Chapter 2

Review of Literature

The psychophysical abilities involve the perception of frequency, intensity and the temporal parameters of sound. Frequency analysis refers to the ability of the auditory system to resolve the acoustic components of a complex sound which can be measured through tasks such as masking and frequency discrimination (Moore, 1995). Intensity discrimination refers to the ability of the auditory system to detect differences in the intensity of sound. This ability can be evaluated using modulation detection and increment detection function (Plack & Carlyon, 1995). Temporal parameters may be conceptualized in terms of temporal processing abilities. Temporal processing ability is an umbrella term involving sub processes such as temporal resolution, temporal patterning, temporal integration and temporal masking (Shinn, 2007).

2.1. Factors affecting psychophysical abilities

There are various factors which can affect the perception of psychophysical abilities. These include age, hearing loss, background noise, cognition, etc. These factors have been studied in individuals with normal hearing sensitivity across age groups and have been compared with those having hearing problems. Psychophysical studies have indicated age related changes on various auditory abilities. The common complaint of elderly individuals with normal hearing sensitivity and those with hearing loss is difficulty in speech perception, especially in difficult listening environments (Dubno, Lee, Matthews, & Mills, 1997). Psychophysical experiments have shown age related declines in frequency discrimination (König, 1957), intensity
discrimination (Harris et al., 2007), duration discrimination (Abel et al., 1990), gap detection (Fitzgibbons & Gordon-Salant, 1995; Phillips et al., 1994), and temporal order determination (Humes & Christopherson, 1991; Trainor & Trehub, 1989).

2.1.1. Frequency discrimination. It is the ability of an individual to identify changes in frequency over time. There are several studies on frequency discrimination in individuals with normal hearing sensitivity (Harris, 1952; Moore, 1973; Nordmark, 1968; Shower, 1931; Wier, 1977). All the studies are in agreement that the difference limen (DL) increases with the increase in frequency in individuals with normal hearing sensitivity.

Frequency discrimination can be measured through various ways, such as two interval forced choice method, three interval forced choice method, and so on. Studies have shown that as the number of alternatives is increased from 2 to 4, the variability of repeated threshold estimates decreases or remains constant, and the accuracy of the estimator, in most cases, improves (Schlauch, 1990). The physiology behind frequency discrimination has been explained by Moore (1973); Sek and Moore (1995). For pure tone stimuli of 1000 Hz and above, frequency discrimination is primarily due to place mechanisms based on spatial changes in the basilar membrane excitation pattern. However, for stimuli less than 1000 Hz, frequency discrimination depends on temporal information (Moore, 1973; Sek & Moore, 1995). It has been assumed that the perception of low frequency discrimination abilities is due to the neural phase locking and for high frequencies, limitations in neural refractory period prevents a phase related response (Rance, 2005). This has been substantiated by Sek and Moore (1995), who gave explanation for frequency discrimination based on the excitation pattern information and not taking into account the phase locking.
Effect of Age. Effect of age on frequency discrimination is well studied. Konig (1957) studied 70 participants with normal hearing sensitivity in the age range of 20-89 years. 10 participants were taken from each and frequency difference limen (FDL) was measured for 125, 250, 500, 1000, 2000, 3000 and 4000 Hz at 40 dB SL. Results indicated that the pitch discrimination deteriorated in a linear manner between the ages of 25 to 55 years, and after 55 years the size of difference limen increases more abruptly. Abel et al. (1990) measured FDL among participants with normal hearing sensitivity at 500 and 4000 Hz to compare the age effect. Results showed that older adults had higher FDL by a factor of 1.8 at 500 Hz and 2.3 at 4000 Hz, compared to younger adults.

He et al. (1998) measured frequency discrimination on 13 participants (7 young & 6 elderly) with normal hearing sensitivity. They measured FDL at 500, 1000, 2000 and 4000 Hz using the maximum likelihood procedure starting at 40 dB SPL followed by 80 dB SPL. Frequency discrimination was poorer for aged participants compared to younger participants with maximum difference at 500Hz. Aged participants also showed larger intersubject variability than young participants and age related difference was greater at low than at high frequency. Clinard, Tremblay, and Krishnan (2010) measured FDL on 32 participants (22-77 years) with normal hearing sensitivity at 500 and 1000 Hz using a two-interval forced choice procedure. Results demonstrated a significant decline in FDLs for both 500 and 1000 Hz, with increase in age. Thus, it can be concluded that frequency discrimination ability declines with age and there is large intersubject variability among them.
**Effect of frequency.** Frequency discrimination would also depend upon the frequency for which it is obtained. Henning (1966) measured FDL from 250 Hz to 12500 Hz using 250 ms tone bursts. Results indicated that discrimination was poorer at high frequencies mainly above 5000 Hz and frequency discrimination varied with loudness level. He reported that at higher frequencies participants may use intensity fluctuations as cues to discriminate frequency changes.

Wier, Jesteadt and Green (1977) measured FDL from 200 Hz to 4000 Hz. They reported that the DL was approximately 1 to 1.5 Hz at 200 Hz to 800 Hz and approximately 2 to 3 Hz at 1000 Hz to 2000 Hz. The DL increased to around 18 Hz for the frequency region of 4000 Hz. They also reported that the effect of sensation level on frequency discrimination was more for low then for high frequencies. Similar results were reported by other investigators as well (Freyman & Nelson, 1991; Sek & Moore, 1995).

