503.11
SD	-	9.141	21.042

*Reliable FFR recording could not be obtained on P1.

FFR is claimed to extract the envelope of the signal (Moushegian et al., 1973; Hall 1979, Smith et al, 1978; Greenberg & Marsh, 1979; Greenberg et al, 1986; Chambers et al., 1986; Krishnan, 2007; Gockel et al, 2011). In accordance with this statement, the current study showed that there was a good correspondence between the envelope modulation frequency (periodicity) of the stimuli and the frequency extracted by the FFR, for S1 and S2. In the case of S3, the above claim did not hold good, because the stimulus waveform shows a dual periodicity (Figure 4.5) whereas FFR was found to have a single periodicity. Greenberg et al. (1987) also reported comparable findings using an odd harmonic complex.

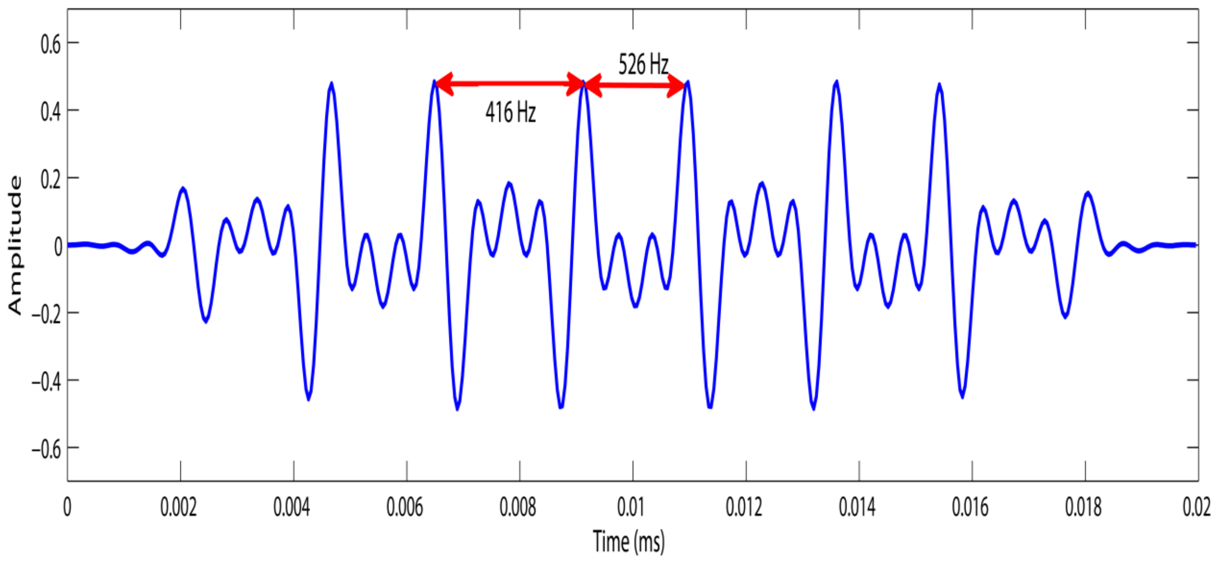
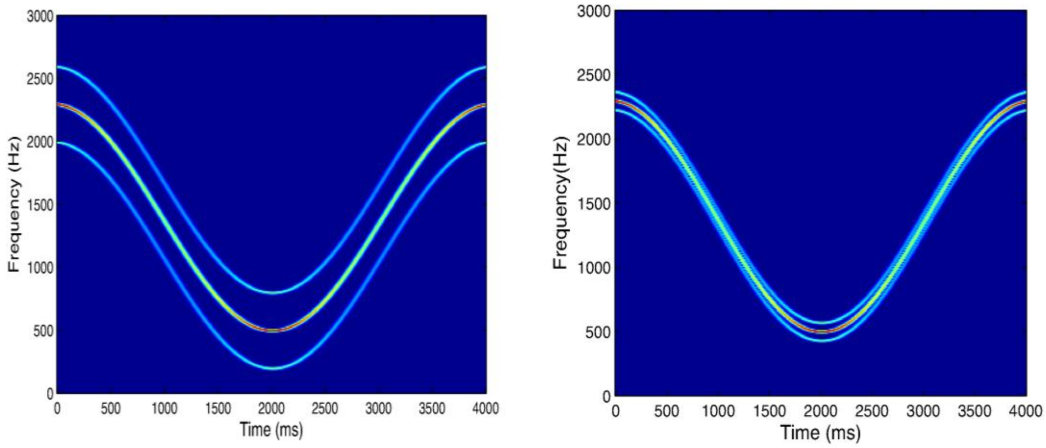


