AUDITORY ATTENTION TO FUNDAMENTAL FREQUENCY OF COMPLEX TONES

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ABSTRACT

Two experiments were conducted. The first was a control condition and used the probe signal method similar to Greenberg and Larkin (1968) to see if a filter-like attentional mechanism was acting when listeners were presented with pure tone stimuli in the presence of background noise. The second experiment also used the probe signal method of Greenberg and Larkin (1968) to investigate the extent to which listeners direct their attention to a particular fundamental frequency (f0) when detecting complex tones masked by noise. Twenty adult listeners ranging from 23 years to 54 years with a median age of 28 years participated in both experiments. Of the 20 listeners, 8 were male and 14 were female. Both experiments used a Two Interval Forced Choice (2IFC) procedure. There were two types of trials, the target signal trial and the probe signal trial. The target frequency was presented on 71% of trials, and the probe frequencies on the remaining 29%. The results of Experiment 1 were similar to those obtained in Greenberg and Larkin's (1968) pioneering study. The 1000 Hz target tone was detected at a significantly higher proportion than probe signals differing in frequency ($p < 0.05$). Detection scores were observed to be higher when probe signals had a frequency close to the 1000 Hz signal compared to when they had a frequency positioned further from the 1000 Hz target tone. Experiment 2 using complex target tones with f0 of 115 Hz (part 1) and 220 Hz (part 2) revealed a similar pattern to Experiment 1. Listener's detection scores decreased the further the f0 of probe tones were positioned from the f0 of the target tone, revealing the shape of a band-pass filter. This pattern is consistent with the presence of an auditory attentional filter in the f0 domain for complex tones.

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Terms

2IFC	Two Interval Forced Choice
F0	Fundamental Frequency
BM	Basilar Membrane
RT	Reaction Time
4IFC	Four Interval Forced Choice
2AFC	Two Alternative Forced Choice
SNR	Signal to Noise Ratio
SAM	Sinusoidal Amplitude Modulation
SPSS	Statistical Package for the Social Sciences
ANOVA	Analysis of Variance

1 LITERATURE REVIEW

1.1 INTRODUCTION

An individual is faced with multiple changing complex acoustic environments on a daily basis. It is vital for humans to segregate a single relevant sound source from irrelevant acoustic stimuli or "noise". Attention is one mechanism that contributes to segregation (Broadbent, 1958; Desimone & Duncan, 1995; Treisman, 1960). Attention can be broken down into top-down and bottom-up attention. In this research bottom-up attention is of relevance, and it will be discussed further in subsequent chapters. Auditory filters can be used to model an individual's auditory selection process. Auditory filters are devices which allow certain frequencies to pass whilst attenuating others. A band-pass filter allows a range of frequencies within a certain bandwidth to pass through while those outside the cut off are attenuated. The auditory system is thought to act as bank of overlapping band-pass filters. An individual's auditory filter originates from frequency-specific activity along the basilar membrane (BM). The cochlea is capable of separating auditory input into separate channels dependent on the frequency of the acoustic signal (Moore, 1986). The bandwidth in Hertz decreases from the base to the apex of the cochlea due to the tuning of the BM to both low and high frequencies. Fletcher (1940) was the first to discover individuals make use of band-pass filters centred at the signal frequency on the BM of the cochlea when detecting a signal in background noise. These auditory filters have been studied extensively since the work of Fletcher (1940) and are now well established. Various studies have explored the effects of attention and found the presence of a similar filter shape. These have been termed as "listening bands" or "attentional filters" (Schlauch &Hafter, 1991; Hafter, Sarampalis & Loui, 2007). These auditory attentional filters can be used to model an individual's auditory selection process and are capable of selecting the most relevant auditory content in the acoustic environment based on acoustic properties such as frequency. Information is then forwarded on for further processing higher up the brainstem (Zhou, 1995). This results in a frequency region of enhanced auditory processing (Botte, 1995; Dai & Buus, 1991).

The majority of research utilising the probe single method has focused on the use of pure tone stimuli to measure individual auditory attentional filters. However, complex tones show more real world relevance as individuals are continuously exposed to environments containing complex stimuli on a daily basis.

1.2 AUDITORY SCENE ANALYSIS

As alluded to previously, individuals are often placed in environments where multiple sound sources are present (Sinex, 2005). For example, a person may be talking in the presence of multiple talkers, or two people may be holding a conversation in the presence of various unrelated environmental sounds. In these particular acoustic environments, signals are generated by multiple simultaneous sound sources. Here the waveforms produced by individual sound sources often overlap in both of the time and frequency domains. These sounds add linearly, arriving at each of the listener's ears as a single waveform whose spectrum includes all the components associated with all the sources (Sinex, 2005). The signal that arises from the addition of multiple sounds can be referred to as the 'composite' signal.

Various terminologies have been given to the process of segregating the spectrum and identifying the individual sound generating objects that contribute to the composite signal. Bregman (1990) referred to the process as auditory scene analysis, a term that is widely used today. The outcome of the process was called the perception of auditory entities by Hartmann (1988), auditory object perception by Handel (1995), and auditory image perception by Yost (1991). Yost later suggested the term sound-source determination (Yost & Sheft, 1993). These authors do however agree that sound source determination is an essential function of the auditory system. Figure 1 gives a schematic representation of auditory image perception and analysis. The sound sources are objects in the auditory environment which produce an acoustic signal via a vibratory signal. However, if multiple objects are present, it can be termed as a ‘complex sound field’, representing the sum of each object's vibratory pattern (Yost, 1991). Not every sound source will produce an auditory image as some may not be strong enough to be perceived by the listener. The formation of an auditory image has two components: segregation and fusion. Segregation refers to process of breaking down stimuli into individual components. Fusion is the term given to those processes that form each of the auditory images from the individual components. Yost (1991) argues that an individual may or may not be able to identify the sound source purely on the auditory image produced. It is therefore stated to be unnecessary to identify the sound source for an auditory image to be perceived. Image formation may be more closely related to cognitive processing (Bregman, 1990). A large number of top-down processes based on the listener’s previous encounters can probably be used to supplement the auditory system in selectively attending to and essentially sorting among the auditory images that may be generated by various objects in a complex auditory scene (Bregman, 1990). It is important to also consider bottom-up processes as to what variables are used in the formation of auditory images. Yost (1991) outlines several variables that may contribute to the formation of auditory images.

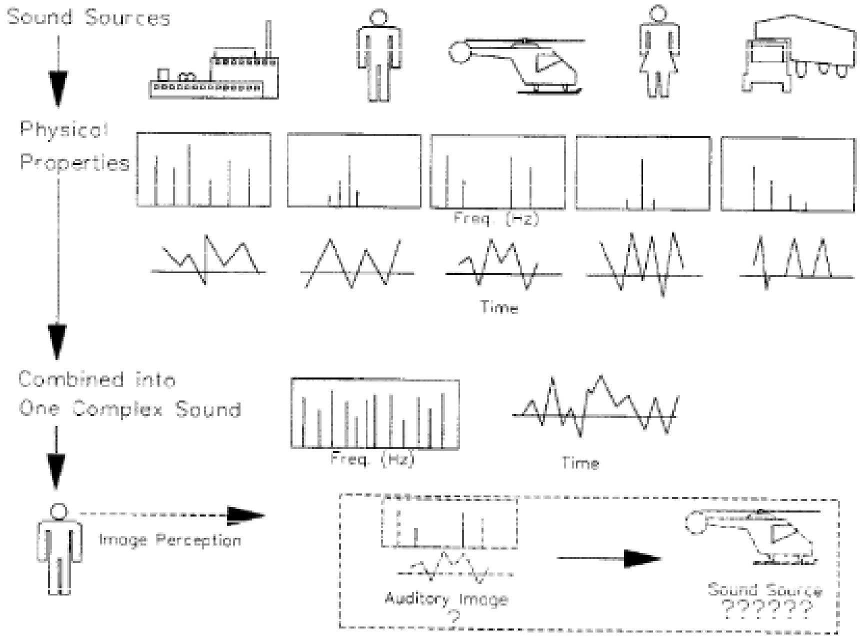

Figure 1. Steps in the auditory image perception and analysis. Represented are five sound sources, each with a temporal and spectral waveform. (Source: Yost, 1991).

Without the ability to segregate the vital information from various sound sources, it would be virtually impossible to identify the spectral profile of any single source. The spectral profile provides information about whom or what made the sound and can convey meaning beyond simply identifying the source of the sound. Human speech would be much less understood if its spectral profile as represented by the auditory system were not stable in the presence of competing sounds.

Cherry (1953) described what is now known as the cocktail party effect, that is, that normal hearing listeners have the capability to extract relevant or important features of the auditory stream, whilst ignoring irrelevant, meaningless stimuli such as competing speech or background noise. Cherry's research consisted of objective dichotic listening experiments to contribute to the solution of the general problem of the decoding of speech signals. Dichotic refers to the simultaneous stimulation of the right and left ears by different acoustic stimuli

(Cherry, 1953). Two experiments were reported, the first exploring the behaviour of the listener when presented with simultaneous speech signals delivered to both ears and two, the behaviour of the listener when two different speech signals were delivered to the two ears. One of Cherry's findings from these experiments was that a change in voice from one ear to the other from a male speaker to a female speaker (or vice versa) was nearly always recognised. Therefore he concluded the ability to separate speech signals from background noise is affected by numerous factors, such as f0.

Following the work of Cherry (1953), Speith, Curtis and Webster (1954) undertook research to examine which conditions played a role in an individual's ability to separate and attend to relevant stimuli and attenuate irrelevant stimuli. To measure this, the listener's ability to answer one of two messages was measured. Manipulated variables included: horizontal separation of the sound sources in space, visual cues, and the shaping of the spectrum of the messages using filtering. Findings were that performance was enhanced for messages that were spatially separated horizontally; however, visual cues did not appear to aid performance. Performance was measured by the percent of correct identifications of the manipulated variables used in each condition. Furthermore, it was demonstrated that high-pass filtering one message above 1600 Hz, while at the same time low-pass filtering the other message below that frequency, segregation of the two messages becomes easier. This was reflected by having a mean performance increase from 66% to 86% of words correct with the addition of filtering. This result provided evidence for the role of frequency in aiding auditory stream segregation, and confirmed Cherry's suggestion that the frequency plays a role in the ability to separate relevant from irrelevant auditory stimuli.

1.3 AUDITORY ATTENTION

Attention is commonly understood as the ability to focus on some stimuli, whilst ignoring others. However, one person may define attention slightly different to another.

Moray (1969) identified various subsets of attention. Mental concentration, vigilance, search, set, selective attention and activation were all reported as falling under the word attention.
In this research thesis selective attention in the auditory system is of importance. Auditory attention involves the selective perception of a particular auditory signal and the relative suppression of competing sensory information (Picton & Hillyard, 1974).