**Effect of sensation level.** Frequency discrimination has also been studied at various sensation levels. In a study by Freyman and Nelson (1991) on five participants with normal hearing sensitivity and seven participants with hearing impairment, DL was obtained at ten different intensity levels, for short (5 ms) and long (300 ms) duration pure tones of 500, 1000 and 2000 Hz. The short duration pure tone did not show an increase in DL with the increase in intensity. However, for long duration pure tones, there was an increase in DL with increase in intensity. Kamath (1989) also measured DL of frequency on 40 adults at various sensation levels (20 dB SL, 40 dB SL, 60 dB SL & 80 dB SL) for octaves between 250 to 4000 Hz. She
concluded that FDL obtained across the frequencies and sensation levels did not differ significantly.

**Effect of hearing loss.** Frequency discrimination has been studied in individuals with normal hearing sensitivity across age groups and has also been compared with those having hearing loss. Hall and Wood (1984) measured frequency discrimination on 10 participants with normal hearing sensitivity and 10 participants with cochlear hearing loss for pure tones of 500 Hz and 2000 Hz at durations of 200, 50, 20, 10 and 5 ms at 90 dB SPL. Results indicated that FDL was 1.9 Hz at 500 Hz and 4.4 Hz at 2000 Hz for 200 ms duration stimuli. DL value increased with decrease in stimulus duration and DL function of hearing impaired listeners were parallel to that of normal hearing, showing poorer discrimination overall.

Moore and Peters (1992) measured FDLs on four groups of participants including young and elderly participants with normal hearing sensitivity and those with hearing loss. Results showed that FDL of both hearing impaired groups were higher than the FDL of younger group with normal hearing sensitivity. Simon and Yund (1993) measured FDL for each ear on 34 participants with bilateral cochlear hearing loss. They reported that FDLs could be different for the two ears when the absolute thresholds were same and FDLs could be same when the thresholds of the two ears were different. Thus, it is evident across studies that frequency discrimination depends on various factors such as age, frequency, hearing loss, sensation level, etc. Studies comparing frequency discrimination ability across age have shown that FDL is poorer in the elderly population and effect was more prominent for low frequencies.
2.1.2. Intensity discrimination. It is the ability of a person to detect small changes in intensity. Gelfand (2009) reported that DLs for intensity becomes smaller as the sensation level increases for mid frequency stimuli. Intensity discrimination can be measured through two interval forced choice method, four interval forced choice method in a similar manner as frequency discrimination. Loudness sensations evoked by sounds are usually thought to detect the changes in intensity or to compare the intensity of two separate sounds. Loudness growth is reported to be usually more in individuals with cochlear damage than normal hearing individuals for given changes in intensity. Studies have been done to determine the effect of age, frequencies, hearing loss, and sensation level on intensity discrimination.

Effect of age. Florentine et al. (1993) measured intensity difference limen (IDL) on two older listeners and they reported that IDL was larger in older adults compared to those of young listeners with comparable hearing sensitivity. He et al. (1998) compared IDL for 13 participants with normal hearing sensitivity (7 young & 6 elderly). DL was measured at 500, 1000, 2000 and 4000 Hz using the maximum likelihood procedure starting at 40 dB SPL followed by 80 dB SPL. DL was uniform across participants and frequency with an overall mean of 2.98 dB. Aged subject showed larger intersubject variability than young subject and age related difference was greater at lower than at high frequency.

In an another study, Harris et al. (2007) compared DL of intensity for younger and older subject using P1N2 complex of late latency responses at 500 Hz and 3000 Hz where the intensity increment was varied randomly from +0 dB to +5 dB and +0 dB to +8 dB for 500 Hz and 3000 Hz respectively. Results indicated that at low frequencies DL decreased with enhanced
amplitudes; however latencies were delayed in some older participants. This could be due to the reduced inhibitory control of the central auditory nervous system with ageing.

Fostick, Ben-Artzi and Babkoff (2013) measured IDL on 89 participants (21-82 years) with normal hearing sensitivity at 40 dB SL. Results showed that intensity discrimination did not decline with age. Thus, it is evident from the above studies that intensity discrimination varies with age, but the results are not conclusive and needs further study.

**Effect of frequency.** Jesteadt, Weir and Green (1977) measured DL of intensity in three participants with normal hearing sensitivity at 5, 10, 20, 40 and 80 dB SL for frequencies of 400, 600, 800, 1000, 2000, 4000 and 8000 Hz. They did not find any frequency effect on DL at any given SLs. However, Florentine, Buus, and Mason (1987) reported that DL of intensity was poorer at higher frequencies than the low and middle frequencies. The difference in the results of two studies can be attributed to the difference in methodology.

**Effect of sensation level.** Gelfand (2009) reported that the DLs for intensity reduce as the sensation level increases for mid-frequency stimuli. Miller (1947) measured DL for white noise in participants with normal hearing sensitivity and he reported that DL in level was constant regardless of the absolute level. The value was about 0.5-1 dB for white noise, presented at 20 dB to 100 dB above absolute threshold in normal hearing individuals. Another study by Jesteadt at al. (1977) also supports the same results. It has also been reported that with increase in intensity the change in DL was less for pulsed tone than modulated tone (Moore, 1995).
Iyanger (2000) measured intensity DL for 1000 Hz tone at 10 and 40 dB SL using a ‘yes-no’ procedure on 21 adults with normal hearing sensitivity. She reported that the mean DL was 3.84 dB and 2.87 dB at 10 and 40 dB SL respectively. It was concluded there was no significant difference in DLs at two sensation levels.