Figure 4.5 : A 20ms waveform of S3 depicting the dual periodicity at 416Hz (1/0.0024s) and 526Hz (1/0.0019s).

To explain these paradoxical findings, a hypothesis was made suggesting the existence of two types of envelope-following responses (FFR) – one that originates from the interactions in the cochlea (pre-FFR), and another which arises due to temporal encoding at the auditory nerve and higher structures (post-FFR). The pre-FFR can be obtained due to cochlear interaction only when the components are unresolved or very closely spaced on the basilar membrane. This envelope obtained at the cochlea, is further carried by the auditory nerve (Picton, 2011). On the other hand, when the harmonic components are resolved or spaced widely on the basilar membrane, minimal cochlear interaction can occur. Hence for such a stimulus, a temporal envelope (representing the difference between the harmonics) is generated only at the neural level.

To investigate this hypothesis, a small additional experiment was carried out on 5 subjects wherein FFR was recorded to frequency swept complex tones. The spectrogram of the stimulus used for this experiment is shown in figure 4.6(a)(b). This signal consisted of one component whose frequency varied from 2000Hz down to 300Hz and again back to 2000Hz. To this signal, two other frequency swept signals were added such that the frequency difference between these signals remained 300Hz at every point of time. This generated a complex with a 300Hz envelope as shown in Figure 4.6 (a). Similarly, another signal was generated comprising of a 70Hz envelope as shown in Figure 4.6(b).



(a) (b)

Figure 4.6: Spectrogram of the stimulus used in the additional experiment (a) the frequency swept stimulus with 300Hz envelope (b) the frequency swept stimulus with 70Hz envelope

The averaged FFR obtained for these stimuli were subjected to spectral analysis. Results of this analysis are depicted in Figure 4.7. As depicted in this figure, for the 300Hz stimulus, FFR was obtained only between 1500-2500ms, before and after which there was a drastic decrease in amplitude. This time corresponds to a 300-1000Hz carrier, beyond which there was drop in amplitude. This finding can be explained by the fact that, a 300Hz envelope will be resolved on the basilar membrane, resulting in minimal cochlear interactions. Thus, its FFR is obtained only if the auditory nerve and higher structures were able to temporally code the carrier frequencies. Since phase locking of the nerves deteriorates with increasing frequency, the responses above 1000Hz were severely reduced in amplitude. This finding supports our previously stated hypothesis. Moreover, if the 300 Hz response was due to cochlear overlap, the response would be largest at high carrier frequencies.

