ACOUSTIC DEPTH ESTIMATION ABILITY IN MONAURAL LISTENERS[1]

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ABSTRACT

Eight clinically defined monaurals of varied loss types, levels, and etiologies were tested on a depth perception task in which they adjusted the position of a movable comparison source of one frequency until it appeared to be in physical alignment with a statically positioned standard source of a different frequency. The data were compared with the results of normally hearing subjects tested on approximately the same task, but at a different time. In practically all aspects, the data of the monaurals corroborated that of the normals, indicating that this new adjustment approach to depth study is viable. As before, the most significant variable was the initial position of the comparison source, while learning and frequency as main effects were not significant. Clearly however, the combined data of the monaurals and normals shows that the lower the frequency of the comparison relative to that of the to-be-judged acoustic depth, the more accurate the estimate. For both groups the comparison's direction of movement appears to be a factor in making correct depth estimates, and both underestimate the standard's depth for movement away from themselves and do the opposite when moving the comparison towards themselves. With one subject excluded, the analyses of the clinical factors all proved to be statistically unrelated to the ability to accurately judge depth in this manner. It is expected that with increased subject numbers and the use of bilaterally debilitated persons, there will be observable differences in the ability to accurately estimate the depth of sources.

SOMMAIRE

Huit sujets durs d'oreilles d'une façon monaurale et differencés suivant leur genre de surdité, leur degré et leur étiologie divers ont été étudiés pour leur habilité de percevoir la gravité du son. Pour mesurer cette habilité, deux sons alternants ont été présentés dans le plan médian-sagittal. Un son (de 1.0 kHz) était fixé à trois mètres du sujet et un autre (non-fixé) (soit de 0.5 ou 3.5 kHz) etait placé selon un registre

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qui variait au hasard. Les sujets, assis et aveuglés, devaient aligner les deux signaux manuellement avec une boîte de contrôle. Deux tests sur un total de quinze, donnés à chaque sujet avaient une fréquence référence de 0.5 kHz et 2.0 kHz chaque. Les résultats des sujets monauraux étaient semblables en tout respect avec ceux de sujets normaux examinés un an auparavant, avec cette nouvelle méthode. Ceci indique que cette méthode est valable. La variable la plus significative était la position initiale non-fixée du son. Aucune signification statistique s'est démontré par la variation de fréquence ou d'épreuve. Les données combinées des normaux et des monauraux indiquent que la gravité du son (non-fixé) avec la fréquence la plus basse était determiné avec le plus de précision. Aussi, la direction de mouvement des signaux est un facteur important pour les deux groupes afin d'apprecier la gravité du son. Finalement, les types, le degré et les causes de diminution de l'audition, ne semble pas avoir un rapport avec l'habilité des sujets à apprécier la gravité des sons.

INTRODUCTION

Recently, Gatehouse (1983) reported on a "new approach" to the investigation of auditory depth perception. Basically, the system consisted of a ceiling mounted track from which a vertical mast with a TDH-39 speaker (for "comparison" signal delivery) at its lower end, is suspended. The mast can be moved forward and backward over a distance of 8 m in an open reverberant classroom (9 x 11 m) by means of a subject held switch which activates a silent motor powering the mast. A second or (fixed position "standard") speaker sat on the upper end of a floor mounted stand 3 m from the observers' position. Blindfolded subjects, seated on a height adjustable chair that permitted alignment of their aural planes with the centre of the fixed position speaker, were asked to adjust a movable "comparison" source of one frequency until they auditorily perceived it to be in physical alignment along the median sagittal plane with an alternately sounding and statically positioned "standard" source of a different frequency. The chair was positioned so that if the subjects kept their heads steady during signal presentation and adjustment, as instructed to do, the two speakers would be on their median-sagittal plane. The task was designed, unlike most previous depth or distance estimation tasks, to have Ss judge sources that, to a minimal extent, were in dynamically changing relationships to each other, and to do the task free of any possible confounding effects of visual input.