A variety of complex, shifting acoustic environments present an individual with enormous challenges for attentional focus on auditory features or objects. Auditory attention allows humans to rapidly and precisely hone in on the stimuli of interest in an acoustic environment (Fritz, Elhilali & Shamma, 2007). Attention can be defined as top-down or bottom-up. Top-down attention is a selection process in which cortical processing resources are focused on the most important sensory information in a conscious manner. This top-down control allows goal directed behavior to be achieved in the presence of multiple competing distractions and compromises several distinct neural and behavioural processes operating at multiple levels (Fan & Posner, 2004). Bottom-up attention more importantly of interest in this thesis plays a role in interpreting the acoustic environment and selectively gating relevant signals (Kayser, Petkov, Lippert & Logothetis, 2005). This type of attention is pre-conscious occurring at lower levels of processing. The auditory nervous system makes use of both top-down and bottom-up mechanisms. The human brain is not capable of fully processing all acoustic stimuli at once, therefore a neural mechanism must exist which selects a small subset of available auditory stimuli before further processing. First, stimulus-driven fast-acting bottom-up processing of the auditory scene occurs that attracts attention in an unconscious manner (Kalinli & Narayanan, 2007). Next, top-down processing shifts an individual's attention voluntarily towards locations of particular cognitive interest. Only the selectively attended location is allowed to progress through cortical hierarchy for high level processing to analyse auditory details.

Research in the field of attention seeks to build on the current theories and hypotheses of auditory processing. Specifically, research is exploring the interplay of pre attentive processing of the acoustic scene, the relationship between top-down and bottom-up mechanisms and the influential role of attention (Fritz et al., 2007).

1.3.1 Theories of auditory attention

1.3.1.1 Early selection theories

Broadbent's filter theory of attention (1958) was one of the first hypotheses, with the proposal of an early selection model of attention. That is, Broadbent suggested that human's process information with limited capacity and must select information to be processed initially. Broadbent's goals were at first largely of a practical nature. He wanted to determine the best way to arrange sound sources in order to optimise communication in noisy environments. Broadbent (1958) hypothesised that all auditory stimuli are processed initially for basic physical properties such as temporal characteristics, spatial locus and spectral content. It was believed semantic features would impose a limited capacity on the ability to temporally store the incoming signal (Figure 2). Thus, he believed the selective filter allowed certain stimuli to pass through based on physical features for additional processing in the brainstem, essentially discarding unattended or irrelevant stimuli. When developing this model, Broadbent emphasized the splitting of the incoming signal into channels, namely attended and unattended channels. This channel selection is thought to be guided by attention (Lachter, Forster & Ruthruff, 2004). The role of the filter was to prevent overloading of the limiting capacity mechanism which is found beyond the filter. This mechanism processes the acoustic input and can make information available for short term memory and the manipulation of the selected information before long term storage (Figure 2). This selection theory placed the filter very early in the auditory system, without proposing a specific physiological hypothesis.

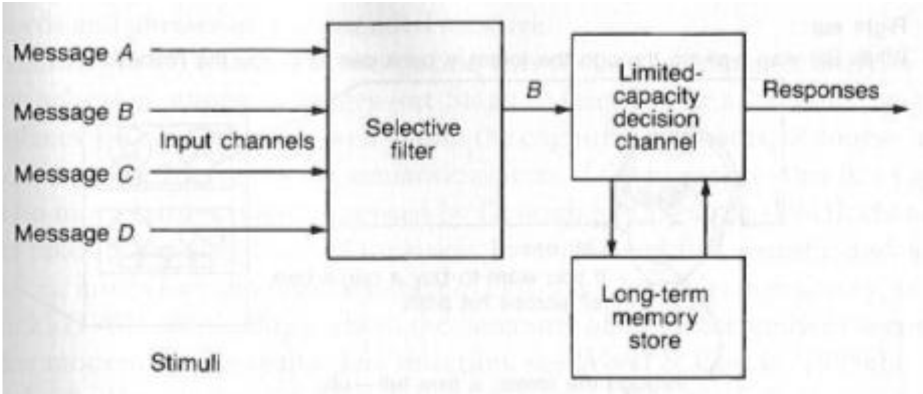

Figure 2. Broadbent's early selection theory of attention. Four incoming auditory messages are presented, with only one entering the limited capacity decision mechanism. (Source: Broadbent, 1958).

Treisman (1960) pointed out some shortcomings of this filtering theory, and proposed that some information from rejected stimuli could reach consciousness. Aside from this adjustment, which Broadbent readily accepted, no other basic change has been made to the filter model within the attention literature to date.

As research has progressed considerably since the work of Cherry and Broadbent, more sophisticated measures reveal individuals do have an attentional filter. It is now however thought to be integrated into a broader cognitive system (Lachter et al., 2004). This system compensates for the controversies of limited parallel processing in Broadbent's original findings. A major component of the system entails sensory memory (Baddeley, 2010). Sensory memory can be broken down into iconic and echoic memory (Clark, 1987). The aforementioned represents visual and auditory memory respectively, which functions pre-attentively. Given the existence of such a pre attentive memory store, it makes it possible for stimuli to work in a serial manner (Lachter et al., 2004). Research focusing on iconic memory has identified a visual hierarchy of the visual system. This indicates specific neurons are activated before stimulus recognition, supporting Broadbent's theory of pre-attentive processing.

More research has shown that physical features of a stimulus guide attentional selection (Lachter et al., 2004). It has consistently been found that listeners are capable of correctly separating relevant from irrelevant stimuli due to physical rather than semantic features. This indicates selection channels are heavily influenced by physical features, supporting Broadbent's idea.

Allocation of attention is a product of both voluntary and reflexive attention. Goals and behaviours drive attention but may also be influenced by external stimuli of particular strength. Such research evidence confirms Broadbent's concept of the presence of voluntary attentional mechanisms (Goldstein, 2010).

1.3.1.2 Late selection theories

Late selection models have been proposed which posit information is selected for after the processing for meaning compared with earlier stages of processing (Deutsch & Deutsch, 1963). Late selection theories state that low levels of auditory processing remain unaffected by attention. Under this model, it is argued all auditory stimuli are attended to, whether intentionally or unintentionally. The filter intensifies the important acoustic information and attenuates the intensity of the stimuli deemed to be unimportant (Yantis and Johnston, 1990). This feature implies internal decisions must be made as to the stimulus relevance, before it reaches conscious awareness.

Gray and Wedderburn (1960) found evidence to support a late theory of attention using a method similar to Broadbent's. Participants heard an assortment of numbers and words in each ear such as; "dear – 7 – Jane" in the right ear and " 9 – Aunt – 6" in the left ear. Subjects were asked to report back what they heard. Gray and Wedderburn (1960) stated if an early selection model was acting, participants should report back all items presented to one ear first and items presented to the other ear second. However, participants reported back hearing "Dear Aunt Jane" and "9, 7, 6". This finding was suggested to indicate individuals select stimuli based on meaning rather than physical features, thus supporting a late selection theory of attention.

1.4 BOTTOM-UP AUDITORY ATTENTION

As described previously, there are two suggested mechanisms of attention. As top-down processing is not of interest in this current research thesis, emphasis will be placed on bottom-up processing.

As outlined earlier, bottom-up auditory attention is a low level involuntary process commonly termed as stimulus driven attention or exogenous attention. Bottom-up mechanisms play an important role in auditory scene analysis (Okamoto, Stracke, Lagemann & Pantev, 2009). In bottom-up processing of auditory stimuli, the processing is driven by the properties of the auditory stimulus such as frequency. This attention acts in a pre conscious manner. For example a listener may attend to a sudden loud noise whether they want to or not. Sound sources contain different acoustic properties such as fundamental frequency, duration and intensity that can facilitate this pre conscious attention. It is well known that this stimulus driven attention can effectively improve auditory performance in even the most complex acoustic environment (Deutsch & Deutsch, 1963). The acoustic property of particular interest in this thesis is f0. Lagemann, Okamoto, Teismann and Pantev (2010) reported that bottom-up driven attention plays an important role for an individual to process auditory information in background noise. They stated that bottom-up attention would allow an individual to track a certain auditory signal in noisy situations without voluntarily paying attention to the auditory modality. The bottom-up driven involuntary mechanism was hypothesised to appropriately and automatically adjust the distribution of processing resources based on the surrounding noise level, resulting in better auditory performance in noisy environments.

Studies exploring the effects of attention have used the measurement of reaction time (RT) in audition, tonotopic mapping and the probe signal method. These methodologies have proved useful in highlighting the relationship between frequency and bottom-up attention.

1.5 THE PROBE SIGNAL METHOD

The detection of auditory stimuli may be degraded by the presence of background noise. An individual is expected to perform optimally in a listening situation if the portion that best represents the signal can be selected from the sum of auditory input. In auditory environments, an observer's selection can be modeled as a filter (Broadbent, 1958). When attending to a tone at a specific frequency, listeners may be sensitive to that tone and others within a restricted band of frequencies surrounding it. The attention band is the band pass filter function derived from the differences in detectability between a fully attended target at the centre of the band and unattended probes at other frequencies (Dai, Scharf & Buus, 1991). This region of enhanced sensitivity can be measured using the probe signal method (Greenberg & Larkin, 1968; Dai et al., 1991). The probe signal method is based on the assumption that an individual responds only to sounds within the filter centred on the expected frequency (Hafter, Schlauch & Tang, 1993).

The probe signal method involves the detection of a signal in noise that is presented on the majority of trials at an expected (target) frequency. Unexpected (probe) frequencies are presented less frequently on randomly determined trials. These probe signals are sampled from a band of frequencies centred around the target frequency as seen in Figure 3. Both the target frequencies and probe frequencies presented all contain equally effective energy, therefore identical amplitudes (Greenberg and Larkin, 1968).

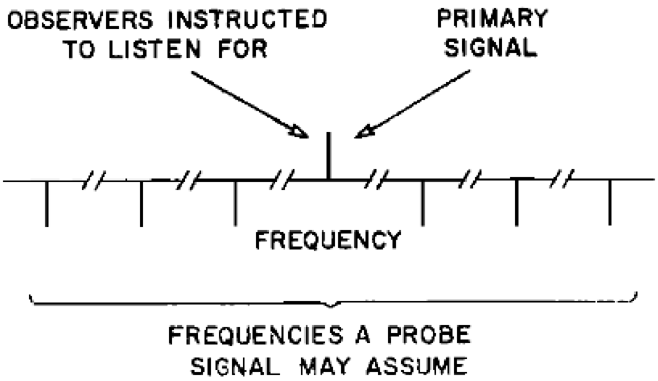

Figure 3. Representation of the probe signal method. The method provides data for a frequency response characteristic of the observer detecting the primary target signals of a single frequency (Source: Greenberg and Larkin, 1968).