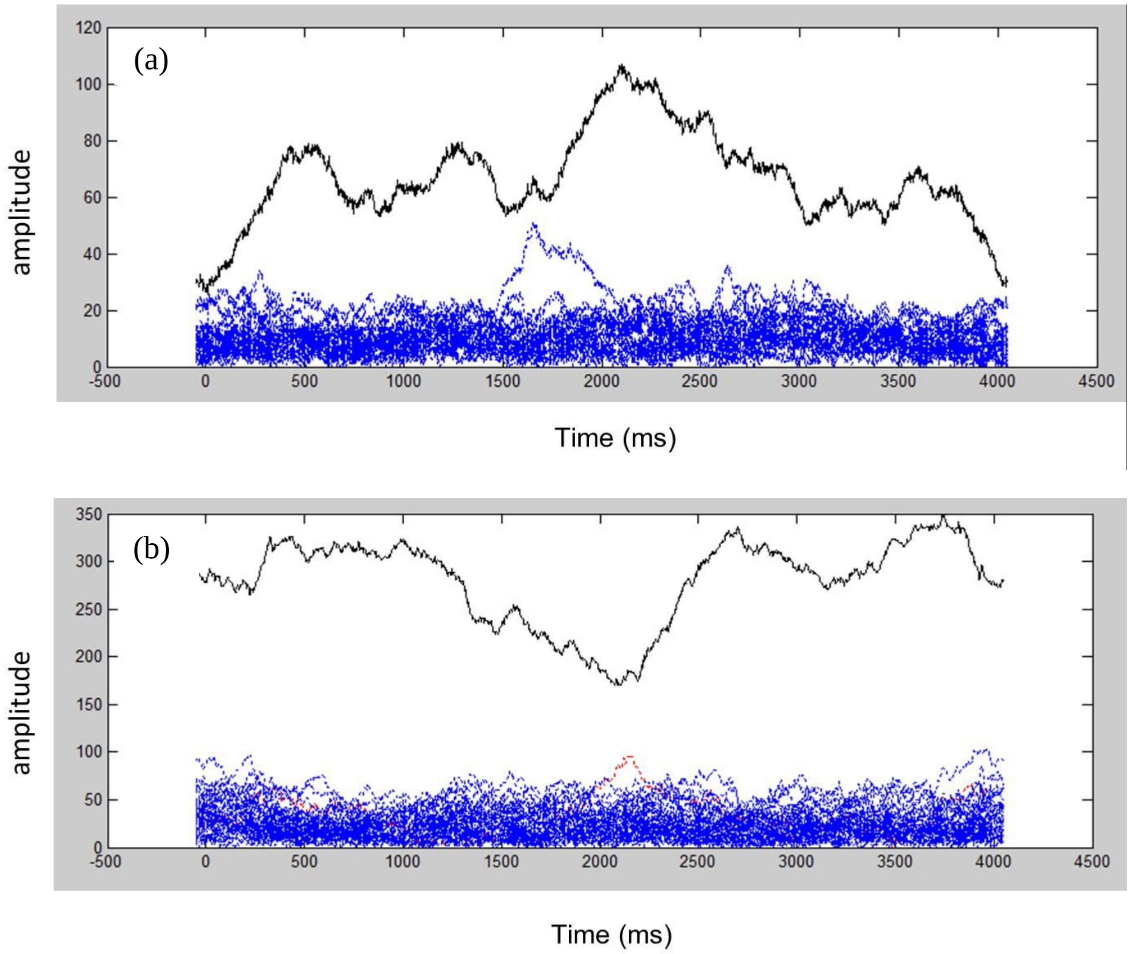


Figure 4.7: Responses obtained to the swept complex signals. X axis depicts the duration of the signal. Y axis depicts the amplitude of the response. Each blue line represents response of each frequency and black line response of 300Hz (a) &70Hz (b).Panel (a) shows the response obtained for 300Hz modulation. It can be noted that response is good between 1500-2500ms which corresponds to the lower frequencies (300-1000Hz) & reduced for high frequencies beyond 1000Hz. Panel (b) shows the response obtained to stimulus with 70Hz modulation. There is a good response from 0-1500ms and 2500-4000ms (high frequencies >800Hz) with a small reduction in response between 1500-2500 (low frequencies <800Hz).

On the on the other hand, FFR for the 70Hz stimulus was obtained at all carrier frequencies as shown in figure 4.4(b), though there was a decrease for the lowest carriers where the overlap in the cochlea is reduced due to narrow auditory filters. This finding too is in agreement with the hypothesis described previously. Since 70Hz is clearly unresolved, interactions did occur on the basilar membrane and envelope was extracted at the cochlea itself, which was then transmitted to the auditory nerve. If the 70 Hz response was due to encoding of the individual carrier components at the auditory nerve, we would expect the response to be largest for low carriers as phase locking is better at low frequencies.

The results of the above investigation verify the earlier proposed hypothesis that there are really two types of FFR. Based on this hypothesis, the unexpected results seen with S3 can be explained. S3 had harmonics at 672Hz, 1120Hz, 1568Hz and 2016Hz, with a frequency difference of 448Hz, which is well resolved in the cochlea. Hence for the added waveform, interaction at the cochlear level was negligible and the envelope responses are be hypothesized to be post-FFR/ neural response. Therefore, for such a well resolved stimulus, temporal coding in the auditory nerve codes the difference in the inter-spike intervals which occurs at 448Hz, as seen in the added FFR response to S3. Furthermore, the hypothesis that there are two types of FFR also explains the occurrence of a peak in the spectrum for S1 at 224Hz and at 448Hz for S2. This hypothesis is acceptable since these values are equal to the difference between the frequency of their harmonic components (224Hz and 448Hz respectively).