In the initial study, normal hearing subjects listening with both ears, were given 1/3 octave narrow band signals, centered at 1.0 kHz for the standard and either 0.7 or 1.3 kHz for the comparisons, which alternated in 3-second bursts. The (IP's) initial comparison speaker positions (i.e., prior to any subject-controlled speaker movement) were at +200, +100 from, or 0 cm (already at equidepth) with the standard. The +200 cm IP was 1 m in front of the observers. With considerable individual variability, subjects could approximate the depth of the statically positioned standard by movement of the comparison. The most salient feature in depth judgement considered in this manner was the comparison's initial position (IP). Movement direction, away from or toward the perceiver, was also important. The former resulted in underestimations of the standard's true depth and the latter in overestimations. Comparison source frequency was not significant but it did interact with IP when the averaged estimated distances of the standard's depth was considered as a ratio of the total distance to achieve "true" equidepth. Finally, there were no learning effects observed for the task.

Data using this novel method largely supported those of earlier distance estimation studies (e.g., Coleman, 1968; Mershon et al., 1975, 1979 and 1980) in which, for the most part, normally hearing Ss estimated depths of statically positioned signals in non-adjustment paradigms. That is, as previously reported, observers found acoustic depth judgement was a hard task; overestimation was common when a comparison source was "close to," while underestimation of the real depth of a to-be-judged acoustic signal occurred when the comparison was "far away from" hearers, or beyond the depth of the standard. The study did not corroborate earlier findings indicating that signal frequency content was a major factor in making acoustic depth estimations.

The present study attempted to confirm or negate the Gatehouse (1983) findings and to extend the data by using other comparison frequencies. Finally, it attempted to see if and/or how much debilitated hearing (monaurality) of different loss types (i.e., Sn's, Conductives), loss levels (minimal, moderate, etc.), and different etiologies affect depth perception. There is not, to these authors' knowledge, any previous literature on depth perception in non-normal hearers.

METHOD

Subjects: Eight subjects with clinically diagnosed monaural losses of various types, levels, and etiologies, referred for testing by the second author or with the consent of other otolaryngologists. All were given pure tone (a.c.) testing (.125 to 8.0 kHz) to provide up-to-date confirmation of previous clinical findings for the purposes of classification, prior to their participation. One subject (WM), on this latter testing seemed to have considerable previously undetected loss in his "good" ear and for some analyses his depth estimating ability was not included. Descriptive data of the subjects are presented in Table 1.

Apparatus: The depth judgement apparatus was the same as that outlined in the Introduction. Signals generated via two H-P (204-D) oscillators were fed through a home-built interval timer and switch which enabled the speakers to be independently and alternately activated (3-second bursts) and thence successively through Krohn-Hite (3202) filters and an Electra SA200 amplifier to the TDH-39 speakers. A 1.0 kHz standard signal frequency was retained but the comparison signals were now 0.5 and 2.0 kHz. Signal levels (80 ± 2 dB SPL re 2 bar) at the fixed position speaker, were checked (B & K 2204 sound level meter) prior to and after each subject's daily participation. Amplifier adjustments were made where necessary.

Procedure: The procedure was similar to that of the previous study except comparison speaker initial positions (IP's) relative to the statically placed standard's, were slightly reduced by an experimental error (i.e., ±183, ±91 cm; previously the comparable IPs were 200, and +100 cm). The +183 IP in this study then was 117 cm away from the subjects' ears. All Ss received an accustomization period of 1.0 kHz signals presented once from each of the five IPs and with no adjustment of the movable source permitted. Following this, observers were blindfolded and asked to adjust the comparison speaker (signal of either 0.5 or 2.0 kHz) from the various IPs until they perceived it to be in physical alignment with the position ("0") of the 1.0 kHz standard on each trial. As in the earlier study, observers received 15 trials per each comparison signal (i.e., 3 random presentations from each of the 5 IPs). To guard against possible order effects half of the subjects were tested with the 0.5, and half with the 2.0 kHz stimulus one day and the reverse on the next test day.