1.5.1 The original study

It appears the original probe signal method was inspired by research undertaken by Tanner and Norman (1954). Tanner and Norman (1954) used a 4 Interval Forced Choice (4IFC) procedure. The signal to be detected was a 1000 Hz tone burst presented in conjunction with white noise. The participant's task was to identify which of the four intervals contained the 1000 Hz tone burst. It was found after multiple trials that listeners were capable of detecting the target tone 65% of the time. The experimenters then set the tone burst to 1300 Hz and found listeners discrimination scores dropped to 25%. After the subjects were informed the tone signal had been changed slightly their performance increased to 65%, the original value. It was concluded that individuals were capable of selectively attending to the expected frequency of 1000 Hz, while sensitivity to the 1300 Hz tones was decreased (Tanner & Norman, 1954).

Greenberg and Larkin (1968) developed the probe signal method as a means of obtaining a direct behavioural measure of an individual's frequency selection. Sixteen participants took part in the research. Observers undertook four experiments, using a 2IFC procedure. A single experimental session lasted 2-2.5 hours. Each experiment differed in terms of the number of different probe signal frequencies, the distribution of the probe signal frequencies, the frequency range covered by the probe signals and the number of experimental sessions devoted to data collection for the frequency response characteristic (Greenberg & Larkin, 1968). Initial instructions led the observers to believe the frequency of the signals would be constant. To prevent participants becoming aware that signals at frequencies other than the target signal were being presented, probe signal trials were inserted infrequently. No feedback was given as to the correctness of the observer's decision during testing.

Greenberg and Larkin (1968) found the probability of detection to be lower for unexpected probes than for expected target signals. Furthermore, the probability of detecting the signal decreased as a function of increasing distance from the expected target frequency. The frequency response characteristics of the majority of listeners showed correct detection of the centre-frequency signal (1000 Hz) between 75% and 90% of the time. The same curves showed approximately 50% correct or chance detection of signals for frequencies separated by 150-200 Hz from the centre frequency, seen in Figure 4. Greenberg and Larkin found a striking similarity between the obtained curves and the frequency response characteristics of a band-pass filter centred at the target frequency. The results they obtained could be used to support the presence of an attentional filter operating when detecting signals of a single frequency. In the framework of a sensory filter model, the chance level of detection of the outlying frequencies would indicate that signals at these frequencies were attenuated to such an extent they were essentially not heard. Whether these signals were simply not heard, or heard but not considered by the listener was unclear and was outlined as a topic of interest for further research.

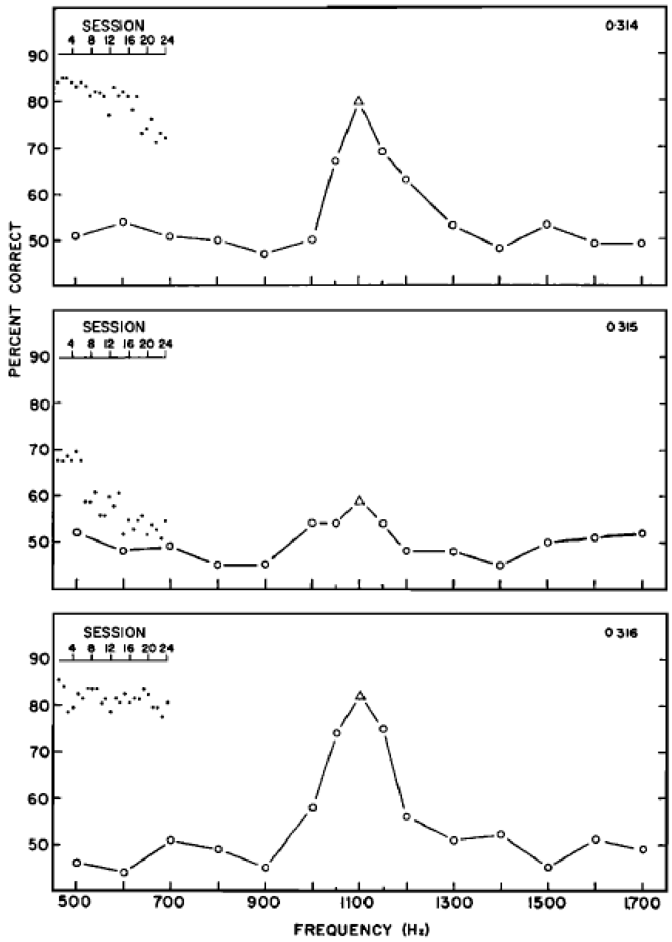

Figure 4. Results obtained from three participants. Circles represent the mean detectability of the signals at various frequencies. The solid dots represent the detectability of the 1100 Hz target signal during each of the 24 sessions. (Source: Greenberg and Larkin, 1968).

1.5.2 Heard and not heeded hypothesis

The extent to which the pattern of results found by Greenberg and Larkin was due to a shift in sensitivity as opposed to some kind of response bias was examined in a series of experiments by Scharf, Quigley, Aoki, Peachy and Reeves (1987). Eighty seven participants initially took part in the research, with 33 observers results disregarded due to incomplete data or low percentage correct scores (<70%). Nine experiments were reported all using pure tone stimuli ranging from 400 Hz – 1500 Hz. Trial by trial feedback was introduced in Experiment 7 to test the heard and not heeded hypothesis. Scharf et al. (1987) wanted to know if the decline in detection seen in their previous experiments was an example of hearing but not heeding. If so, then it was thought that feedback would improve observer's detection performance by allowing them to learn to treat the qualitatively different probes as a signal and not noise. Heard and not heeding assumes the subject is capable of making a conscious (heard) rejection (not heeded) of probe signals. Results from their Experiment 7 showed no improvement in detection when feedback was provided. Therefore it was reported that although the "heard and not heeded" hypothesis may have had some effect on results, the width of the listening band was primarily based on attentional filtering. Scharf et al. (1987) proposed an individual is able to select among sensory events on the basis of special criteria, readying the filter before stimulation. This was thought to facilitate reception of relevant signals. They hypothesized this facilitation may have an influence on filtering of the cochlea, implying the presence of fine tuning in the auditory periphery.

Dai, Scharf and Buus (1991) replicated this result, extending their probe signal procedure to involve target frequencies from 250 Hz to 4000 Hz. Two experiments were reported. The first compared the shape of the attention band to auditory filters from notched noise masking experiments (Patterson and Moore, 1986). The second estimated the attention band centred on 1000 Hz to frequencies distant from the target at a number of different signal levels. This allowed the estimate of the effective attenuation of distant probes. Three participants took part in the 2 experiments, both using a 2IFC procedure. It was reported from the first experiment the width of the attentional band was close to the width of critical band at 1000 Hz and higher but only half that width at 250 and 500 Hz. Experiment 2 found psychometric functions for probe frequencies greater than a critical band away from a 1000Hz target tone to be shifted by around 7 dB in comparison to the psychometric function for the target tone. This 7 dB attenuation of probe signals was much less than expected from the characteristics of a single auditory filter centred on 1000 Hz. According to previous results, the probes in Experiment 2 should have been attenuated by around 20 dB. Listeners were thought to make use of auditory filters that are also tuned to probes as well as the target. They reported maybe individuals assign a reduced weighting to unattended bands in the decision process. This proposed strategy is largely consistent with an effective attenuation of only 7 dB. Furthermore, it was reported the attenuation may be mediated by some more peripheral modification via efferent input to the cochlea.

Penner (1972) varied pay-offs in a modified version of the probe signal method. Two experimental conditions were used. The first led participants to respond to tones with the same frequency as the previous tone. The second condition motivated individuals to respond to tones of different frequencies, even when they weren't identical to the frequency of the cued tone. Results from the first condition mirrored those from Greenberg and Larkin (1968). The observed filter shapes were centred around the cued tone frequency. The second condition gave broader frequency response patterns, with better detection of distant frequency tones and poorer detection of the cue tone frequency. It was reported individuals are capable of employing different subjective listening strategies. Some listeners acted as if they were listening through a narrow, auditory filter like bandwidth, and others appeared to show a much wider filter more inclusive of distant probes.

1.5.3 Frequency uncertainty

In early detection studies the listeners were asked to detect a pure tone signal of a known frequency in the presence of background noise (Macmillan & Schwartz, 1975). Although research using fixed frequencies has contributed well to the understanding of hearing, it is important to consider the role of auditory filters when there is some uncertainty around the signal to be detected (Schlauch & Hafter, 1991). To understand frequency uncertainty, firstly consider a case where the signal to be detected is a single tone whose frequency can be one of X possibilities (Hafter et al., 1993). Performance is optimal when

X=1, and subjects have become familiar with the signal's expected frequency. When X > 1 performance is expected to decline due to the uncertainty about the signals frequency. Greenberg and Larkin (1968) considered the allocation of attention to a single frequency region (i.e., X=1). However, several studies have reported that listeners have the ability to selectivity attend to two or more frequency regions simultaneously (Macmillan and Schwartz, 1975; Buus, Schorer, Florentine & Zwicker, 1986; Schlauch & Hafter, 1991). A complex surrounding where there is some uncertainty around the signal to be detected gives a more accurate picture of real world acoustic environments (Schlauch & Hafter, 1991).

1.5.3.1 Single-band filter model versus multi-band filter model

Models describing frequency uncertainty typically fall under one of two categories, those assuming a single filter and those assuming more than one filter (Macmillan & Schwartz, 1975). If there a single filter operating, the location or width is presumed to be adjusted to deal with the predictability of the stimulus frequency. If however there are multiple filters employed, assumptions are made as to the way in which their outputs are combined to reach a final decision (Green & Swets, 1966). Both of these models assume the observer is capable of adjusting their filtering process in order to optimally perform in various complex acoustic situations (Green & Swets, 1966).

Green (1958) outlined it was necessary to investigate multi-tone detection if one was ever going to explain the recognition of anything other than the simplest auditory signals. He described the first multi band model; hypothesising listeners were able to use multiple attentional filters simultaneously, with the output of these bands being combined. A 4IFC procedure was used to measure the detectability of a signal in background noise for both single and complex signals. A noise spectrum level of 55 dB SPL was used during testing. Each sequence of four test intervals was preceded by a 10-dB drop in noise level. This was employed to ensure observers were reminded of the frequency characteristics and duration of the signal presented. Four frequencies were used; 500, 1000, 1823 and 2000 cps. Complex signals were generated by adding two of these signals. For each signal duration (50, 200 and 1000 ms) each frequency was used as the signal, and it was adjusted in amplitude to ensure a 75% correct detection score. One of the six possible pairs of frequencies was then used as the complex signal at previously determined amplitudes. There were therefore ten signals used; four single frequencies and four complex signals. Four blocks were undertaken each containing 100 trials to determine the probability of correct detection for each signal. Signal durations used were 50, 200 and 1000 ms. The order of conditions was randomly determined. Green (1958) compared results to the statistical summation model (also known as the multi-modal filter model). This model predicts the observer attends to bands at differing frequencies and focuses on the noise power from the masking noise located between frequencies. According to this model, detection performance is expected to drop as the frequencies attended to increase in separation, until the bands no longer overlap. It was found the detectability of the complex signal was somewhat better than the detectability of either single component making up the complex. Comparing this proposed multi-modal model with the single band model, this predicts greater performance (higher detection scores) of signal that have more extreme changes in frequency to what observers are expecting (Swets, 1963).