The added FFR waveform for S3 didn't reveal the dual periodicity present in the stimulus waveform. Hence, the subtracted waveform[2] was also studied to see if it was characterized by this dual periodicity. In the study by Greenberg et al. (1987) the subtracted waveform obtained to the odd harmonic complex was found to have ripples in the FFR spectrum with a prominent peak at 280Hz which they claim correlates with the psychophysically matched pitch obtained for such an odd harmonic complex with fundamental of 122Hz. When the subtracted waveform was extracted for S3, the FFR spectrum showed a major peak at 224 Hz, which is the fundamental. However, Greenberg et al. (1987) did not observe the fundamental (122 Hz) in their subtracted waveform. Looking closely into their method, we find that they used a high pass filter setting of 200Hz for the122 Hz fundamental. This may have eliminated the 122 Hz fundamental from their response.

The subtracted FFR response for the odd harmonic complex (S3) used in the present study is depicted in Figure 4.8. From the figure it is clear that DFT and ACF correspond to the frequency of the fundamental (224Hz) and not at the envelope of 448Hz. This finding can also be explained based on the 'two types of envelope following responses' hypothesis discussed earlier. S3 will technically have less interaction at the cochlear level due to its frequency spacing being larger. Nevertheless, due to the fact that the FFRs were elicited with a high intensity stimulus, some cochlear interaction is inevitable. This may result in the first type of envelope responses, pre- FFR/ due to cochlear interactions. Consequently, a response at the fundamental (224Hz) is obtained, which might have been supressed in the added response.

[2] Subtracted waveform was obtained by subtracting the responses obtained in rarefaction and condensation polarity