Table 1. Various clinical categorizations, sample etiologies, and treatments of the monaural subjects

1 Identity (Sex; Age)	2 Loss Types	3 (Mon Ear) Average Loss (dB) Level	4 Mon. Loss Category	5 Both Ear Average Loss (dB) Level	6 Sample Etiology/ Treatment
ND (F; 19)	C	(L) 53	III	34	Mastoids; stapes replace; tympanoplasty
CC (F;19	SN	(L) 70	IV	43	Head Trauma
CH (F; 35)	C	(L) 35	I	24	Chronic Otitis Myringotomies; Tympanoplasty/Incus Graft
DP (F; 24)	M	(R) 46	II	37	SN diagnosis; Serous Otitis Myringotomies
LL (F; 20)	C	(R) 65	IV	43	Ext. Otitis Myringotomies Mastoiditis; Cholesteatoma
IB (M;24)	SN	(L) 79	IV	45	Acoustic Neuroma
AT (M; 23)	SN	(L) 67	IV	39	Pneumonia; drug treatment induced deafness
WM* (F; 34)	M	L	IV	54	SN diagnosis Menieres

Notes

<u>Loss Types</u> C= conductive; SN = sensori-neural; M = Mixed

<u>Loss Levels</u> Av. loss in dB across one (col. 3) or both (col. 5) ears on a.c. testing from 0.25 to 8.0 kHz

<u>Categories</u> < 35(I); 36-45 (II); 46-55 (III); > 56 (IV)
Col. 3 + Average loss good ear (not shown)/2 = loss level Both Ears(Col. 5)

Col. 6 Arrived at from diagnoses and treatment files: Note for DP and WM files show SN but list external and middle ear problems and reduced low frequence audiograms; thus the (M) mixed loss.

*WM File says monaural; clearly had bilateral difficulties.

The results were analyzed as before using average errors (difference (cm) between the "true" distance to "0" IP and the final or estimated position of it), and the ratio between the average estimated standard position/"true" distance to equidepth from the different IP, s. The data and discussions of them have been separated into two sections. The first part presents general factors that amplify upon those of the earlier study and allow for some comparisons of normal and monaural ability in depth judgement. The second part outlines the effects of the different clinical factors (e.g., loss levels and types) on depth estimation.

RESULTS

Table 2 shows that, in general, mean errors were smaller when the comparison source IP was between Ss and the standard ("true" equidepth position) and this occurred even when the actual distance from the standard speaker was physically the same (e.g., ±183 cm). These findings confirmed the earlier normal subjects' data.

Table 2. Average comparison speaker movement and average errors, for different initial positions and comparison source frequencies.

Initial Position (cm)	Average Comparison Movement (cm) 2.0 kHz	Average Comparison Movement (cm) 0.5 kHz	Average Errors (cm) 2.0 kHz	Average Errors (cm) 0.5 kHz
-182.9 (-2)	55.6	147.6	-127.3	-35.3
-91.4 (-1)	-4.6*	66.5	-96.0	-24.9
0	-17.5	-11.7	-17.5	-11.7
+91.4 (+1)	8.1	60.1	83.3	31.3
+182.9 (+2)	100.2	165.6	82.7	17.3

Note Errors with negative signs (-) are those where comparison was positioned aft of "0".

* On average the subjects moved this comparison stimulus in a more negative direction or farther away from the true equidistant position.

Fig. I compares the average errors of normals and monaurals for the frequencies tested. Slight differences in the IPs of the two studies have been overlooked and the data is presented as though all data was gathered at +200 and +100 cm (here all termed +2, +1). It can be seen that the tendency to greater depth alignment accuracy with the lower comparison frequency was much more pronounced here than it was for the normals. But, it must be recalled that the normals' task might have been more difficult since the comparison and standard speaker frequencies were separated by only 0.3 kHz (std. 1.0, Co.'s 1.3 and 0.7 kHz). When initial distance differences and direction of movements necessary to make estimates were equated (see ratio scores, Table 3) this trend to increasing accuracy was still evidenced.