1.5.3.2 Effect of cueing

Macmillan and Schwartz (1975) employed a modified version of Greenberg and Larkin’s (1968) probe signal method to study the detection of tones with uncertain frequency. The modified probe signal method would allow the frequencies an observer is most sensitive to, to be measured in any given experimental condition. Two experimental conditions were reported. The first, observers performed in uncertain-frequency detection only, with a large number of probe frequencies. In the second experiment, a new group of listeners performed in both uncertain and certain frequency detection conditions, but the number of possible probe frequencies was lowered. Rough estimates of the listener's bandwidths showed little difference between the two experimental groups. Performance was slightly worse with two potential signals than one. The fact that the effects of uncertainty were small may have stemmed from problems inherent with the traditional probe signal method. Typically, subjects may rely on memory to monitor the appropriate frequency band. In two frequency conditions, the random trial by trial selection of the signal meant that one frequency had been cued more recently than the other (Schlauch & Hafter, 1991). Cueing refers to the how individuals perceive incoming stimuli as organized patterns. This may be in terms of onset time, location, similarity of timbre or f0. Here cueing of f0 is of relevance. Evidence that self cueing and its effects on signal memory can affect detection were observed in sequential dependencies found by MacMillan and Schwartz (1975) with performance being best for signals that followed correctly identified signals of the same frequency.

Schlauch and Hafter, (1991) described a method to control for problems encountered by Macmillan and Schartz (1975), in an attempt to better understand frequency uncertainty. A 2IFC procedure was undertaken, with frequency of the signal being randomly chosen from trial to trial to prevent signal memory. The listener was informed of the expected frequency by an acoustic cue presented prior to each trial. The amount of ambiguity was controlled by the number of frequencies making up each cue (X= 1, 2 or 4). Signals and cues were randomly selected from the range 600-3570 Hz to avoid the cumulative effects of memory. The ratio between adjacent cue frequencies could not equate to more than 1.4. On 74% of trials the signal was expected, meaning that it corresponded precisely to one of the frequencies in the cue. The remainder of the signals were unexpected (probe signals). Results indicated that multi-tone cues could successfully direct the observer's attention to listening bands centred at the expected frequencies. Performance was observed to drop systematically for frequencies above and below the expected frequencies (Figure 5).

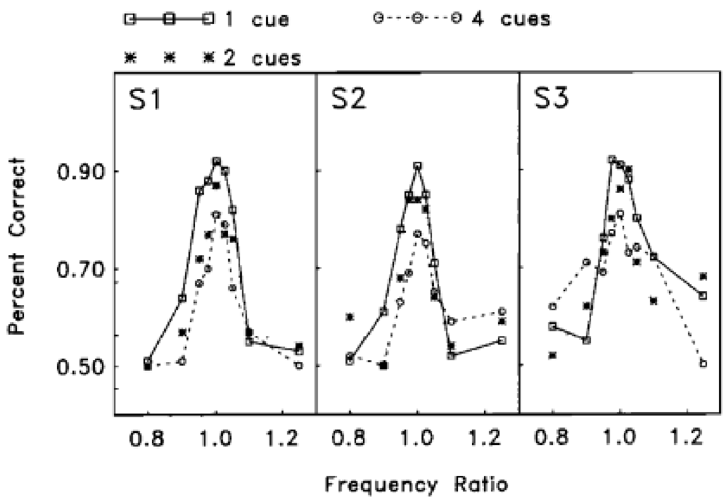

Figure 5. Individual data for subject 1, 2 and 3 in the modified probe signal method that used a one, two and four tone complex as the cue for a single target frequency. The ordinates represent percent correct performance. The abscissa represents the ratio of the signal to be detected to the target frequency (Source: Schlauch & Hafter, 1991).

The listeners reported that on trials that resulted in false alarms, the stimulus timbre was identical to that of the cue, but the perceived level was softer. Timbre refers to tonal quality. This finding combined with the observed decrease in listener's performance for frequencies both above and below the expected frequency is consistent with multi-band listening. This indicates observers are capable of monitoring the output of filters centred on each of the cue components.

Green and McKeown (2007) found clear evidence of involuntary attention to frequency in cued signal detection tasks. They used two cues; informative and uninformative. Cues are defined as informative when the frequency of the cue predicts that of the subsequent signal presented. In other words there is a high probability the signal will match the cued f0. Uninformative cues are the opposite; they are no more likely to indicate the target frequency than they are any other frequency. As these cues are unable to predict the frequency of the target, better performance of targets that match the cued frequency are thought to provide evidence for involuntary bottom-up attention. Four participants underwent a two-alternative forced choice (2AFC) one-up, two-down procedure. All tones used were of 250 ms duration. Background white noise had a spectrum level of 35 dB SPL. Cues and signals were drawn from a set of 12 frequencies ranging from 0.67–5 kHz. Stimuli and noise were mixed and band-pass filtered. Two time delay between cue offset and the first observation interval was either 1 second or 10 seconds. For both delays there were separate conditions in which cues were informative (75% valid) and uninformative (25% valid). Trials were presented in blocks of 48, with each frequency presented. Frequencies immediately above and below were excluded. The minimum frequency ratio between an invalid cued signal and the cue was 1.44. In the informative cued condition each different cue frequency was followed by an invalidly cued signal only once within a block. Therefore nine different blocks were required to ensure all possible combinations were used. The uninformative cued condition however only needed three blocks. Participants were informed of the percentage of valid cues and were instructed to either attempt to focus at the frequency of the cue or conversely attempt to ignore its frequency. Results indicated performance was better for informative cues compared to uninformative cues for both a 1 second and 10 second delay. However it was noted there was a significantly greater percentage correct score and less variability across subjects for the informative cues with a 10 second delay compared with a 1 second delay. Green and McKeown (2007) suggested involuntary effects of cues on detection performance could be explained in terms of the influence of memory from previously presented stimuli.

Tan, Robertson and Hammond (2008) also modified the probe-signal method to investigate the role of frequency cueing using pure tone stimuli. They conducted three experiments. Experiment 1 involved the addition of a cue presented before each trial identical to the target frequency. In the last two experiments, auditory cue frequencies were varied, and the effects were measured on the detection of probe frequencies. Results from their research were consistent with other studies. Mean detection performance was best for the target frequency, and declined when the probe signal deviated from the target frequency. When auditory cues were presented before the target signal, they found detection rates were better when the auditory cue matched that of the target signal. Detection of the signal declined as the probe frequency deviated from the frequency of the cue. Tan et al. (2008) concluded that two auditory mechanisms combine to produce these findings. Firstly, irrelevant frequency stimuli are suppressed based on developed expectations for the incoming signal. Secondly, the detection of the target is enhanced with the presentation of a relevant auditory cue beforehand.

1.5.3.3 Allocation of attention in detection tasks

Given the evidence listeners can attend selectivity to one or more spectral regions, resulting in reduced sensitivity elsewhere, the question arises as to how attention is allocated. Is it controlled strategically by the observer as earlier literature has found, or driven by the spectral characteristics of the cue? As previously described it appears listeners can employ different listening strategies. The following studies make use of cued detection tasks to further explore the allocation of attention.

Of relevance to this issue is a probe signal study reported by Hafter, Schlauch and Tang (1993), in which the frequency of the primary tone was varied randomly across each trial. They used three conditions: (1) maximum uncertainty whereby there were no cues were given in advance of the trial to indicate the signal frequency; (2) minimal uncertainty in which "iconic cues" were identical to the frequency of the primary; and (3) partial uncertainty which used relative cues or so called informational cues, in which the frequency of the primary was set to 1.5 times that of the cue. A 2IFC procedure using the probe signal method was used to estimate the width of the attentional filter. Frequency was chosen randomly for each trial from the range of 750-3000 Hz. Signals were 200 ms in duration with the Signal to

Noise Ratio (SNR) set at 12-13 dB for 90% correct detection scores. They demonstrated that cuing effects could be observed both in the "iconic cue" and the "relative cue" conditions compared to the no cue condition. Results showed performance with relative cues (partial uncertainty) was poorer than with iconic cues (minimum uncertainty) by a factor of 1.4. These iconic cues showed filter shapes similar to those obtained using other methods such as the notched noise method (Dai et al., 1991; Schlauch & Hafter., 1991). It was assumed listeners were attending to the output of a single auditory filter, implying other filters were ignored. The bandwidth measured from relative cues was observed to be wider by a factor of 1.6 compared to iconic cues. These observed wider filters were thought to be a result of subjects pooling the outputs of adjacent auditory filters. It was concluded relative and iconic cues are capable of engaging different mechanisms of attention allocation.

Dai and Buus (1991) report a result which suggests that stimulus-driven attentional allocation can interfere with attempts to listen selectively. This research may indicate that attention cannot be directed independently of the cuing stimulus. Three participants completed a 2IFC procedure for 2 conditions; continuous and gated. In the continuous condition, a 250 ms auditory cue was presented with a visual cue at the beginning of each trial. The auditory cue had the same frequency as the target tone but was set a level 4 dB higher. In the gated condition, a single trial had three noise bursts marking a 500ms cue interval and two 600 ms observation intervals. The noise bursts were separated by 350 ms intervals. A 250 ms cue tone was turned on 300 ms after the onset of the first burst. A 300 ms signal was turned on 300ms after the onset of one of the last tone bursts. The masker was a band of noise (630-1470 Hz) with a spectrum level of 25.8 dB SPL/Hz and an overall level of 55 dB SPL. The target was a 1000 Hz tone with 12 probe frequencies ranging from 700-1370 Hz. Results obtained from using a gated masker showed improved detection of probe signals, indicating participants listened to probes in addition to the 1000 Hz target tone. It was found that when a noise masker was gated on 300 ms ahead of the target rather than being presented continuously, the attentional filter usually displayed in probe signal detection studies was much less apparent. One explanation put forward to account for the broadening of the attentional filter was that participants listen for several bands near the masker onset. Thus attention may be automatically directed towards frequency regions where there is a sudden change in the level of excitation. If this is the case, the result of Hafter et al. (1993) may indicate that their listeners were capable of redirecting their attention during the 300 ms interval between the offset of the cue and the first observation interval. The suggestion that observers engaged in detection tasks can modulate dynamically their relative sensitivity to energy in a particular spectral region raises the possibility that such strategies may be employed in more general listening situations. For example, continuous speech typically provides unfolding information about the identity of upcoming segments which could be exploited by the auditory system to direct attention to critical spectro-temporal regions. Furthermore, the ability to attend selectivity to a number of discrete frequency regions simultaneously may play a role in the auditory systems ability to segregate concurrent sounds.

