

Just Noticeable and Objectionable Group Delays in Digital Hearing Aids

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Abstract

Group delay in a digital signal processing (DSP) hearing aid may be perceived as an echo in the sound heard by a wearer listening to his or her own voice, due to a combination of unprocessed sound received at the ear through head and air pathways and delayed sound reaching the eardrum through the hearing aid. Depending on the amount, this delay may be audible or objectionable and can even result in auditory confusion. This study presents results from 18 subjects listening to their own voices through a DSP hearing aid with a variable group delay. The subjects varied the length of the delay and determined the amounts that were noticeable and objectionable as compared to the undelayed condition, while listening to their own amplified voices. Results indicated that a delay of 3 to 5 msec was noticeable to the listeners in 76 percent of the trials, and a delay of longer than 10 msec was objectionable 90 percent of the time.

Key Words: Delay perception, digital signal processing, digital signal processing hearing aids, group delay

Abbreviations: DAF = delayed auditory feedback, DSP = digital signal processing, KEMAR = Knowles Electronics manikin for acoustic research

Although digital hearing aids have been commercially available since 1995, one of the aspects of digital signal processing (DSP) that has not been widely investigated is the effect of group delay in DSP hearing aids for a user listening to his or her own voice. Group delay in a DSP hearing aid results in a finite time delay created while the signal passes through the hearing aid from input to output. In the audio world, group delay is sometimes also called envelope delay or time delay (Ballou, 1987).

Analog hearing aids have a negligible group delay since they employ continuous amplification, instead of conversion of the input sound into discrete quantities for signal processing in a DSP hearing aid. Delays of up to several hundred msec can be created in DSP hearing aids, depending on the particular architectures and algorithms that may be used to achieve the desired signal processing.

An understanding of the effects of this group delay in DSP hearing aids is important because one effect of group delay is to affect the sound quality of the processed signal. Relatively short group delay causes a slight echo in the sound that may be noticeable to the listener. Longer delay produces a more pronounced echo and may be perceived as being objectionable by the user. As the delay becomes even longer, auditory confusion may result and cause stuttering or other degradations of speech.

Group Delay

The term phase is used to describe the difference in time displacement of one signal relative to another in an electrical or audio circuit. Phase in an audio system is measured as a function of frequency. The phase response of an ideal amplifier is linear. When graphed as a logarithmic or linear plot of phase versus frequency, an ideal phase response will appear as a straight line. Group delay is the slope of the phase response and expresses the relative delay of the different frequencies in a complex waveform (Cabot, 1988). A flat, straight line relationship

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indicates that all of the amplified components of the sound wave will arrive at the same time at the listener's ear. If group delay is linear, as shown by the line being straight, delay will not distort the relationship of frequencies within a complex signal and the delay will not be audible when listening to the sound. When there are deviations from a straight line at various frequencies on the graph, phase distortion is present in the system.

Assuming that a hearing aid designer can minimize the effects of any nonlinearity and the resulting distortion, a remaining important factor is the magnitude of the group delay. Depending on the listener, the delay can cause auditory confusion. Two aspects of auditory confusion may disturb the hearing aid user. One is visual-auditory confusion that results when there is a delay between seeing a talker's lips move and hearing the sound. This is similar to watching a motion picture when the film has slipped out of synchronization and the actors' voices on the soundtrack do not coincide with the movement of their lips on the screen. Summerfield (1992) has noted that sound must lag vision by more than 80 msec for audiovisual intelligibility to suffer. He further recommended that signal processing algorithms for hearing aids to be used for listeners with severe to profound hearing impairments should delay the signal "as little as possible," in order to prevent asynchrony between the auditory signal and visual lip-reading cues. However, he also stated that delays of up to 40 msec (e.g., using a safety factor of two to halve the 80-msec time for which sound and vision problems occur as noted above) should be acceptable.

The other problem resulting from group delay for the user of a hearing aid is the effects caused by delayed auditory feedback. Small amounts of delay will create an echo in the processed sound that may be annoying to the listener. If the delay is long enough, stuttering and other disruptions of speech may occur.

Based on unreported casual observations, Agnew (1997) has suggested that delays on the order of 6 to 8 msec may begin to become noticeable to some listeners. Moser (1999) has reported that contemporary DSP hearing aids introduce a time delay in the range of 2 to 10 msec. Thus, although it is unlikely that delays that will create visual-auditory confusion of the type described by Summerfield (1992) will occur, some hearing aids may create delays in the range that cause coloration of the sound delivered to the user.