**Effect of hearing loss.** Buus, Florentine and Ridden (1982a, 1982b), measured intensity DL in hearing impaired individuals. They reported that the DL was better in individuals with cochlear damage compared to normal hearing individuals when testing was done at equal sensation levels. Similarly, Turner, Zwislocki and Filion (1989) measured the DL for pure tones with gated and continuous-pedestal paradigms in individuals with normal hearing sensitivity and individuals with cochlear hearing loss. The experiments were performed at 500, 2000 and 6000 Hz, and at a wide range of SLs by means of an adaptive two alternative forced-choice procedure. Results revealed that the individuals with hearing loss had smaller DL values than the individuals with normal hearing for both pedestal paradigms at equal SLs. However, when the comparisons were made on the basis of equal SPLs both groups showed similar values for moderate and high SPLs. At relatively low SPLs, the group with hearing loss had a higher DL value. Thus, it is evident from the above study that DL of intensity reduces at equal sensation level in individuals with cochlear hearing loss compared to individuals with normal hearing sensitivity. Humes (1996) reported in his study that older participants had poorer IDL compared to younger participants and when the hearing levels between the two groups were minimized by adding a high pass masker for younger subjects, IDL difference became negligible.
Thus, from the above studies, it can be concluded that intensity discrimination ability depends on various factors such as ageing, hearing loss, frequency, etc. Studies comparing intensity discrimination ability in young and elderly individuals have shown that DL of intensity in older participants decreases at low frequencies which can be due to the decreased inhibitory control of the central auditory nervous system. Studies comparing the effect frequency and intensity on IDL have shown that DL does not vary across frequency and intensity. However, whether cognition plays a role in intensity discrimination has not been studied till date.

2.1.3. Auditory temporal processing. It is defined as the perception of the temporal envelope or the variation in the durational characteristics of a sound in a defined time interval (Musiek et al., 2005).

Duration discrimination. It is the skill of the auditory system to detect minute changes in the duration of acoustic stimuli. Creelman (1962) reported that the smallest detectable change in duration of a stimulus (ΔT) increases with increase in baseline duration (T) of a stimulus. Shylaja (2005) measured duration discrimination on normal hearing adults using 1000 Hz anchor tone having duration of 50 ms at 40 dB SL using a gated method. The results indicated that the participants could differentiate 15 to 25 ms difference in duration between the two stimuli.

Effect of age. Duration discrimination has been studied to examine whether there is any age related difference. Fitzgibbons and Gordon-Salant (1994) studied duration discrimination on 40 participants in four groups consisting of elderly listeners and young listeners with normal hearing sensitivity and with mild to moderate sloping sensorineural hearing loss. Duration discrimination was measured for a tone burst of 500 Hz and 4000 Hz using reference duration of
250 ms at 85 dB SPL. Results indicated that average discrimination for elderly listeners was larger than for younger listeners. However, there was no effect of hearing loss on discrimination ability.

In another study, Phillips et al. (1994) compared duration discrimination in young and elderly participants with normal hearing sensitivity. DL for duration was measured between a standard 1000 Hz tone of 40 ms and a comparison tone of longer duration. The duration discrimination paradigm was presented with a tonal masker following the tonal stimulus at three delay times: 80 ms, 240 ms, and 720 ms and complex stimulus. Age effects were observed on the duration discrimination task with interference, but not on the initial duration discrimination task without interference. These results suggest that the time required to process the duration characteristics of acoustic stimuli is prolonged in elderly listeners.

Kumar and Sangamanatha (2011) measured duration discrimination on 176 participants (20 to 85 years) with normal hearing sensitivity using an anchor stimulus of 250 ms white noise. Scores were similar for individuals in the age range of 20-30 years and 31-40 years. Individuals above 70 years had poorer scores compared to all other age groups. Thus, from the above studies, it is clear that duration discrimination ability deteriorates with age and elderly individual above 70 years showed poorest discrimination ability.

Effect of duration. Abel (1972) measured duration discrimination using stimuli with baseline durations of 10, 100 and 1000 ms and ΔT was found to be around 4, 15 and 60 ms respectively. The results were relatively independent of the overall level of the stimuli and were
also similar for noise bursts of various widths and 1000 Hz tone burst. Thus, it is evident from
the above studies that duration discrimination deteriorates with age and the time required to
process the duration characteristics of acoustic stimuli is prolonged in elderly listeners. However,
there is no effect of overall duration on discrimination ability.

There is growing evidence that cognitive factors such as attention, memory, etc. play an
important role in listening ability. From the literature discussed above, it can be concluded that
the psychophysical abilities have been studied to compare age, hearing loss, etc. However, these
will also depend on the cognitive abilities of the listener which needs to be studied.

**Temporal resolution.** It is the ability of an individual to detect changes in acoustic
stimuli over time. Temporal resolution is important for resolving brief dips in the intensity of the
interfering noise and, therefore, is critical for understanding speech in these situations (Dubno,
Horwitz, & Ahlstrom, 2003; Oxenham & Bacon, 2003; Peters, Moore, & Baer, 1998). The
temporal resolution is typically evaluated through a psychophysical measurement known as gap
detection (Shinn, Chermak, & Musiek, 2009). Amplitude modulation detection is also a measure
to assess temporal resolution.

**Gap detection thresholds.** Gap detection reflects the shortest interval of silence a listener
can detect, whereas amplitude detection reflects an individual’s ability to detect slow overall
changes in the amplitude of a sound (Gelfand, 2009). Gap detection has been compared across
age groups, hearing loss, etc. by various authors.
Effect of age. Gap detection has been studied by various authors across age. Lutman (1990) studied gap detection thresholds (GDT) in 229 participants with normal hearing (50-75 years) and 1764 participants with sensorineural hearing loss (17-80 years). It was measured with shortest detectable silent interval in a 1 sec noise burst centered at 2000 Hz with a 400 Hz bandwidth presented at 85 dB SPL. Results indicated that temporal resolution did not deteriorate with age.