Probe signal experiments have shown that when a masking noise is presented continuously, a long duration signal is more effectively detected at an expected frequency as opposed to an unexpected frequency. (Greenberg & Larkin, 1968; Macmillan & Schwartz, 1975; Dai et al., 1991; Schlauch & Hafter, 1991). However, when the noise masker becomes gated, unexpected signals appear to be detected as well as unexpected signals (Dai & Buus, 1991). One interpretation put forward by Dai and Buus (1991) is that gating the masker noise initially forces the listener to listen to a broad range of stimulated frequencies even though the single tone at an expected frequency is to be detected. This theory fits with the common intuition that novel events, such as the onset of clearly audible sounds, attract attention (Wright & Dai, 1993).

Wright and Dai (1993) explored the effect of masker gating on the detectability of unexpected signals. They were primarily interested in whether changes in the observer's ability to detect unexpected signals were due to masker gating correlated with changes in the shape of the auditory filter measured with notched noise, or changes in threshold due to masker gating. Expectation was varied using a modified version of the probe signal method, leading the subject to expect a target frequency by presenting the signal most often at that frequency. The methodology was capable of measuring sensitivity to other unexpected frequencies via occasionally presented probe tones. Results showed the resulting "probe-signal filters" were frequently broader than auditory filters measured using notched noise in the same subjects. This finding suggests that subjects may monitor multiple auditory filters under the same conditions when undertaking the probe signal task.

1.5.4 The probe signal method using complex tones

So far research reviewed has primarily focused on auditory attentional filters for pure tone frequencies. A complex tone however contains many sinusoidal components with differing frequencies, which is usually the case with natural sounds (Houtsma, 1995). A harmonic complex tone is a sound consisting of frequency components that are all integer multiples of a common f0 (Cedolin & Delgutte, 2004). The pitch elicited by a harmonic complex tone is usually very close to that of a pure tone at the f0, even when the stimulus spectrum contains no energy at that frequency. This phenomenon is known as the "pitch of the missing fundamental". As outlined previously, the peripheral auditory system is thought to be a bank of band-pass filters representing the frequency analysis occurring at the BM. When two partials of a complex tone are spaced sufficiently apart relative to the auditory filter band widths, each of them produces an individual local maximum in the spatial pattern of the BM notion. In this case, the two harmonics are said to be resolved by the auditory periphery. Conversely, when two or more harmonics fall within the band-pass of a single filter they are said to be unresolved. The strength of the pitch percept depends on the extent to which individual harmonics are spaced adequately apart to be resolved by the mechanical frequency analysis taking place in the cochlea (Cedolin & Delgutte, 2004).

Hill, Bailey and Hodgson (1997) explored the effect of complex stimuli on attentional filters using a modified version of the probe signal method. The objective of their research was to see when discriminating between complex stimuli, do observers direct their attention to the expected signal. In other words, do listeners exhibit an attentional filter for complex stimuli? Complex tones comprised of seven logarithmically spaced components at frequencies of 200, 270, 365, 492, 664, 897 and 1211 Hz. These components were gated synchronously in sine-phase with a total duration of 200 ms including a 10 ms cosine squared onset and offset ramp. Each component of the standard was presented at a level of 40 dB SPL. Stimuli were synthesized using a sampling rate of 10 kHz and were converted to voltages using a digital to analog converter. The stimuli were then low pass filtered at 3.5 kHz. Four listeners took part in two experiments and their task was to discriminate between the standard and standard plus signal. The signal was an increment in the amplitude of one of components three through six. Performance was measured using a 4IFC procedure with the signal added to the standard in either interval two or three with equal probability. Participants were given an unlimited amount of time to make their response, after which visual feedback was provided. Prior to the main experiment participants were run on a series of calibration sessions to determine the amount by which each component in the complex had to be incremented to give a performance score of 79% correct discrimination. In Experiment 1 each listener undertook two conditions; the “target-3” condition where the target was added to component three (365 Hz) and the “target-6” condition where the target was added to component six (897 Hz). Experiment 2 was identical to Experiment 1 with the exception that the level of each component was randomized across trials. It was outlined that any observed differences in performance between probes was likely to reflect differences in the distribution of attention across frequency rather than the degree of timbral similarity between the standard-plus-probe and the standard-plus-target. Results of Experiment 1 showed performance was better when the incremented component had a high probability of carrying the signal, as opposed to when the probability of being incremented was relatively lower. This result is consistent that listeners were attending selectively to the spectral region most likely to contain the information needed to do the task. The findings of Experiment 2 were the same as Experiment 1. It was stated to be unlikely the listeners were identifying the target by comparing its profile to a stored template in memory. Overall results were consistent with the hypothesis that listeners were focusing attention on the spectral region defined by the target signal.

Wright & Dai (1998) explored the detectability of sinusoidal amplitude modulation (SAM) at unexpected rates using a modified version of the probe signal method. Modulation rate refers to how rapidly amplitude increases and decreases over time. The modified method used was capable of manipulating the listener's expectation of the rate of modulation to be detected. Three participants undertook the experiment. Their task was to detect SAM of a gated, low-pass noise carrier with a cut-off f0 of 10 000 Hz. The modulation duration was 500 ms, as measured between the half amplitude points on 16.8 ms rise and decay cosine-squared envelopes. Modulation rates were: 4, 8, 32, 64, 128 and 256 Hz. The target modulation rate was 4, 32 and 256 Hz in different tests, with the probe rate using the remaining six rates. The task was a 2IFC procedure with feedback provided. Listeners were asked to detect which of the two intervals contained modulated noise. Results yielded mean performances of 86-94% correct in the target only (expected) conditions. When probe signals were inserted with a 4 Hz modulation rate (unexpected), percentage correct scores decreased by 10% when compared to the target only conditions at every modulation rate. When the expected modulation rate was 32 Hz or 256 Hz, mean performance decreased by 0-10% for probe rates at and above 16 Hz. These scores decreased considerably for modulation rates below 16 Hz. Mean performance for the 4 Hz rate was 58% correct when the 32 Hz rate was ‘expected’. When the 256 Hz rate was expected performance was observed to be at 62% and 91% when the 4 kHz rate was presented alone. Findings indicated modulation at unexpected rates at or greater than 16 Hz were detected only slightly more poorly than at expected modulation rates, regardless of the expected rate of modulation. The results could not be attributed to the idea that listeners hear both expected and unexpected amplitude modulated signals equally well. But also they reject the unexpected signals if they do not sound sufficiently like the expected tone (Scharf et al., 1987). The pattern of results was found to be dependent on the modulation rate of the target. It was reported that it was difficult to see how the listener could reject the probe rate because it was different from the target rate in one condition but not the other. This is especially the case because in the 2IFC task the standard was an un-modulated noise, so any sound different from that standard could have been used as the detection cue. The results indicate that listeners may use two different cues for the detection of modulation: an individual fluctuation cue at low rates and a roughness or pitch cue at higher rates. The pitch or roughness cue explanation could be consistent with results obtained for modulation rates at 32 or 256 Hz. Here mean performance was seen to be best for the unexpected rate of 64 Hz, a value close to the 70 Hz rate which produces the most roughness for broadband carriers (Fastl, 1977).

The main conclusions drawn from Wright and Dai’s research were that individuals detect modulation rates equally well for expected (target) rates and unexpected (probe) rates equal or greater than 16 Hz. However, they only perform well for modulation rates equal or less than 16 Hz when a slow rate is expected. Also, they hypothesized listeners made use of two cues; an individual fluctuation cue at low rates and a roughness or pitch cue at high rates.

2 RESEARCH AIMS AND HYPOTHESES

The present study aimed to determine how small unexpected changes in frequency or fundamental frequency affect the detection of (1) pure tones and (2) complex tones using the probe signal method.

Experiment 1 was designed to mirror Greenberg and Larkin's (1968) original study using the probe signal method with pure tone stimuli to estimate the attentional filter in the f0 domain. This experiment was to act as a control for Experiment 2.

Based on current literature the following hypothesis was proposed:

> Listeners make use of an attentional filter for f0 of complex tones. Specifically, performance will decline with increasing separation between probe tone f0 and target tone f0.

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3 METHODS

3.1 PARTICIPANTS

Twenty adult listeners ranging from 23 years to 54 years with a median of 28 years participated in both experiments. Of the 20 listeners, 8 were males and 14 were female. Fourteen participants were students from the University of Canterbury Masters of Audiology course. The other 6 listeners were recruited from informal emails, word of mouth and personal acquaintances. Subjects were compensated for their time with a $30 shopping mall voucher. Participants read an information sheet outlining a brief summary of what the thesis testing entailed, and signed a consent form.

All of the procedures undertaken using human subjects were approved by the University of Canterbury Ethics Association. Procedures using participants described in this chapter were performed in accordance with the guidelines outlined in the submitted ethics proposal.

3.2 INSTRUMENTATION

MATLAB was utilised for stimulus generation and data collection. All stimulus waveforms were sent from the built in sound card of a Windows PC. The sound card voltage was calibrated with a Tektronix TDS2002 oscilloscope so that levels in dB SPL were accurate to within 1 – 2 dB.

Data with each participant's responses were saved to files in MATLAB, and later transferred to an Excel spreadsheet.

3.3 STIMULI

3.3.1 Experiment 1

The target signal had a f0 of 1000 Hz, presented on 120 trials (Table 1). Probe signals were pure tones at 950 Hz and 1050 Hz (condition 2) or 990 Hz and 1010 Hz (condition 3). Each probe frequency was presented on 24 trials. The tone duration was 400 ms. The masker was a flat spectrum noise, low pass filtered at 8 kHz. The masker duration was 440 ms, and tones were presented in the temporal centre of the noise. The masking noise was always presented at a level of 65 dB SPL. Sounds were presented over Sennheiser HD280 Pro earphones.

Table 1. Sequence and Characteristics of Conditions for Experiment 1: Pure tones

Condition	Stimuli	Number of Trials
1. Control	Target = 1000 Hz Probe = 1000 Hz	120 target trials at 1000 Hz 48 probe trials at 1000 Hz
2. Near probe	Target = 1000 Hz Probe = 1000 Hz ±50 Hz	120 target trials at 1000 Hz 24 probe trials at 950 Hz 24 probe trials at 1050 Hz
3. Distant probe	Target = 1000 Hz Probe = 1000 Hz ±100 Hz	120 target trials at 1000 Hz 24 probe trials at 900 Hz 24 probe trials at 1100 Hz
4. Control	Target = 900 Hz Probe = 900 Hz	120 target trials at 900 Hz 48 probe trials at 900 Hz
5. Control	Target = 1100 Hz Probe = 1100 Hz	120 target trials at 1100 Hz 48 probe trials at 1100 Hz

3.3.2 Experiment 2

Experiment 2 was identical to Experiment 1 except that harmonic complex tones were presented instead of pure tones. The harmonic complex tones used here consisted of components at consecutive integer multiples of a f0 (Figure 6). All the harmonics were synthesised up to 8000 Hz. Components had equal amplitudes and were band-pass filtered from 100-4000 Hz, to maintain a consistent excitation pattern, regardless of f0 (Moore, 1982).