Delayed Auditory Feedback

Delayed auditory feedback (DAF) occurs as a result of a time delay in a talker hearing his or her own voice. Degraded sound quality and auditory confusion may result when the talker's voice reaches the ear through a combination of a direct undelayed pathway and a delayed pathway. For a hearing aid wearer, there are several possible direct pathways involved (Fig. 1). One direct acoustic pathway is through slit leakage around an earmold or custom shell of a hearing aid in the ear. Another direct pathway is through a vent in an earmold or custom shell. Other direct links are provided through various transmission pathways inside the head, such as via bone conduction, acoustic conduction through soft tissues, or through the eustachian canal and middle ear. For the wearer of DSP hearing aids, the delayed pathway is caused by the signal passing through the digital processing. Thus, any group delay in the hearing aid causes a time delay to occur between the unprocessed signal received via the various direct pathways and the acoustic signal reaching the eardrum after being processed through the hearing aid.

The effects of DAF are well known and have been used in clinical testing (Silman and Silverman, 1991). If a talker's own voice is delayed for a long enough period of time before being heard, stuttering and other speech degradations may result. This auditory confusion is reported to start for some individuals when the delay in the sound pathway back to the lis-

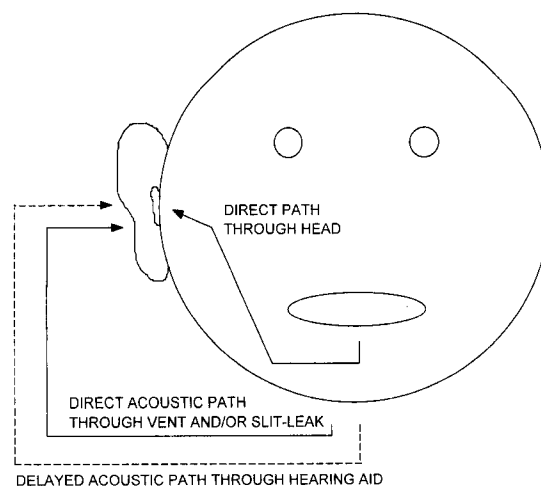


Figure 1 Diagram showing direct pathways for a talker's voice through the air and through the head, along with the delayed pathway through a DSP hearing aid to the ear.

tener's ear is as little as 20 msec (J Punch, personal communication, 1995). The maximum disruptive effect generally occurs at around 200 msec of delay for adults, although the same effects may require a longer delay for equivalent results in children (Borden and Harris, 1984). Values of 500-msec delay have been reported to create maximum disruption among 4 to 6 year olds (MacKay, 1970).

Stone and Moore (1999) studied the effects of delay on a group of 20 subjects with normal hearing. Recordings from two talkers were combined with one of five values of delay and processed with one of four simulations of hearing loss, then amplified with simulations of a hearing aid with four channels of full dynamic range compression. The subjects then listened to these recordings. This procedure resulted in the subjects rating a series of recordings with different delays and simulated hearing impairments, combined with the effects of listening through models of a hearing aid to a voice that was not that of the listener. The data showed that increasing the delay and increasing the simulated hearing loss resulted in monotonically increasing values of delay before the delays were rated as disturbing by the listeners. The authors reported that delays of 20 to 30 msec were rated as disturbing with the simulation of mild to moderate hearing losses.

The study reported here was initiated to measure the amounts of delayed auditory feedback that were required to produce two noticeable effects. One goal was to determine the amount of delay that was noticeable to each subject while listening to their own amplified voice, as compared to the undelayed condition. The other goal was to determine the amount of delay in the amplified sound that was considered to be objectionable to each subject when listening to their own voice, as compared to the undelayed condition. The ultimate intent of the study was to try to obtain a value for group delay that could be used as a worst-case limit for the design of hearing aid DSP architecture and signal processing schemes.

METHOD

Test Hardware

The delay used in this study was created with a general-purpose portable DSP processor with two independent channels of amplification. This processor was originally developed for general

hearing aid research tasks and was specifically configured for these experiments to replicate a DSP hearing aid with linear amplification and a variable time delay in each channel.

The gain in each channel was independently adjustable via slider potentiometers. The delay through the processor was varied by a laptop computer that was calibrated to display a read-out of the time delay through the hearing aid system. All perceptual delay measurements were made in real time with each subject's own voice, since that was felt to be the most likely listening situation for a hearing aid user.