In another study, Snell (1997) measured GDT on 20 young and 20 older participants with normal hearing sensitivity who were matched in audiometric configuration for frequencies between 250 Hz to 4000 Hz. Stimulus used was 150 ms low pass noise bursts digitized with cutoff frequencies of 1000 or 6000 Hz with an inter stimulus interval of 600 ms. GDT was estimated in quiet, in the presence of white noise and high frequency masker at two intensity levels (70 & 80 dB SPL) and at two levels of modulation (0% & 12.6 %). Results indicated that mean gap of older participants was larger than younger participants and they were more sensitive to noise. Mean GDT scores was higher in both groups for high frequency masker.

In a similar study, Strouse, Ashmead, Ohde and Grantham (1998) measured GDT on 12 young adults and 12 elderly adults with normal hearing sensitivity. The GDT was measured through computer generated 1000 Hz, 200 ms, sinusoidal signal in the presence of a continuous noise with a spectral notch at 1000 Hz. The mean GDT for younger and older participants was 4.8 dB and 16 dB. Results indicated larger GDT in elderly listeners the gap between young and elderly participants increased at low sound levels.
Snell and Frisina (2000) measured GDT on 40 young and 40 older participants with 150 ms modulated noise burst which had a cutoff frequency of 1000 or 6000 Hz. The gaps were measured at 80 dB SPL in three background conditions (quiet, continuous noise floor and continuous noise floor with a high frequency masker). Results showed that the mean gap thresholds ranged between 2.6 and 7.8 ms for younger participants and between 3.4 and 10.0 ms for older participants. It was also noted that the mean GDT were significantly higher in older participants for all six conditions.

In an Indian study, Shivprakash (2003) estimated GDT on 60 participants with normal hearing sensitivity. The participants were divided into six cross-sectional age groups of 7 to 12.11 years and 30 normal hearing adults using noise bursts of 300 ms duration with a silence of different durations at 40 dB SL. The results indicated that normal hearing adults could detect a mean gap of 3.3 ms and children aged 7 years could detect a gap of 4.05 ms. However, GDT did not differ significantly between children and adults.

Harris et al. (2010) measured GDT on 10 young and 10 older participants with normal hearing sensitivity. GDT was assessed in two conditions: (1) when the gap was fixed at 5%, 50% or 90% of the total noise duration of 500 ms and (2) when the gap was varied from trial to trial which was randomly presented from the same three values with a maximum gap set to 12 ms. Results suggested that GDT was more for older participants and it increased with random gap detection suggesting that the cognitive load increases during random task compared to fixed task.
Schneider, Pichora-Fuller and Daneman (2010) compared GDT among young and old participants with normal hearing sensitivity. The results showed that the GDT was highly variable in older listeners and it was two times greater than that of young listeners. Kumar and Sangamanatha (2011) measured GDT in 176 participants with normal hearing sensitivity in the age range from 20 to 85 years divided into six cross-sectional age groups. GDT was measured with a 750 ms broadband noise and temporal gap was presented in the center of the noise. GDT in individuals >70 years of age was almost eight folds greater than those for young adults (20–30 years of age).

John, Hall and Kreisman (2012) studied the effect of age and sensorineural hearing loss on temporal resolution using Gaps-in-Noise test in 154 participants. Results showed that the thresholds were poorer in older listeners’ with hearing loss compared to both younger and older listeners with normal hearing sensitivity. This was attributed to the changes taking place in the central nervous system and central auditory processing with ageing. Similar results were reported by Palmer and Musiek (2014), where gap detection was assessed using electrophysiological and behavioral procedure on older adults and younger adults. Results indicated that GDT was significantly poorer in older adults compared to the younger adults and there was no significant difference between the GDT using either procedure for both the groups.

However, in contrary to above studies Moore, Peters and Glasberg (1992) reported that ageing does not have an impact on temporal resolution. They measured GDT in elderly participants with normal hearing sensitivity and with hearing loss using sinusoidal signals from frequencies between 100 to 2000 Hz. Results showed that for the older listener’s, GDT did not
differ significantly from that of younger listeners. Thus, across majority of studies, it is evident that gap detection ability becomes poorer with age and it also deteriorates with increase in cognitive load.

*Effect of frequency.* Shailer and Moore (1987) measured temporal gaps in sinusoidal signals for center frequencies between 200 and 2000 Hz. GDT was about 5 ms for center frequencies of 400, 1000 and 2000 Hz. Psychometric functions for gap detection using sinusoidal signals depend on the phase at which the signals are turned on and off. For some phase conditions, the psychometric functions are distinctly non-monotonic showing oscillations at the period of the signal frequency. Non-monotonicities are not observed when the signal following the gap starts at the phase it would have had if the gap were not present. The non-monotonicities decreased with increasing center frequency.

Moore, Peters and Glasberg (1993) measured GDT on 11 female participants with normal hearing sensitivity for 100, 200, 400, 800, 1000 and 2000 Hz at 25, 40, 55, 70 and 85 dB SPL. Results indicated that thresholds varied slightly for frequencies at 400-2000 Hz (6-8 ms), but increased markedly at 100 and 200 Hz (17 ms). Thus, it is evident across studies that GDT does not vary much with frequency, however, threshold increases at very low frequency.

*Effect of sensation level.* GDT has also been studied at various sensation levels. Penner (1977) reported that gap threshold was around 2-3 ms for broadband noise at high SLs which was almost constant for moderate and low levels. However, Moore et al. (1993) reported that gap threshold increased at low levels. GDT for narrow band and broad band noise reduced with
increase in stimulus level till 30 dB SL and it remained constant for higher stimulus levels (Buus & Florentine, 1985).