Independent ANOVA's were computed on the average error scores collapsed across subjects to assess the effects of frequency at the different initial positions of the comparison (i.e., F x IP), and sessions or learning (i.e., L x IP). Neither frequency ($F = 0.99$) nor learning effects ($F = 0.43$) were obtained (both comparisons df = 1; $p > .05$). Instead in both analyses only IP of the comparison stimulus proved significant -- in frequency comparisons $F = 27.9$ and in the learning comparison $F = 27.8$ (both, df 4/28 and $p < .001$). Fig. II shows the IP effect (collapsed over all other variables) for the monaurals and the normals. The functions, despite the methodological diferences (i.e., IP and frequency changes) are quite similar. Finally, unlike the earlier study there was a F x IP interaction ($F = 11.5$; df 4/28; $p < .001$) that occurs near to the point of true equidepth.

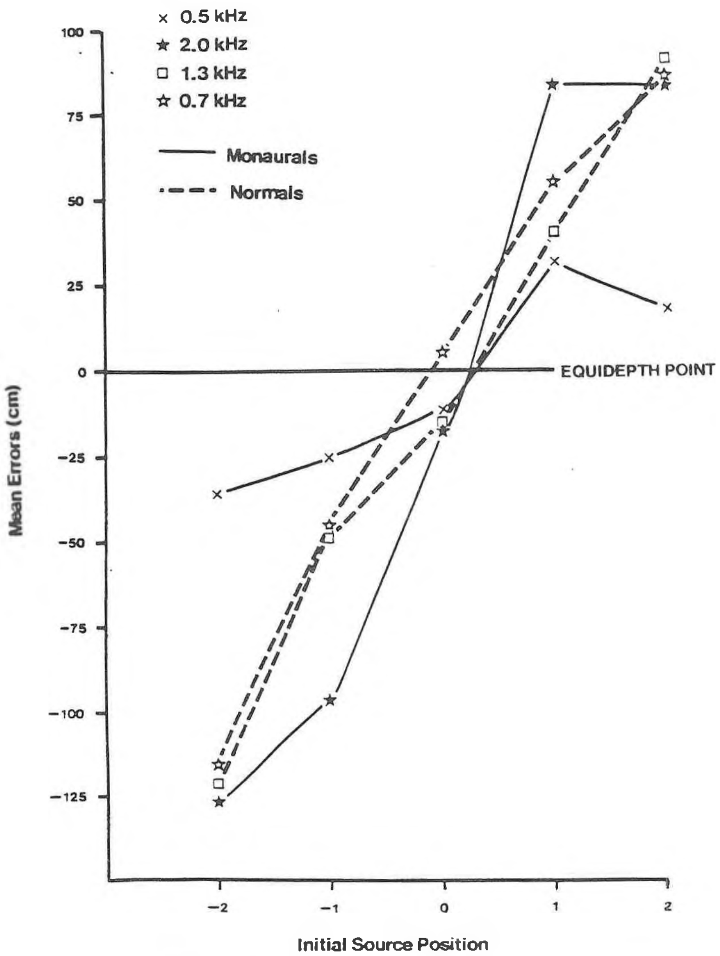


Figure I: Normal and monaural hearers' mean errors (cm) as a function of frequency