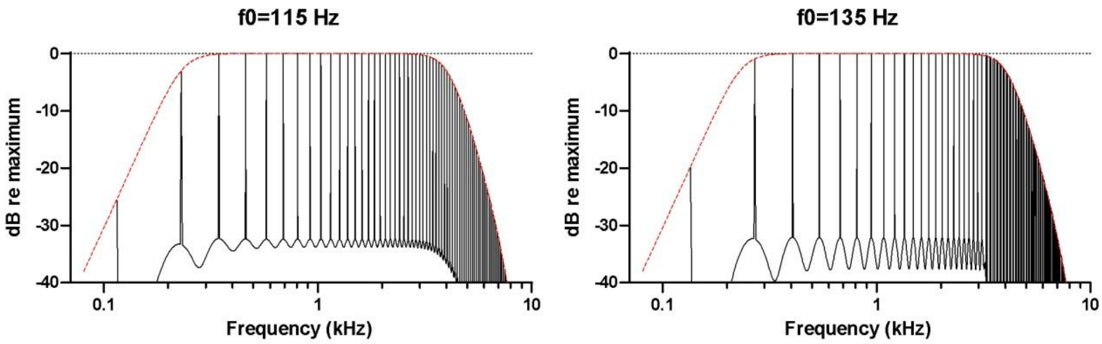

Figure 6. Comparison of the harmonic spectra of complex tones with different f0. The two complex tone f0's consist of components at consecutive integer multiples. Left panel: f0=115 Hz. Right panel: f0-135 Hz.

3.3.2.1 Part 1

Part 1 utilised a target signal of 115 Hz, presented on 120 trials (Table 2). Probes were spaced from the target signal at 105 Hz and 125 Hz (condition 2), and at 95 Hz and 135 Hz (condition 3). Each probe frequency was presented on 24 trials. The control condition held the frequency of the target and probe constant at 115 Hz (condition 1).

Table 2. Sequence and Characteristics of Conditions for Experiment 2 Part 1: Complex Tones

	Condition	Stimuli	Number of Trials
1.	Control	Target = 115 Hz Probe = 115 Hz	120 target trials at 115 Hz 48 probe trials at 115 Hz
2.	Near probe	Target = 115 Hz Probe = 115 Hz ±10 Hz	120 target trials at 115 Hz 24 probe trials at 105 Hz 24 probe trials at 125 Hz
3.	Distant probe	Target = 115 Hz Probe = 115 Hz ±20 Hz	120 target trials 24 probe trials at 95 Hz 24 probe trials at 135 Hz

3.3.2.2 Part 2

Part 2 consisted of three conditions with the target signal being set at 220 Hz (Table 3). This target was presented on 120 trials. The control condition kept the target and probe signal constant at 220 Hz (condition 1). Probes were spaced at equal distances from the target signal at 10 Hz (condition 2) and at 20 Hz (condition 3). Each probe f0 was presented on 24 trials.

Table 3. Sequence and Characteristics of Conditions for Experiment 2 Part 2: Complex Tones

	Condition	Stimuli	Number of Trials
1.	Control	Target = 220 Hz Probe = 220 Hz	120 target trials at 220 Hz 48 probe trials at 220 Hz
2.	Near probe	Target = 220 Hz Probe = 220 Hz ±10 Hz	120 target trials 24 probe trials at 210 Hz 24 probe trials at 220 Hz
3.	Distant probe	Target = 220 Hz Probe = 220 Hz ±20 Hz	120 target trials 24 probe trials at 200 Hz 24 probe trials at 240 Hz

3.4 PROCEDURE

A 2IFC procedure probe signal method was used. Two types of trials were presented, the target signal trial and the probe signal trial. In target-trials only target signals were presented, each with the same frequency. In probe-trials, two possible probe signals were presented, either slightly above or slightly below the target frequency or f0. In blocks with both types of trials, the order of presentation of the two types of trials was randomly determined by the computer software, with the constraint that no probe trials were allowed in the first 10 trials in a block. The target-trials made up 71.4% of the total number of trials (120 out of 168). Probe-trials were presented on the remaining trials (48 out of 120).

Listeners sat comfortably in front of a laptop in a single walled sound booth at the University of Canterbury Hearing Clinic. Participants sat in front of a lap top screen, displaying two boxes, one for interval 1 (labeled “Int1”) and one for interval 2 (labeled “Int2”). For each trial, participants heard two intervals each containing noise, with one interval containing the signal. The inter-stimulus interval was 100 ms. Participants were instructed to indicate their response by clicking on the box corresponding to the interval that included the tone. If subjects were not sure which interval contained the signal, they were required to guess in order to continue in the trial block. A pause / rest of 3 minutes was given as needed. Visual feedback was provided after every response, with the correct interval highlighted.

A series of practice trials was completed in both experiment 1 and 2 prior to each condition to determine the appropriate SNR for the actual experiment. Practice blocks each consisted of 12 trials. Initial practice blocks were manipulated to allow the signal to be identified easily in background noise (5 dB SNR) for the listener to become familiar with the task. The SNR value was then lowered until the discrimination percentage was observed to be around 65-85% and was therefore deemed appropriate. Typical values fell between -11 and -13 dB SNR. No data was saved from the practice block.

The SNR chosen during the practice trials was fixed across conditions. Control conditions were included to determine the detectability of target signals when presented alone. The order of the experimental conditions for Experiment 1 and 2 was determined using a random number generator. Part 1 and 2 in Experiment 2 were counter-balanced across listeners. Each participant completed both experiments in a single session that lasted approximately 1.5 hours.

3.5 STATISTICAL METHODOLOGY

Statistical analysis was done with the Statistical Package for the Social Sciences (SPSS version 19). The significance level was set at 0.05.

Two way repeated measures Analysis of Variance (ANOVA) was run on participant's discrimination scores from both Experiment 1 and 2 to look at the condition effect, frequency effect and condition by frequency effect.

Follow-up pair-wise comparison procedures using the Bonferroni test were undertaken on both Experiment 1 and 2 to reveal any between-frequency differences.

4 RESULTS

4.1 EXPERIMENT 1: DATA SET 1 (1000 HZ TARGET PURE TONES)

Figure 7 shows the percent correct detection averaged across all 20 participants. There is a clear and obvious difference in detection as a function of frequency of the signal in target plus probe conditions (refer to solid line on Figure 8). For probe signals with a f0 of 900 Hz and 1100 Hz, participants scored around 60-65%. As the f0 of the probe signals neared 1000 Hz (950 Hz and 1050 Hz) detection performance increased. At these two f0's percentage correct scores were around 66-70%. At the 1000 Hz target tone, participants scored around 78%. In control conditions (refer to dotted line on Figure 8) participants scored around 79% at 1000 Hz, dropping to 74% at 900 Hz and 72% at 1100 Hz. Figure 7 shows a clear band-pass filter shape in target plus probe conditions.

Two-way (5 conditions by 3 frequencies) ANOVA conducted on the percent correct scores in Experiment 1 revealed a significant condition effect [$F(4, 76) = 5.252$, $p = 0.001$, $\eta_p^2 = 0.308$], a significant frequency effect [$F(2, 38) = 8.438$, $p = 0.001$, $\eta_p^2 = 0.217$], and a significant condition by frequency interaction effect [$F(8, 152)$ 4.731, $p < 0.001$, $\eta_p^2 = 0.199$].

Follow-up pair-wise comparisons using the Bonferroni Test revealed no significant between-frequency difference with the exception of the target being significantly higher than the low frequency and high frequency probe tone in condition 2 and 3.

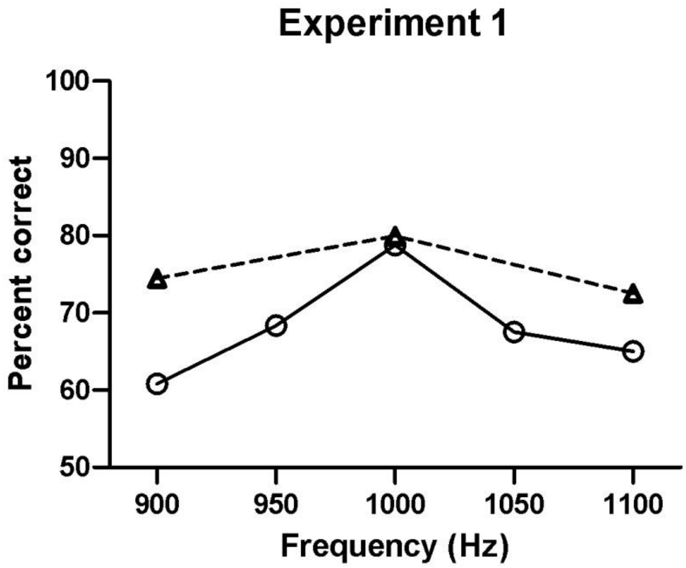

Figure 7. Results obtained from the probe signal method in Experiment 1. Data points represent the mean detectability of signals (percent correct detection) at various frequencies. Triangles represent the control condition scores, where target and probe frequencies were kept constant. Circles represent the target plus probe tone scores.

4.2 EXPERIMENT 2: DATA SET 2 (115 HZ TARGET COMPLEX TONES)

Figure 8 shows the percent correct detection for all 20 participants. There is a clear and obvious difference in detection as a function of f0 of the signal. For probe signals with f0 of 95 Hz and 135 Hz, visual inspection revealed participants scored around 66% and 60% respectively. As the f0 of the probe signals neared 115 Hz, detection performance increased. Percentage correct scores were observed to be around 68% for 105 Hz probes and 66% for 125 Hz probes. At the target f0 of 115 Hz participants scored around 76% for both the control and target plus probe conditions. Figure 8 shows a clear band-pass filter shape.

A two-way ANOVA (three conditions by three f0's) was conducted on the percent correct scores of Experiment 2 part 1, revealing a significant condition effect [$F(2, 38) = 8.234$, $p = 0.001$, $\eta_p^2 = 0.302$], a significant frequency effect [$F(2, 38) = 15.13$, $p < 0.001$, $\eta_p^2 = 0.443$], and a significant condition by f0 interaction effect [$F(4, 76) = 2.853$, $p = 0.029$,

$\eta_p^2 = 0.131$]. The target f0 yielded a significantly higher mean percent correct score than the low and high probe tones in both conditions 2 and 3 ($p < 0.05$). There was no observed difference in mean percent correct scores for the target and probe f0 in condition 1. In addition, the difference in percent correct score between the target frequency and the low probe frequency and between the target frequency and the high probe frequency were submitted to a two-way (3 conditions by 2 comparisons) ANOVA showed a significant condition effect [$F(2, 38) = 9.554$, $p < 0.001$, $\eta_p^2 = 0.335$] but no significant frequency effect [$F(1, 19) = 3.536$, $p = 0.075$, $\eta_p^2 = 0.157$] or condition by frequency interaction effect [$F(2, 38) = 0.096$, $p = 0.909$, $\eta_p^2 = 0.005$]. Overall, there is a significant linear trend of the difference score increasing with increased condition [$F(1, 19) = 21.185$, $p < 0.001$, $\eta_p^2 = 0.527$]. This finding suggests the further the probes are placed from the target f0, the lower the performance (percentage correct score).