The processor and hardware were configured to use a single microphone for the input and two receiver modules to deliver the sound output to both ears simultaneously. In this way, an identical sound with the same delay was presented simultaneously to both ears. Using a single microphone with two receivers avoided the possibility of coloration of the signal by additional time delays due to head shadow effects. Transit times for low frequencies around the head are on the order of 600 to 700 μ sec, which were considered to be of a magnitude that could affect the measured results.

The microphone used was a Knowles Electronics model EM4046 hearing aid microphone. The receivers were Knowles Electronics model ED7235. Each receiver was housed in an in-the-ear hearing aid module. The receiver modules were made from an ear impression for KEMAR and had a generic shape, and thus were useable for all of the subjects. Because the receiver module was not a custom fit for each subject, a small slit-leak acoustic pathway was created around the case to the ear to reproduce the vent/slit-leak pathway shown in Figure 1.

The use of ear-level modules provided sound reception and transmission to the ear in a configuration that was similar to popular DSP hearing aids. The modules were wired with shielded cables from the ears to the processor, which was located on a table in front of the subject during the testing.

Since hearing compensation was not a requirement for this testing, the frequency response of the amplification was configured to be flat, with the overall frequency response of the system being determined by the frequency response of the hearing aid microphone and receiver. It was felt to be important for the listener to receive as wide a bandwidth as possible in order to be able to accurately hear any subtle effects that might have been lost when using a shaped frequency response.

Variation of the time delay was performed through a mouse-controlled sliding bar on the computer screen that determined the length of a digital delay line configured in the processor. As the sliding bar was moved to the right, the amount of the time delay was lengthened and vice versa. The time delay was adjustable in intervals of 0.0006 msec. Two mouse-controlled buttons on the screen, one to present the sound without any delay and one that introduced delay, allowed the subject to choose immediately between undelayed sound and delayed sound without changing the test set-up, in order to perform a rapid auditory comparison.

Subjects and Test Method

The subjects who participated in this study consisted of 18 male engineers from our electronics design group. None had any reported previous hearing difficulty. Ages ranged from 25 to 51 years of age (mean = 36.6, SD = 9.7). Since Stone and Moore's (1999) data indicated that increased hearing loss resulted in monotonically increased values of delay before the delays were rated as disturbing by the listeners, it was felt that our test group would probably provide lower values of delay than subjects with a known hearing loss, and thus provide us with a worst-case limit for signal-processing design purposes.

Data were gathered with each subject seated inside a 7 ft × 7 ft single-walled audiometric test booth. The booth was located in a quiet area of our laboratory; thus, the lack of a double wall was not considered sufficient to affect the listening task. The portable processor and the laptop computer were located on a table in front of the subject, who remained seated during the testing.

In order to create what was felt to be a typical talking situation, each subject was asked to speak continuously whatever they wished in what they perceived to be a normal tone of voice and a normal speaking pace. While doing this, they adjusted the gain controls of the processor to their most comfortable level with the slider potentiometers. Although this method left the test sound relatively uncontrolled from subject to subject, we felt that this represented a typical listening situation for the user of a DSP hearing aid.

Each subject was then asked to continue to talk and, simultaneously, to find and record two different time delay settings while switching between the delayed and undelayed sound. One setting to be recorded was the setting at which any effects of the time delay became noticeable.

The subjects were instructed that "noticeable" was defined as the amount of time delay at which some form of coloration was perceived by the listener to be introduced into the sound. We assumed that this would be a noticeable echo in the amplified sound. However, this could be any other coloration of the sound that was perceived by the subject to be undesirable and that judgment was left to each subject's interpretation.

The other setting to be recorded was the point at which the length of the time delay became objectionable. Objectionable was defined as coloration of the sound produced by an amount of time delay to which the subject would not wish to listen for an extended period of time. Each task was repeated three times and the setting was noted for each trial.

RESULTS AND DISCUSSION

Results from the measurements of the 18 subjects are shown in Tables 1 and 2. Table 1 contains the data for the noticeable time delay experiment and Table 2 contains the data for the objectionable time delay experiment. In both tables, columns two, three, and four show the individual results from the three listening tri-

Table 1 Measured Added Delay Time in msec to Achieve a Change in Sound Quality That Was Noticeable Between Sound With No Delay and With Delay Added