Effect of hearing loss. Fitzgibbons and Wightman (1982) compared GDT in individuals with normal hearing sensitivity and hearing loss. Results showed that the temporal resolution was significantly poorer in individuals with hearing loss compared to individuals with normal hearing. This was seen regardless of whether the comparison was made at the equal SPL or at the equal SL.

Roberts and Lister (2004) measured GDT on eight young listeners with normal hearing sensitivity, eight older listeners with normal hearing sensitivity and eight older listeners with high frequency sensorineural hearing loss. GDT was measured within channel (monotic and diotic) and across the ear. Results for the gap detection task indicated the following: (a) scores in the across ear condition was poorer than in either of the within-channel conditions, and there was no difference in performance between the within-channel conditions; (b) older listeners with normal hearing sensitivity demonstrated the poorest performance for the across-ear condition; and (c) the pattern of gap detection performance remained the same for an equal presentation level control condition.

Thus, from the above studies discussed, it can be concluded that GDT depends on various factors. It is evident that GDT reaches adult like values by around 7 years of age and it deteriorates in an elderly population. Gap detection values increases at very low frequencies and
at low sensation level. GDT was poorer in hearing impaired participants compared to normal hearing participants. However, effect of cognition on gap detection still needs to be probed upon.

**Temporal modulation transfer function.** Another measure to assess temporal resolution is through temporal modulation transfer function (TMTF). Amplitude modulation detection assesses the capability to hear the sinusoidal amplitude modulation of a continuous sound (Moore & Jorasz, 1992; Yost, Sheft, & Opie, 1989). Several authors have reported the attenuation slope of TMTF in normal hearing individuals. Attenuation slope of -6dB per octave (Rodenburg ,1977) and about -3dB per octave is reported in individuals with normal hearing sensitivity (Bacon & Viemeister, 1985; Eddins, 1993; Formby & Muir, 1988; Forrest & Green, 1987; Viemeister, 1979). The modulation detection thresholds obtained as a function of frequencies can be characterized in terms of peak sensitivity and bandwidth (Viemeister, 1979).

**Effect of age.** Hall and Grose (1994) measured TMTF in listeners aged 4 years to adult in order to characterize the maturation of temporal resolution abilities in children. Sensitivity to the sinusoidal modulation of a noise carrier of a band pass noise from 200-1200 Hz was determined for modulation frequencies of 5, 20, 100, 150, and 200 Hz. The data from all the listeners indicated a decreased sensitivity to modulations with increasing frequency of modulation. Sensitivity to modulation was found to be reduced in the children of 4-5 and 6-7 years of age, as compared to adults, and in the children of 4-5 years of age as compared to children of 9-10 years of age.
He et al. (2008) measured amplitude modulation (AM) detection for 500 and 4000 Hz tonal carriers in younger and older participants with normal hearing sensitivity. Results indicated that AM detection increased with increasing modulation frequency in older participants. This shows that age related decline in temporal resolution is more for faster envelope fluctuations. Results also showed that age related changes were more for the lower frequency carrier when the modulation frequency was above the transition frequency. This could be because, for low frequency carrier, both temporal and spectral cues are available, however, for the higher frequency carrier, only spectral cues are available. These changes could be attributed to the diminished synchronization of neural responses for the carrier waveform as well as the envelope fluctuation with ageing.

Kumar and Sangamanatha (2011) measured TMTF in 176 participants with normal hearing sensitivity in the age range from 20 to 85 years using a 500 ms Gaussian noise which was sinusoidally amplitude modulated at 8, 20, 60, and 200 Hz modulation frequencies. Results indicated that AM detection thresholds for the higher modulation frequencies (60 & 200 Hz) deteriorated faster when compared to the lower modulation frequencies (8 & 20 Hz). For lower modulation frequencies, deterioration began at 60 years whereas, for higher modulation frequencies, deterioration began by 40 years of age.

Similarly, Jin, Liu and Sladen (2014) investigated the effects of ageing on temporal processing and speech perception in noise among participants with normal hearing sensitivity and with cochlear implant. Temporal processing was assessed using amplitude modulation detection thresholds at 2, 4 and 8 Hz. Results showed significant effect of ageing on amplitude
modulation detection for all three modulating frequencies. Thus, it can be concluded that AM detection deteriorates with age and the deterioration is faster for the higher modulation frequencies compared to lower modulation frequencies.

**Effect of hearing loss.** Modulation detection ability also deteriorates with hearing loss. Bacon and Gleitman (1992) measured modulation detection in five normal hearing participants and in eight participants with flat, slight-to-moderate hearing loss. The broadband noise was sinusoidally amplitude modulated from 2 to 1024 Hz. The carrier intensity ranged from -10 to 50 dB SPL. Results indicated that the TMTFs from the normal hearing participants were independent of carrier level. However, TMTFs from seven of the eight hearing impaired participants were similar to those of normal hearing participants when the carriers were presented at equal SPLs, except that the derived time constants were larger in the participants with hearing impairment.

Bacon and Opie (2002) measured AM detection of a target carrier presented in isolation and in the presence of an additional (masker) carrier in participants with normal hearing sensitivity, bilateral hearing loss, and unilateral hearing loss. The modulated rate of 10 Hz was used for signal and the masker was unmodulated or was modulated at a rate of 2, 10, or 40 Hz. Results showed that AM detection was not affected with hearing loss signifying that mild cochlear hearing loss does not have an effect on the ability to process AM in one frequency region when the competing AM was present in another region.
Thus, it is evident across studies that amplitude modulation detection ability deteriorates with age and age related decline was more for faster envelope fluctuations. Although, mild cochlear hearing loss does not show an effect in the ability to identify amplitude modulation. However, whether cognition will affect the ability to process the amplitude modulation has not been studied.