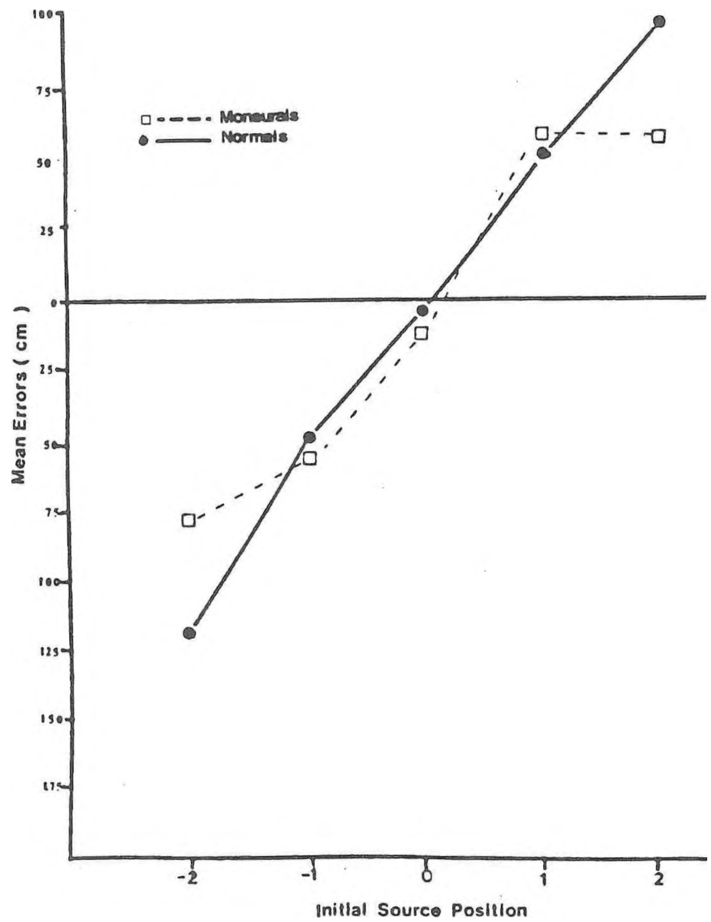


Figure II: Normal and monaural hearers' mean errors (cm) as a function of IP

Table 3. Ratio scores (average estimated distance of the "standard position "/ real distance to equidepth) for the four frequencies (1.0 kHz standard).

	Frequency (kHz)			
Initial Position*	2.0	1.3	0.7	0.5
-2.0	.30	.40	.43	.81
-1.0	-.05	.52	.55	.73
1.0	.09	.60	.45	.66
+2.0	.55	.55	.57	.91

Note * For ease IP's are presented as ±2.0 and ±1.0, although with normals the distances were ±200 and ±100 and with monaurals ±182.9; ±91.4.

+ 1.3 and 0.7kHz were tested in the study on normal hearers.

The one negative ratio indicates that on average subjects moved the comparison stimulus further away from "0" than its original placement.

The saliency of IP in this study pointed, as it did with normals, to the possible role in this paradigm of direction of movement in making depth estimates. With the "0" IP's omitted, it can be seen (Fig. III) that positive directional movements (towards observer) result in overestimations of the position of "true" equidepth, while negative movements yield underestimations. But, unlike the normals of the earlier study, the hearing-impaired subjects' underestimations of "0" position were not tied to the actual distance to be covered to get to equidepth. That is, they underestimated less from the closest IP to themselves and overestimated more than normals from positions nearest to actual equidepth.