Follow-up pair-wise comparison procedures using the Bonferroni Test revealed no significant between-f0 difference except that target was significantly higher than the low f0 probes (95 and 105 Hz) and high f0 probes (125 and 135 Hz) in condition 2 and 3.

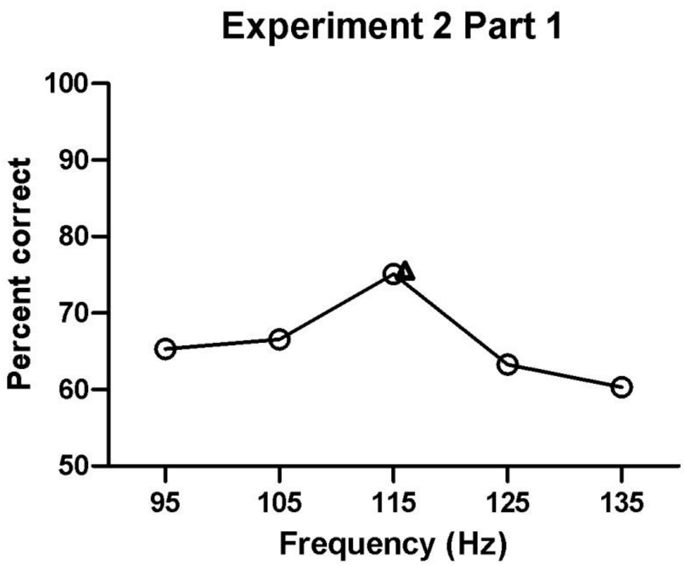

Figure 8. Results obtained from the probe signal method in Experiment 2, part 1. Data points represent the mean detectability of signals (percent correct detection) at various frequencies. The triangle represents the control condition score where the target and probe f0 were equal. Circles represent the target plus probe tone scores. The target tone point at 115 Hz (triangle) has been displaced for visibility.

4.3 EXPERIMENT 2: DATA SET 3 (220 HZ TARGET COMPLEX TONES)

Figure 9 shows the percent correct detection for all 20 participants. There is a clear and obvious difference in detection as a function of f0 of the signal. For probe signals with a f0 of 200 Hz and 240 Hz, participants scored around 60%. As the f0 of the probe signals neared 220 Hz (210 Hz and 230 Hz) detection performance increased. At these two f0's percentage correct scores were around 75-77%. The target tone with a f0 of 220 Hz revealed a mean score of 75% for the target plus probe conditions. In the controlled condition, where the probe and target f0 was 220 Hz, a mean score of 77 % was obtained. Figure 9 shows a clear filter shape.

Results of the two-way (3 conditions by 3 f0's) ANOVA conducted on the percent correct scores revealed a significant condition effect [$F(2, 38) = 13.355$, $p < 0.001$, $\eta_p^2 = 0.413$], a significant f0 effect [$F(2, 38) = 3.779$, $p = 0.032$, $\eta_p^2 = 0.166$], and a significant condition by f0 interaction effect [$F(4, 76) = 4.247$, $p = 0.004$, $\eta_p^2 = 0.183$]. The target f0 (220 Hz) yielded a significantly higher mean percent correct score than the low f0 (200 and 210 Hz) and the high f0 (230 and 240 Hz) probe tones in condition 3 ($p < 0.05$) only. Condition 1 revealed no observed difference between the target and probe f0 percent correct scores. Likewise, condition 2 revealed no observable difference in mean percent correct scores for the target and probe tones.

Follow-up pair-wise comparison procedures using the Bonferroni Test revealed no significant between-f0 difference in condition 1 and 2. It was revealed there was a significant between-f0 effect for condition 3, with the target shown to be significantly higher than the f0 of all probes.

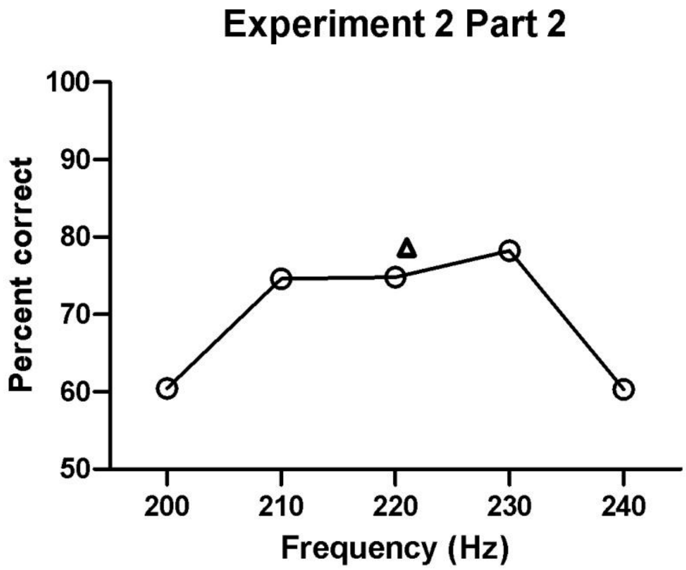

Figure 9. Results obtained from the probe signal method in Experiment 2, part 2. Data points represent the mean detectability of signals (percent correct detection) at various f0's. The triangle represents the control condition score where the target and probe f0 were equal. Circles represent the target plus probe tone scores.

4.4 SUMMARY OF MAIN FINDINGS

Results from Experiment 1 using pure tone stimuli showed a clear difference in percent correct scores as a function of signal frequency. This pattern of results resembled a band-pass filter shape and therefore can be interpreted as indicating the presence of an attentional filter.

Results from Experiment 2 were similar to findings from Experiment 1. Part 1 and part 2 both revealed a decline in performance (percentage correct score) when f0 was set further away from the f0 of the target tone. The obtained curves therefore identified the presence of an attentional filter in the f0 domain, due to the similarity to the filter reported by Greenberg & Larkin (1968) and replicated in the control experiment.

5 DISCUSSION

5.1 RESEARCH HYPOTHESIS

The main purpose of this study was to investigate the possible presence of an auditory attentional filter for f0. Previous literature has identified an attentional filter operating for pure tone stimuli. Experiment 1 was expected to reveal the same research finding. This thesis was therefore primarily focused on extending the use of the probe signal method to complex stimuli.

It was hypothesised for Experiment 2 (complex tones) there would be observed differences in percent correct scores as a function of the f0 of the signal. Specifically, the percentage correct scores would decrease as probe signals were positioned further away from the target frequency.

Experiment 1 revealed a significant difference in percentage correct scores in condition 2 when probes were positioned at 950 Hz and 1050 Hz ($p<0.05$). The same finding was observed in condition 3 when probes were placed further away from the 1000 Hz target tone at 990 Hz and 110 Hz ($p<0.05$).

Similarly, for Experiment 2 part 1 and 2, there was an observed filter effect much like those seen in Experiment 1. Lower percentage correct values were revealed when probe signals were positioned 10Hz and 20 Hz either side of the 115 and 220 Hz target complex tone (Figure 8 and 9). Both part 1 and part 2 showed a drop in performance (percent correct score) when the f0 of probe signals were place further from the f0 of the target tone. This result is consistent with the presence of an attentional filter for f0.

Findings from Experiment 2 supported the hypothesis. Listeners correctly identified the target tone more readily than the probe signals of differing f0's. This pattern of results for complex stimuli is consistent with a low level attentional mechanism operating in the f0 dimension.

5.2 PREVIOUS LITERATURE

5.2.1 The use of the Probe Signal Method for pure tone stimuli

Experiment 1 mirrored Greenberg and Larkin's original study using the probe signal method. Recall the purpose of Experiment 1 was to act as a control to ensure the method employed in Experiment 2 was capable of indicating the presence or absence of an attentional filter when pure tone signals were substituted for complex tone signals.

In the traditional probe signal experiment by Greenberg and Larkin (1968), the pattern of performance for probe signals showed a steady decline as the frequency separation between the probe frequency and target frequency was increased. This pattern was proposed to indicate the likelihood of an attentional filter due to its similarity in shape to a band-pass filter measured in notched noise experiments (Patterson, 1976). A similar finding was evident in the replicated experiment. In both conditions 2 and 3 there was significantly higher identification for the 1000 Hz target signal compared with the outlying probe signals ($p < 0.05$). Moreover, percentage correct detection scores dropped off when probe tones were placed further from the 1000 Hz target tone. This finding is visually apparent in Figure 7. As results from Experiment 1 demonstrated the presence of an attentional filter for pure tone stimuli, the concerns regarding the large number of subjects and small number of trials were eliminated. It could therefore be assumed the methods undertaken in Experiment 2 were adequate to demonstrate a filter for complex stimuli.

Other previous investigations have also shown a pure tone in continuous noise to be better detected at an expected frequency than at an unexpected frequency (e.g., Scharf et al., 1987; Dai et al., 1991; Dai & Buus, 1991; Schlauch & Hafter, 1991). In those experiments, expectation was manipulated via variations of the original probe signal method by Greenberg and Larkin (1968). Such methods lead the listener to expect a target frequency by presenting the signal more often at that frequency and only occasionally at other unexpected probe frequencies. These previous research papers revealed the presence of an attentional filter. This same finding was observed in the present study when participants were presented with complex tones. Specifically, there was a significant observed decline in performance (percentage correct scores) when probe frequencies of both pure and complex tones deviated from the target frequency ($p<0.05$).

It is important to note there was no significant difference in detection performance in conditions where the probe and target frequencies were identical (Figures 7, 8 and 9). This lack of significant difference between detection scores between probe and target stimuli confirms listeners could equally detect target signals when presented in the absence of any probe signals. If listeners did not make use of an attentional mechanism to make a response to the f0 of complex tones they would be expected to detect probe and target f0's equally. Given that probe identification performance was shown to markedly increase in these control conditions when presented at the same f0 as the target tone, it can be assumed attention plays a role in the observer deciding whether or not a tone was presented.