Subject	Trial			Mean
	1	2	3	
1	3.78	3.17	4.39	3.78
2	1.95	1.95	2.56	2.15
3	3.17	1.95	1.95	2.36
4	2.56	5.62	4.39	4.19
5	3.91	3.78	4.39	4.03
6	4.39	3.17	3.17	3.58
7	3.17	9.28	8.67	7.04
8	4.39	3.78	3.78	3.98
9	3.78	3.78	3.78	3.78
10	5.00	4.39	4.39	4.59
11	3.17	3.17	3.78	3.37
12	3.17	2.56	2.56	2.76
13	4.39	5.62	5.00	5.00
14	4.39	5.00	5.00	4.80
15	4.39	4.39	5.00	4.59
16	5.00	3.78	4.39	4.39
17	5.00	5.62	4.39	5.00
18	3.17	4.39	4.39	3.98
Mean				4.08
Median				4.01
Range				2.15-7.04
SD				1.11

Table 2 Measured Added Delay Time in msec to Achieve a Change in Sound Quality That Was Objectionable Between Sound With No Delay and With Delay Added

Subject	Trial			Mean
	1	2	3	
1	15.99	12.94	12.33	13.75
2	5.00	4.39	5.62	5.00
3	5.62	5.00	5.62	5.41
4	8.06	8.06	8.06	8.06
5	10.50	9.89	10.50	10.30
6	15.38	13.55	18.16	15.70
7	23.68	19.65	21.48	21.60
8	12.33	9.89	11.72	11.31
9	10.50	10.50	10.50	10.50
10	46.88	44.62	45.85	45.78
11	16.60	14.16	15.01	15.26
12	14.16	14.16	12.33	13.55
13	14.77	14.16	12.94	13.96
14	11.72	12.33	12.33	12.13
15	9.89	9.89	9.89	9.89
16	11.54	10.93	13.37	11.95
17	26.37	22.09	23.93	24.13
18	9.28	9.89	9.28	9.48
Mean				14.32
Median				12.04
Range				5.00-45.78
SD				8.72

als. Column five reports the mean of the preceding three data columns.

As can be seen from the last rows of column five of Table 1, the mean value of the readings for the delay time that the subjects felt was noticeable was 4.08 msec. The median value was 4.01 msec, the range was 2.15 to 7.04 msec, and the standard deviation was 1.11. Table 1 shows a reasonably close grouping of the data, except for the second and third trials for subject 7. For some unaccountable reason, these values were considerably longer than for this subject's first trial and for the other subjects.

For ease of interpretation, the data in Table 1 from the three trials for each subject have also been plotted in Figure 2 as a histogram with 1-msec bins. The largest number of the readings (41%) fell in the 4- to 5-msec bin, with 35 percent of the results falling between 3 and 4 msec. Overall, 76 percent of the data fell between 3 and 5 msec.

Table 2 uses the same format as Table 1 for the data for each subject's setting of the amount of the delay time that was perceived to be objectionable. For subjects 2 and 3, very small amounts of delay were noticeable (see Table 1), and any amount of delay longer than about 5

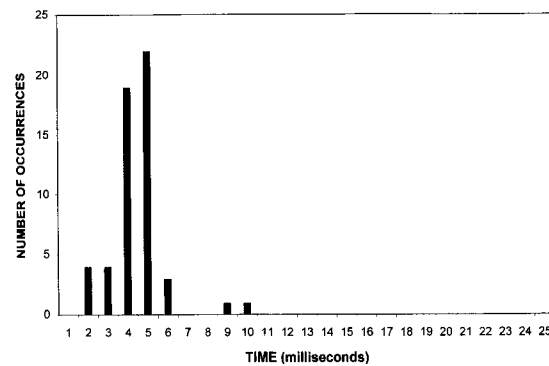


Figure 2 Histogram showing the number of occurrences of measured delay times that were considered to be noticeable, divided into 1-msec bins.

msec was considered to be objectionable (see Table 2). Interestingly, in Table 1, these two subjects indicated the shortest amounts of delay time for the values that appeared to them to be noticeable. Conversely, for subject 10, large amounts of delay were tolerable, and delay times of up to about 45 msec were considered to provide acceptable sound quality. In Table 1, this subject did not exhibit any particular difference from the group data. In addition, subject 17 displayed a large degree of delay, as compared to the other subjects, and subjects 6 and 7 display a fairly large degree of variability across trials.

As would be expected, between the extremes, most listeners rated the amount of delay that was objectionable to them to be greater than their perception of noticeable. The last rows of column five in Table 2 show that the mean value of all of the readings for the perception of objectionable was 14.32 msec. The median value was 12.04 msec, the range was 5.00 to 45.78 msec, and the standard deviation was 8.72.