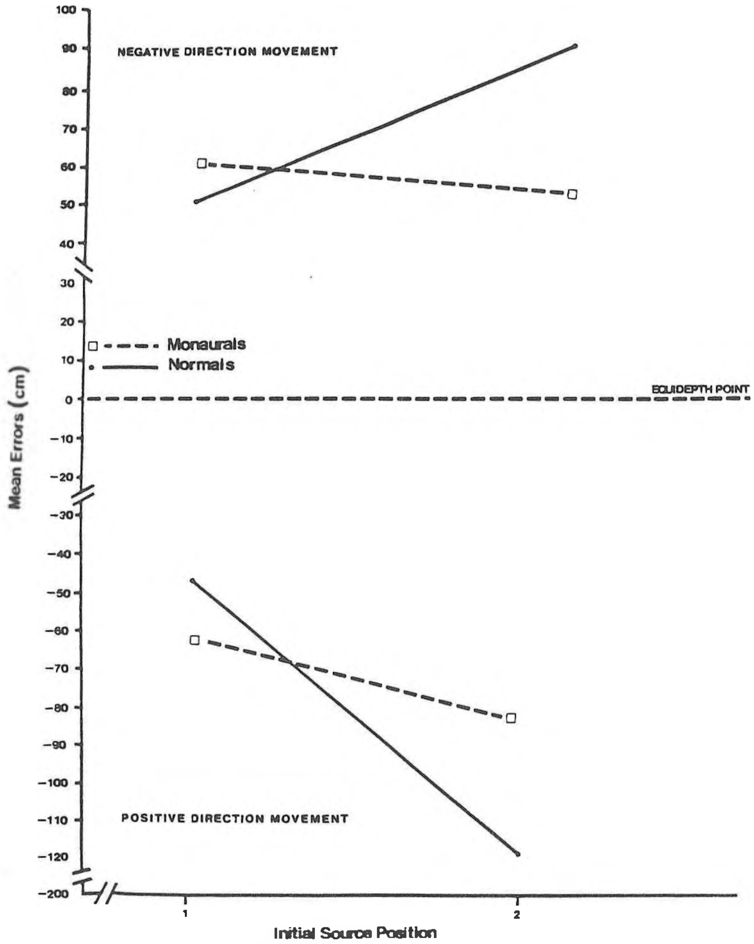


Figure III: Normal and monaural hearers' mean errors (cm) as a function of movement direction.

DISCUSSION

The trend to increasingly accurate depth perception with lowered comparison stimulus frequency is more obvious with monaural hearers than it was for normals. But, it must be remembered that the latter subjects, even with their hearing advantage, were faced with a more difficult task -- i.e., the frequency differences between the comparison sources and the standard were only 0.3 kHz, and perhaps when this close, frequency effects that might have appeared have been submerged by other factors. Nonetheless, the data on frequency effects appear supportive of Mershon and

King (1975) and Coleman (1968) who indicated that low frequency content is important in acoustic depth estimation accuracy. The specific way it is involved here however, is not so clear given that our observers were expected to judge a standard signal's depth via the changing position of a comparison source. Perhaps Ss make an initial ordinal comparison of which stimulus, the comparison or the standad, has higher frequency content. Then, for the duration of that first trial and thereafter the rest of that test day's trials in which the same comparison continues to be presented, they use the position of whichever stimulus contains the lower frequency content as the anchoring point against which to make their adjustments. In the everyday case of judging acoustic depth, where the signals are in changing dynamic and/or static relationships, a similar mechanism may work -- i.e., observers quickly assess the frequencies for which a depth judgement is required, determine which is lower, and then they focus attention upon the latter to make judgements about the signal's changing spatial depths relative to their own position.

The fact that normals and monaurals make different types of errors in judging acoustic depth (recall monaurals are more accurate than normals when IP's are farthest from the real equidepth, but slightly less accurate when the starting position of the comparison was initially close to the "0" IP) is interesting. It is almost as thoug , where binaural cues have already been reduced (median sagittal plane signal presentation), that monaurality can in some instances be an advantage. Perhaps in some way and for some signal complexes, the monaural hearers extract more distinct intensity or other information from the alternating and spatially separated signals on this plane.

In summary, this adjustment approach to acoustic depth estimation appears to give quite consistent across study results even though there were subject and methodological differences in them. That is, the results diverged very little from the originally presented findings (1983), the greatest difference being seen in the error patterns of the monaurals and normals. As well, the results appear to be consistent with other acoustic depth findings determined via other paradigms. Finally, it cannot be said that monaurals were debilitated in their auditory depth perception compared to normals, and in fact, for the 0.5 kHz stimuli they were better at it. It remains to amplify all of the relationships looked at to this point, and especially to further explicate the role of frequency in depth estimation. For example, it might have been noted that the best and poorest accuracy obtained were with frequencies that were harmonically related. Therefore this should be followed up. It is also obvious that the position(s) and frequency of the standard speaker should be varied.

CLINICAL FACTORS IN DEPTH PERCEPTION

To determine if clinical factors make a difference to acoustic depth perception, the data of all Ss except WM (Table 1) were grouped in several different ways and were subjected to unequal and small "n" ANOVA evaluations (NWAYANOVA STATLIB, University of Guelph).