**Temporal patterning.** It is the skill of the auditory system to perceive and recall the order of sounds presented in a sequence. Temporal patterning can be measured through various tests such as duration pattern test, pitch pattern test. Studies have been done to see the effect of age and hearing loss on patterning task.

**Effect of age.** Trainor and Trehub (1989) measured temporal order recognition and discrimination tasks on younger and older adults. Participants were asked to discriminate among two different component orders in four-tone sequences with alternating higher and lower frequencies presented below 1000 Hz. The study was designed to measure the effect of perceptual organization (Bregman & Campbell, 1971), on temporal ordering. Results showed that the temporal ordering was significantly poorer in the older adults compared to the younger adults. However, differences related to ageing were independent of the type of task (discrimination vs. identification), amount of practice and the stimulus presentation rate.

Humes and Christopherson (1991) compared different auditory processing abilities among younger and older participants with normal hearing sensitivity and hearing loss by means of the Test of Basic Auditory Capabilities (TBAC) (Johnson, Watson, & Jensen, 1987). TBAC has two tests which measures temporal order, one test had four-tone sequences, and other test
consist of one four-syllable sequences with different consonant-vowel combinations. Results indicated that older participants performed significantly poorer on temporal ordering task compared to younger participants and there was no effect of hearing loss.

In a similar study, Fitzgibbons and Gordon-Salant (1998) investigated the effect of age on the ability to discriminate and identify the temporal order of tonal sequences. Temporal ordering was done on temporally adjacent three-tone patterns with a 1/3 octave frequency range centered at 4000 Hz. The result indicated that the discrimination and the identification task were poorer in older participants compared to the younger participants for faster stimulus presentation rates. It was furthermore reported that the order discrimination was easier than the order identification for all participants. However, hearing loss had minimal effect on the ordering task.

Kolodziejczyk and Szelag (2008) measured temporal order judgment across the life span of approx. 80 years, i.e. in young, elderly and very old participants. Results showed an age related decline in temporal ordering performance, with slight changes in elderly participants and significant decline in centenarians which was more in women than in men. This age related decline in temporal ordering may be attributed to slowing of information processing.

Kumar and Sangamanatha (2011) measured duration pattern perception ability in 176 participants (20 to 85 years) with normal hearing sensitivity. Results showed that there was no significant difference in mean duration pattern scores till 60 years of age. However, participants of 61–70 years and participants above 70 years had significantly poorer duration pattern scores.
**Effect of hearing loss.** Studies have shown that hearing loss has minimum effect on pattern discrimination (Fitzgibbons & Gordon-Salant, 1998; Humes & Christopherson, 1991). The performance of the older listeners and younger listeners were compared on ordering task where older listeners had a high frequency hearing loss. Results indicated no obvious influence of audibility factors on temporal ordering.

Thus, it is evident from the above studies that hearing loss has minimal effect on temporal pattern perception ability. However, it deteriorates with age and order discrimination is easier than order identification for listeners of all age groups. The age related decrease in temporal ordering can be explained by slowing of information processing which can also be studied by evaluating working memory.

**Temporal masking.** The temporal masking (forward and the backward masking) have been reported to depend on the stimulus intensity, duration of the masker and the interval between the two stimuli. Moore and Glasberg (1987) reported that the effect of backward masking is higher than the effect of forward masking, keeping all the other factors constant. They also reported that the maximum effect could be approximately 30 dB in individuals with normal hearing sensitivity and this maximum effect was seen when the duration between the stimuli or masker duration or intensity of the masker was reduced. However whether ageing has any effect on backward masking still needs to be studied.

2.2. **Factors affecting speech perception in noise**
Speech perception is a complex phenomenon involving auditory processing and language processing of the information (Kalikow et al., 1977). It is affected by various factors such as redundancy in the stimulus, rate of speech, background noise, signal to noise ratio, age, knowledge of the language and cognitive abilities.

2.2.1. Effect of age. It is a well-documented fact that the proportion of the population, which experience difficulties in the perception of speech increases progressively with age. This difficulty does not increase in a linear manner with age, but it rather accelerates with older age (Pronk et al., 2013). These difficulties manifest themselves primarily in the presence of ambient noise and reverberation. Previous studies have indicated that individuals above the age of 60 years start exhibiting speech perception problems in the presence of noise. They require at least 2 to 3 dB larger signal-to-noise (S/N) ratio than the minimum S/N ratio normal listeners need to understand speech correctly (Plomp, 1977, 1986; Plomp & Mimpen, 1979).

Studies have also shown that hearing in noise depends on both sensation and cognition (Frisina & Frisina, 1997; Humes, 2002). There are age related changes in cognitive process which have a significant role in the comprehension of language spoken in everyday life. Studies have shown that cognitive ageing leads to slowing of perceptual and cognitive operations which can be associated with decline in working memory and attention (Salthouse, 1996).

Humes and Coughlin (2009) assessed the effects of higher processing load on the speech identification ability among young and older adults. The speech from target talker and the speech of a competing talker, speaking a similar sentence, were presented simultaneously to the same ear. The processing load of speech identification was manipulated by using three combinations:
talker uncertainty, gender match among target and competing talkers, and meaningfulness of the speech. Results revealed that older adults performed poorer than young adults and they also showed lesser improvement in speech identification as the processing load was decreased.

In another study, Jin et al. (2014) examined the effects of ageing on temporal processing and speech perception in noise among participants with normal hearing sensitivity and with cochlear implant. Results showed that older individuals with normal hearing sensitivity and cochlear implant listeners performed poorly in speech recognition in noise. However, there was no age effect seen for speech recognition in quiet performance.