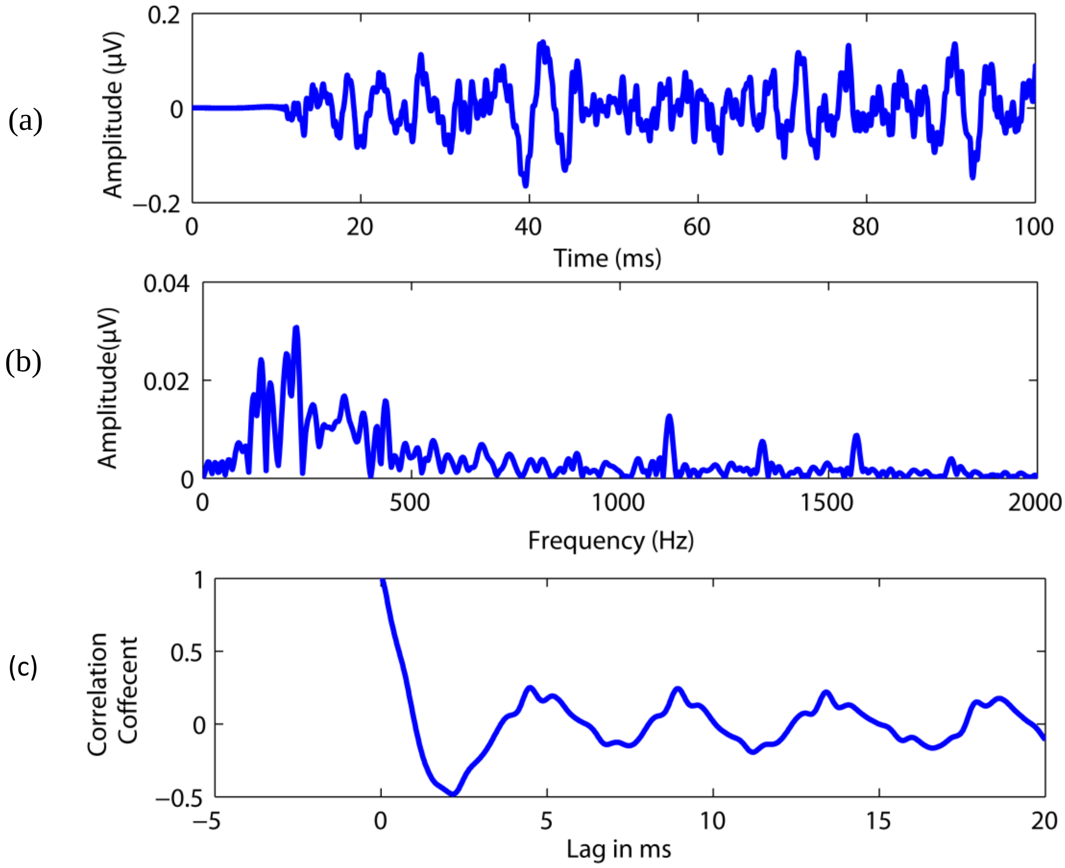


Figure 4.8: Spectral analysis for the grand averaged subtracted response to S3. (a) subtracted waveform (b)DFT of this waveform (c) ACF of the response.

The results of the present study are in accordance with studies by Hall (1979), Chambers et al. (1986), and Gockel et al. (2011) who claim that FFR cannot be considered as a correlate of pitch perception. However, these studies conclude that FFR extracts the envelope periodicity of the signal, which fails to explain the coding of a stimulus with dual periodicity such as S3. Hence, a hypothesis that there exist two types of envelope following responses was proposed to explain the paradoxical findings with S3.

Chapter 5

SUMMARY AND CONCLUSIONS

Pitch processing has been studied extensively using behavioural and electrophysiological measures (Frequency Following Response). There are a group of investigators (Greenberg et al., 1987; Galbraith, 1994; Galbraith & Doan, 1995; Krishnan, 2002, 2007; Krishnan et al., 2004, 2005; Wong, Skoe, Russo, Dees & Kraus, 2007; Skoe & Kraus, 2010) who claim that the pitch processing at the auditory brainstem is represented by the Frequency Following Response (FFR). On the contrary, there have been reports which demonstrated that FFR cannot be considered as a correlate of pitch perception; it only reflects an extraction of the envelope of the stimulus waveform (Hall 1979; Chambers et al., 1986; Gockel et al., 2011). Hence the present study was aimed at assessing the relation between FFR and behavioural pitch perception.

In this study, FFR was obtained on 11 normal hearing individuals, in response to three stimuli with a 224Hz fundamental- a missing fundamental complex (S1), even harmonic complex (S2) and odd harmonic complex (S3). The resultant FFR waveforms were subjected to spectral analysis (Discrete Fourier Transform and auto-correalation) to determine the frequency represented in the FFR. Subsequently, behavioural pitch matches were also obtained for these three stimuli using a pure-tone comparison stimulus. The data acquired for each stimulus was tabulated and analysis revealed the following findings-

- The frequency extracted by the FFR in response to S1 (224Hz) and S2 (448Hz) was found to correspond well to the frequency of the pure tone at which their respective pitch match was obtained (234Hz for S1 and 435Hz for S2).

- For the odd harmonic complex (S3), the frequency coded by the FFR (448Hz) and that matched during the behavioural task varied considerably. The pitch estimated behaviourally was found to have a dual pitch (407Hz and 503Hz) which corresponded well to the dual periodicity (416Hz and 526Hz) reflected in the signal. However, this dual envelope periodicity was not reflected in the obtained FFR.

To explain these paradoxical findings with S3, a hypothesis that there exist two types of envelope following responses was developed. The first type consists of a pre-FFR, wherein an envelope is obtained as a result of cochlear interaction. The second type comprises of a post-FFR, which is obtained due to temporal coding of the difference between the frequency components of the stimulus, starting at the auditory nerve level. It is this post-FFR that results in a response at 448Hz for S3.

From the results of this study we can conclude that FFR cannot be considered as a correlate of pitch perception. Furthermore, the FFR does not code the envelope periodicity of a stimulus waveform. More research on FFR with various types of stimuli is required to validate the relation between FFR and pitch as well as to determine what the FFR truly represents.

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