Similar to Figure 2, the data for the measured objectionable delay times in Table 2 have been plotted as a histogram with 1-msec bins in Figure 3. The data for subject 10 have been excluded from Figure 3, since they were far removed from the rest of the data. The data in Figure 3 do not show as clear a grouping as in Figure 2. Perhaps this should not be unexpected. As is typical with descriptive sound quality judgments, as opposed to bipolar measures, such as measurements of hearing threshold, it can be theorized that part of the reason for the wider spread of results in Figure 3 than in Figure 2 may be due to variations in individual subjects' opinions of what they consider to be "objectionable."

The results reported in this study indicate that a delay of 3 to 5 msec was noticeable

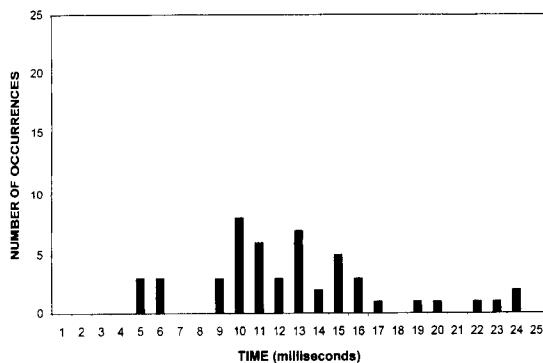


Figure 3 Histogram showing the number of occurrences of measured delay times that were considered to be objectionable, divided into 1-msec bins.

to the listeners in 76 percent of the trials. Anecdotal observation from two subjects while familiarizing themselves with the equipment was that the effects of the delay, perceived as an echo, became less noticeable when they spoke at a faster rate. The casual observations mentioned by Agnew (1997) were made in the semi-reverberant open test area of an electronics laboratory with a higher level of ambient noise than that existing in the audiometric test booth during this study. The listeners in these observations said that a delay of 6 to 8 msec was necessary for a noticeable change in the quality of the amplified sound. It can be theorized that the conditions of the experiments reported here, speaking normally in a quiet audiometric booth, may represent optimum listening conditions more conducive to noticing small changes in sound quality than in an environment with interfering noises and reflections present that may have provided some masking effects, such as the observations made in the semi-reverberant laboratory condition. It would be instructive to repeat this same study with controlled amounts of ambient noise present, in order to determine if different data would be obtained under different listening conditions of background noise and reverberation.

Another interesting consideration is that many thousands of DSP hearing aids have been fitted and complaints of sound quality due to group delay are infrequent, although anecdotal reports of echoes in the amplified sound are not unknown. One reason that such complaints are not more prevalent could be that the hearing aid user does not have a reference condition in which to compare any delay in the hearing aid to an undelayed condition. The experiments under-

taken in this study directly and immediately compared the delayed sound to the undelayed sound as the subjects switched between the two conditions. Without the reference listening condition of the undelayed sound, it would have probably been more difficult for the subjects to detect a 2- to 3-msec echo in the delayed sound as being noticeable.

The other obvious point is that most contemporary hearing aids have group delays on the lower end of the range quoted by Moser (1999) and thus do not cause a noticeable problem. The potential for aggravated effects is that more complex signal processing currently under development among hearing aid researchers and manufacturers could lengthen group delay times into the range where there could be noticeable audible effects.

A delay of longer than 10 msec was objectionable 90 percent of the time to listeners in this study. Stone and Moore (1999) noted that, in their study, increasing delay became more tolerable with increasing hearing loss. They commented that a delay of 20 to 30 msec was disturbing for subjects with mild to moderate hearing loss, increasing to 40 msec with moderately severe hearing loss. Thus, our measured data of 10 msec for subjects with normal hearing appear to be another data point in this pattern and do not seem to be inconsistent with the trend of their results.

CONCLUSIONS

Moser (1999) has reported that contemporary DSP hearing aids introduce a time delay in the processed sound in the range of 2 to 10 msec. Data gathered in this study indicated that a delay of 3 to 5 msec became noticeable to the listeners in 76 percent of the trials. The listeners also reported that the sound became objectionable to them with a delay of longer than 10 msec for 90 percent of the trials. These values are shorter than the 20 to 40 msec reported by Stone and Moore (1999) for listeners with hearing impairments. These delays are also shorter than the 80 msec noted by Summerfield (1992) that sound must lag vision for visual-auditory confusion to occur. Thus, these results suggest that group delays through DSP hearing aids can be of a length that can have the potential to create undesirable coloration of the processed sound; however, DSP hearing aids should not create a problem if careful attention is paid to keeping any delays short during the design of algorithms and DSP hardware.

Acknowledgment. The authors would like to thank Bryant Sorensen at the Starkey Colorado Research Center for valuable assistance in designing the processor hardware and test algorithm.

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