2.2.2. Effect of hearing loss. Studies have shown that speech perception in noise deteriorates with hearing loss. Humes, Burk, Coughlin, Busey and Strauser (2007) measured speech perception ability to elderly hearing impaired listeners. They concluded that hearing loss affects speech recognition abilities. In another study, Best, Gallun, Mason, Kidd and Shinn (2010) measured the effect of hearing loss on an individual’s ability to understand messages spoken simultaneously on young hearing impaired listeners. The test stimuli consisted of two messages presented at equal level to the two ears separately which were degraded by adding speech-shaped noise. Participants were asked to either perform a single task of reporting one message and a dual task of reporting both the messages. Results revealed that the participant’s ability to understand a secondary message was sensitive to noise and hearing loss. It was concluded that the task which involves the processing of two simultaneous messages would help in assessing hearing handicap and the benefits of rehabilitation.
2.2.3. Effect of cognition. Studies have shown a link between cognition and speech perception in noise. However, in most cases cognition plays only a minor role and hearing loss plays the major role in speech perception in noise. Gatehouse et al. (2003) assessed speech perception on 50 hearing impaired individuals in aided and unaided conditions. Assessment was done using words, (FAAF: Foster & Haggard, 1987) static and modulated noise (ICRA 2-talker), modulated noise (ICRA 6-talker). Cognitive abilities were assessed through visual digit test (Knutson et al., 1991) and visual letter test. Other tests included were spectral degradation, temporal degradation and upward spread of masking. Results indicated that the cognitive abilities are influential in speech understanding and interact strongly both with the benefits delivered by different hearing aid regimes and with the temporal characteristics of test environment. Other investigators have also reported similar findings (Humes, 2002; Humes et al., 2007; van Rooij, 1989).

Meister et al. (2013) investigated the association between working memory and speech recognition with different background maskers in older individuals. Results showed that older individuals performed poorly compared to the younger individuals in the presence of all background maskers. The scores of speech recognition correlated well with working memory task and it was also observed that working memory was the only significant predictor variable. Thus, they concluded that an individual’s working memory ability should be taken into account for aural diagnosis and rehabilitation.

Moore et al. (2014) investigated the link between speech perception in noise and cognition (processing speed, memory, and reasoning) on about half a million participants of 40 to 60 years
of age. Regression analysis showed an exponential decline in speech perception in noise for both sexes by around 50 years of age. They also reported that this decline in speech perception in noise was significant in participants with poorer cognitive abilities. It was concluded that both old age and reduced cognitive ability are independently associated to poor speech perception in noise.

Besser et al. (2015) evaluated age effect on listening performance with the Spatialized Noise Sentences (LISN – S) test on older group and younger group with normal hearing sensitivity. All the participants completed four auditory temporal processing tests, a cognitive screening test, a vocabulary test, and tests of linguistic closure for high- and low-context sentences. Results showed that the older group performed poorer on the LISN-S test compared to the younger group. It was reported that older listeners find it difficult to ignore the interfering talker’s speech.

In a similar study, Souza and Arehart (2015) investigated the relationship between working memory capacity and speech recognition among 94 older adults with different degree of hearing loss and 30 younger adults with normal hearing sensitivity. Results revealed that working memory had a good correlation with speech recognition, wherein listeners with poorer working memory had more difficulty understanding speech in noise after accounting for both age and degree of hearing loss. Similar results have been reported by Rönnberg, Rudner, Lunner and Stenfelt (2014), wherein they concluded that participants with higher working memory had better speech recognition at various signal to noise ratios compared to people with lower working memory capacity. However, a study by Supernant and Watson (2001) is an exception where they
concluded that there was a weak correlation between cognition and speech perception in noise. This could be because speech signal is quite redundant and there are multiple cues to each phonemic distinction.

Thus, it is evident from the above studies that speech perception in noise gets affected by various factors. However, in normal hearing individuals ageing and cognition plays an important role. Studies have shown that cognitive ageing leads to slowing of perceptual and cognitive operations which can be associated with decline in working memory and attention.

2.3. Working Memory

Working memory is an ability to sustain and manipulate information in mind for short duration of time. It plays a significant role in various cognitive tasks such as learning, analytical thinking, problem solving, and language comprehension. It consists of a central executive control system which monitors two subsystems including visuospatial sketchpad (VSS) and phonological loop (PL). VSS is responsible for a spatial processing and PL is responsible for nonspatial, primarily verbal information processing (Baddeley 1986, 1992). The working memory function depends on the frontal lobe and it controls and manages the functioning of two subsystems: the PL and the VSS (Baddeley 1986).
In Figure 2.1, central executive manages the entire working memory system (e.g. the boss of working memory) and assigns function to the subsystems (VSS & PL). Further, it deals with other cognitive tasks like maths and problem solving. The PL assist in remembering spoken and written material. It has two parts:

- **Phonological Store** – It is associated with speech perception and maintains speech-based information (i.e. spoken words) for about 1-2 seconds.
- **Articulatory control process** – It is associated with speech production and is used to practice and store the verbal information from the phonological store.

The above model recommends that each component of working memory has a restricted ability, and each component is rather independent of each other. It formulates two predictions: 1)
if two tasks use same component (of working memory), then they cannot be executed simultaneously and 2) if two tasks use different components, it is possible to execute them simultaneously as well as separately.

2.3.1. Evaluation of working memory. Working memory involves variety of tasks such as, verbal reasoning, comprehension, reading, and problem solving and visual and spatial processing. It can be evaluated through various tests such as operation span task and reading span task (Kane et al., 2004) and auditory working memory test.