5.2.2 Frequency Uncertainty

Greenberg and Larkin's original study (and therefore Experiment 1) explored the allocation of attention to a single frequency region. This meant subjects could familiarise themselves with the signal's expected frequency region of 1000 Hz (target tone). It is well known the choice of frequency region is determined by experience with samples of the target tone. Thus, individual filters are set by the anticipation of the frequency region that will contain the signal of interest. Hafter et al. (1993) reported performance is optimal when listeners are expecting the signal to be presented, in this case a 1000 Hz target tone i.e. $X=1$. Performance is expected to decline when there is uncertainty around the signal to be presented ($X>1$). Although individuals were exposed to both 115 Hz and 220 Hz target tones in Experiment 2, the two f0's were not mixed within a single experimental block. Therefore, like Experiment 1, there was little uncertainty about the signal to be presented (X=1). Taking this into account, results from Experiment 2 would be expected to reveal similar detection scores to those observed with pure tones in Experiment 1. Performance for the 1000 Hz target tone in Experiment 1 was observed to be around 78%, similar to detection scores observed for the 115 and 220 Hz complex tones in Experiment 2. Target tones with a f0 of 115 (part 1) gave a 76% correct detection score, and target tones with a f0 of 220 Hz gave an observed performance of 75% correct identification. As there was little uncertainty around the signal to be presented it is likely listeners were capable of familarising themselves with the signal's target tone f0. This would allow them to anticipate the frequency region they would be presented with from previous knowledge.

5.2.3 Early versus late selection theories

The attentional filter is thought to be operating in the early stages of sensory processing, making results consistent with Broadbent's (1958) original filter model of attention. Similarly, recall that Treisman (1960) proposed an attenuation theory. She also proposed that the filters (as described by Broadbent) act as attenuators for incoming stimuli. This is consistent with the current results showing attenuation of unexpected stimuli, presumably via the skirts of the attentional filter.

The late selection theory does not square with current results. If low levels of processing were unaffected by attention then it would be anticipated the detection of unexpected signals would be the same as that for expected signals. Clearly this was not the case as probe signals deviating further from the f0 of the target tone yielded lower percentage correct scores (Figures 8 and 9).

5.2.4 Single band versus multi band model

Recall the two proposed models put forward to explain performance patterns for signal detection in noise experiments. The single-band model makes the suggestion individuals attend to the output of a single auditory filter. Conversely, the multi-band model suggests listeners monitor multiple frequency bands simultaneously. The outputs of each filter are then compared in a decision making process.

One surprising finding was that the mean performance range was somewhat less than that found in previous experiments. Other experiments (Greenberg & Larkin, 1968; Scharf et al., 1987) found detection rates for the target to be around 90%, while those for distant probes were observed to be at 50% (chance levels). In the current experiment, performance ranged from approximately 60% for distant probes, to 80% for target signals. One explanation is that some participants may not have undertaken an adequate number of trials to fine tune their listening to the frequency region of the target. The single band model was stated to predict that detection will suffer when the listener is not tuned as precisely as possible to the frequency presented (Swets & Kristofferson., 1970). If this prediction was correct, it is plausible that participants did not receive enough encouragement to tune their listening to the target frequency due to the short experimental session time, and therefore the likelihood they could detect the tone would decrease. Similarly, the improved performance of probe signals may be accounted for by the fact the participants were not capable of fine tuning themselves to the target f0 and thus were better at detecting the f0 of distant probes.

With regards to the multi-band model, band-pass filtering of the stimulus was done to eliminate the issue of participants monitoring bands or the frequency of the stimuli. As the width of the excitation pattern was constant, the number of bands a listener may have monitored was also constant and therefore unrelated to f0. Therefore no conclusion can be drawn from the results as to whether participants monitor multiple filters simultaneously.

5.2.5 Listening strategies

Greenberg and Larkin (1968) reported the filter like results may be due to individuals hearing and not heeding the signals. However, this original study did not provide listeners with any information as to the correctness of their decision. Feedback was provided in the current research which allowed listeners to respond to frequencies other than the expected signal (target frequency) by making them aware of the correctness of their decision. This feedback is thought to have no effect on an individual’s response pattern (Scharf et al., 1987). It is therefore likely the addition of feedback in this current research did not have any effect on auditory attentional filter patterns.

It is conceivable that, regardless of the informativeness of the stimuli presented, with only a small number of possible frequencies used (at most 3), listeners may have attempted to monitor all three frequencies. Previous research suggests this could be achieved reasonably successfully (Macmillan & Schwartz, 1975; Schlauch & Hafter, 1991). When participants were exposed to the 220 Hz target tone, they may have also attempted to monitor the 210 Hz and 230 Hz probe tones (Figure 9). These complex tones (210, 220 and 230 Hz) gave similar detection scores of around 75-77%. However, when the probes were spaced further from the 220 Hz target at 200 Hz and 240 Hz, the detection scores were much lower (around 60%). It can be assumed these probes were not being monitored as they had a f0 further from the 220 Hz target.

5.2.6 The existence of an attentional filter for stimulus dimensions other than pure tones.

To date very few studies have explored attentional filtering for stimulus dimensions other than pure-tone frequency. Therefore results from the current study have been compared in large to studies using pure tone stimuli.

Hill et al. (1997) and Wright & Dai (1998) demonstrated the existence of an attentional filter for a stimulus dimension other than sine wave frequency. These two studies therefore found the same result as what is presented here, an attentional filter in the f0 domain.

5.3 CLINICAL IMPLICATIONS

The suggestion that observers engaged in detection tasks can selectively attend to one frequency region and essentially attenuate other frequency regions raises the possibility that such strategies may be employed in a more general everyday listening situation (Woods & Colburn, 1992). For example, continuous speech typically provides unfolding information about the identity of upcoming segments which could be exploited in the auditory system to direct attention to critical spectro-temporal regions (Watson & Foyle, 1985). The attentional band for f0 could assist a listener in the segregation of one talker's speech from a background of competing noise or speech with a different f0. The presence of an attentional filter may be part of the explanation for why listeners are capable of separating relevant from irrelevant stimuli.

As alluded to previously, attention is an important part of auditory processing. Auditory processing disorders may reflect deficits in auditory attention (Moore et al., 2010). Better understanding of the effect of low-level attention on the processing of complex signals may have clinical implications. Furthermore, in treating hearing impaired individuals and for designing hearing aids it is important to consider enhancing the SNR ratios as a primary goal. Many hearing impaired people have difficulty in background noise; however it is likely the difficulty stems from impairments of auditory image formation. That is, the impaired auditory system may not be capable of resolving the differences among sound sources as well as the normal system. If so, then the solution should not be to reduce the noise, but to find ways to enhance the system's ability to perceive auditory images.

5.4 LIMITATIONS AND FUTURE DIRECTIONS

Greenberg and Larkin (1968) suggested that six sessions are required in order to get a good approximation of the response characteristic of any given listener. In their first experiments each participant completed 24 sessions, made up of ten blocks of 100 trials. Their final experiment was reduced to six sessions which was found to be adequate to obtain the necessary data. In other research using the probe signal method, participants received at least seven hours of practice before the data collecting stage (Macmillan & Schwartz, 1975). Similar research making use of the probe-signal method has concluded that 960 trials, completed within a two hour time frame is required to get a relatively consistent idea of a subject's attention band at any one frequency (Dai et al., 1991).

The current experiment was undertaken by participants in on average 1.5 hours and consisted of a single session with 5 blocks of 168 trials. Before the session began, participants were run through a practice session which was limited a 12 trial blocks. It is likely that additional trial blocks may have improved the reliability of each individual's results. Also, the short experimental time for participants to undertake the two experiments may have meant the obtained results did not reflect their optimal performance. Nevertheless, the design was still effective for obtaining group data which emerged as being comparable to that of previous experiments.

To date there is limited research undertaken looking at the effect of attention on complex stimuli using the probe signal method. It may be useful to explore the effect of signal uncertainty on the detection of complex stimuli. Signal uncertainty provides a better representation of real world acoustic situations, as individuals are continuously exposed to unpredictable stimuli on a daily basis. Studies drawing comparisons between varying levels of uncertainty around a presented signal have found differences in attentional filters using the probe signal method with pure tone stimuli (Macmillan and Schwartz, 1975; Schlauch and

Hafter, 1991). Extending the use of pure tones to complex tones may give greater insight into one's ability to segregate relevant stimuli from irrelevant background noise where there is some uncertainty of the signal being presented.

5.5 CONCLUSION

Results from this thesis provide clear evidence of an attentional filter operating in the f0 domain. The presence of this attentional filter may help listeners segregate speech from competing sounds, or assist in the extraction of one talker's f0 amongst a background of multiple speakers with differing f0's.

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APPENDIX A – Information Sheet

University of Canterbury
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Information Sheet

You are invited to participate in the research project entitled *The Effects of Fundamental Frequency and Auditory Selective Attention on the Perception of Complex Tones in Noise*

The aim of this project is to evaluate the effects of attention on complex tones in background noise. Your involvement in this project will involve one session, lasting approximately 2 and a half hours (including rest breaks as needed), during which you will listen to sounds presented over headphones in background noise. The pre-test provides practice and allows us to compare your performance with the performance of other individuals. If your performance matches an expected pattern, you will continue to the second part of the experiments; however some individuals may be excused at that point. In the second part, you will be asked to listen to tones in the presence of background noise over numerous trials. After each presentation of a tone, you will be asked to identify which of the two intervals it was played in.

You will be rewarded a $30 petrol voucher or $30 Westfield Mall voucher in appreciation for your time.

You have the right to withdraw from the project at any time for any reason without penalty. Withdrawal will not affect any ongoing or future relationship with the University of Canterbury Speech and Hearing Clinic or the Department of Communication Disorders.

The results of the project may be published, and a Master's Thesis is a public document, accessible via the University of Canterbury library database but you may be assured of the complete confidentiality of data gathered in this investigation: the identity of participants will not be made public. To ensure anonymity and confidentiality, the information gathered will be assigned a number and all identifiable information removed. Data and back-up files will be kept on hard drives which are accessible only to the investigators. This data will be kept for ten years after which time it will be destroyed.

The project is being carried out as a requirement for a Masters of Audiology by Anna Suckling under the supervision of Donal Sinex. The project has been reviewed ***and approved*** by the University of Canterbury Human Ethics Committee. (This statement will be included when reviewed and approved)

If you have any further questions about the research project, please do not hesitate to contact either my supervisor or myself at the University of Canterbury.

This project has been reviewed ***and approved*** by the University of Canterbury Human Ethics Committee.

Yours Sincerely,

Anna Suckling

Master of Audiology Student

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APPENDIX B – consent form

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19 March 2012

Consent Form

The Effects of Fundamental Frequency and Auditory Selective Attention on the Perception of Complex Tones

I have read and understood the description of the above-named project. On this basis, I agree to participate in the project, and I consent to publication of the results of the project with the understanding that my anonymity will be preserved.

I understand also that I may withdraw from the project at any time or for any reason, without penalty. I understand that withdrawal will not affect any ongoing or future relationship with the University of Canterbury Speech and Hearing Clinic or the Department of Communication Disorders.

NAME (please print): ……………………………………………………………….

Signature:

Date:

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