Operation span task. In the operation span task, each part consists of a math problem which is followed by a word (e.g., Is \[8*5\] -25 = 20? FISH). The participant is asked to read the math problem loudly and indicate whether the problem is right or wrong and then say the word loudly. When all the elements in an item are presented, the participant is asked to write or repeat the words in the correct sequence.

Reading span task. In the reading span task, each part consists of a sentence which is followed by a syllable (e.g., The policeman stopped him because he did not use a helmet? Ra). The participant is asked to say the sentence aloud and indicate whether the sentence is correct or not and then say the syllable. Similar to operation span task, when all the elements in an item are presented the participant is asked to write/repeat the syllables in correct sequence.

Sequencing and span. Working memory can also be assessed through auditory number sequencing and auditory digit span. In the auditory number sequencing participants are presented
with cluster of numbers increasing in length and they have to arrange the numbers in lowest to highest order for ascending span or highest to lowest order in descending span. The auditory digit span test is divided into forward and backward digit span. In this cluster of digits are presented in random order with the increasing levels of difficulty and participants are asked to repeat the numbers in same or reverse order. Working memory capacity can be calculated as the total number of digits that the person can successfully recall in auditory number sequencing and digit span test.

2.3.2. Effect of age. Studies have indicated age related decline in working memory (Spilich, 1983; Wright, 1981). Morris et al. (1988) assessed the effect of ageing on working memory using operation span task. Results indicated that older participants responded slowly and, increase in the memory load and in sentence complexity was associated with longer verification latencies. Hester et al. (2004) compared auditory working memory using digit forward and digit backward tasks among adults and older individuals. Results showed an age related decline in both digit forward and digit backward tasks and both the abilities deteriorated to the same extent. Thus, it is evident that working memory abilities decline with ageing.

2.4. Psychophysical abilities, speech perception in noise and cognition
The relationship between psychophysical abilities, speech perception in noise and cognition has been compared in the past by few authors. vanRooij, Plomp and Orlebeke (1989) measured speech perception, temporal resolution and frequency selectivity among young and elderly listeners. The cognitive abilities of the participants were assessed through digit span test, reaction time and memory scanning. The results were heterogeneous for elderly listeners and cognitive factors seem to have relatively less effect on auditory factors.

Humes et al. (1994) measured the speech recognition ability on 50 elderly participants. The participants underwent audiological evaluations, measures of auditory processing (TBAC) and cognitive function (Wechsler Adult Intelligence Scale-Revised [WAIS-R], and the Wechsler Memory Scale-Revised [WMS-R], Wechsler, 1981, 1987). Results revealed that hearing loss had an effect on speech recognition performance among the elderly participants and the auditory processing abilities and cognitive function showed no significant effect on speech recognition.

Suprenant and Watson (2001) compared speech perception and psychophysical abilities on 45 normal hearing adults. Speech measures included recognition of syllables, words and sentences and non-speech tasks included frequency, intensity and duration discrimination and temporal order identification. The cognitive abilities of participants were also assessed through intellectual and cognitive function (SAT-V, SAT-M) and academic performance (GPA). Results revealed that there was a weak correlation between speech and non-speech task. This could be because speech signal is quite redundant and there are multiple cues to each phonemic distinction which is not present for non-speech task.
In a similar study, Humes (2002) measured aided and unaided speech recognition scores on 171 elderly participants using hearing aid. Auditory discrimination ability of participants was assessed using TBAC at 30 dB SL. Cognitive assessment was done through WAIS-R (Wechsler, 1981). It was found that there was an age related difference in scores which could be attributed to cognitive factors.

Akeroyd (2008) did a metanalysis on 20 articles related to speech perception in noise and cognition and he observed a link between hearing and cognition. He noted that in complex and acoustically challenging situations, listeners use previous knowledge to understand speech. Hence, when speech signals are degraded, missing, or ambiguous top-down skills are used to resolve the acoustic input. It has been hypothesized that higher level factors like cognition plays a significant role in speech understanding when speech is made audible through amplification (Humes 2007).

Mukari et al. (2010) measured the effect of ageing and working memory on dichotic listening ability and temporal patterning on 20 young and 20 older adults with normal hearing sensitivity. Results revealed that the older adults had significantly poorer scores on all measures of dichotic listening and temporal sequencing compared to the young adults. Working memory correlated well with pitch pattern task but not with dichotic digit test.

Harris et al. (2012) assessed the effect of age, attention, and cortical processing speed on gap detection using cortical event related potentials on 25 younger and 25 older normal hearing participants. Results showed that GDT was significantly poorer in older adults and they also had
slower processing speed. It was also noted that for older adults, P2 latencies prolonged and N2 amplitude decreased with attention. It was concluded that decline in gap detection with ageing could be contributed to the differences in cognitive abilities or attention related processing deficits with ageing.

Grassi and Borella (2013) assessed age related differences in auditory abilities and also tried to establish the effect of audition on cognitive abilities. Results showed that some of the auditory abilities (i.e., frequency, duration and timbre discrimination, and amplitude modulation detection) could explain a significant variation noted in the processing speed of older adults. This suggests that auditory abilities also do have an effect on cognition.

In contrary, Kidd, Watson, and Gygi (2007a) measured individual differences in auditory abilities, through identification of nonsense syllables, words, and sentences and from 16 psychophysical tests (expanded TBAC) in 340 normal hearing adults. These auditory abilities were correlated with the common intellectual ability of the participants using scholastic aptitude test. Results showed that there was little or no relationship among general or specific auditory abilities and general intellectual ability.

From the above studies, it is evident that the age related difference is seen on various psychophysical tasks which can be attributed to cognitive factors. However, the results are not consistent and studies are done mostly on elderly listeners. Thus, whether cognition plays a role in the perception of psychophysical aspects or vice versa still needs to be probed across various age groups.