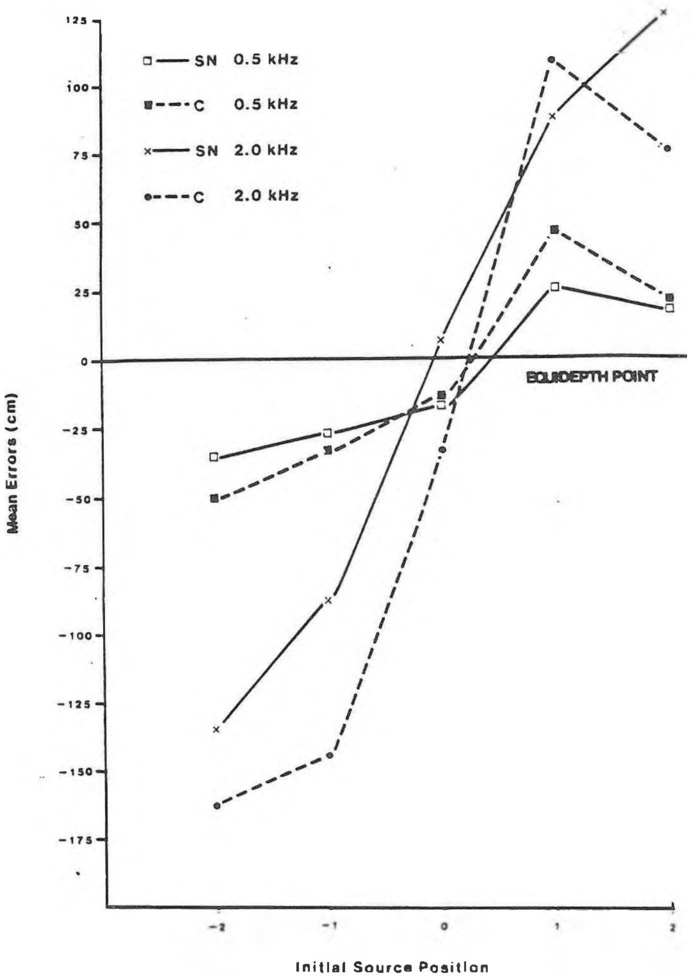
Prior to looking at the data however, the data of Table 1 should be re-examined and several things noted. First, we obtained a full range pure tone average (PTA) using eleven individual threshold points from .25 to 8.0 kHz for the left and right ears separately. The PTA determined in this way is different from usually reported ones which include only 4 or 5 frequency thresholds. Column 3 presents the monaural ear loss level arrived at this way, while column 5 presents an average for both ears.

From these, and the usual audiometric definition that hearing is considered within normal limits where the loss level is less than 25 dBHL, we placed observers into 4 monaural level categories (column 4). These were: I (average losses between 26-35 or minimal loss); II (36-45; mild); III (46-55; moderate); and IV (>56 dB). Obviously, such categorizations can present difficulties. For example, air conduction thresholds are not likely to be accurate within a few dB as implied, and individuals may thus be incorrectly classified. Subjects CH and DP for instance sit on the borders of other loss level categories. Likewise, for this sample, we have no category II Ss, and only one in category I (column 4). Etiological classifications of column 6 might also be inaccurate since they represent the first author's condensations from patient files. For example, diagnoses were not always clearly stated within the frameworks (e.g., SN, C, etc.) used here, and in some there were multiple symptoms and several treatments done over several years.

RESULTS

There were no differences in depth judgement accuracy observed by side of deafness (i.e., 5 lefts, 2 rights, $F = 2.85$, $df = 1$, $p > .15$) or by deafness type (3 CNs, 3 SNs, $F = 1.19$, $df = 1$, $p > .30$); and, loss type did not interact with either IP ($F = 0.58$, $df = 1$, $p > .40$) or with frequency ($F = 1.47$, $df = 1$, $p > .25$). But as can be seen in Fig. IV, C's appear to have more difficulty judging depth using a high frequency comparison source from the farthest IPs, while the SN's are poorest at the nearest position to their own. In general, these findings follow from those of monaural's localization ability (Gatehouse, 1976); i.e., side and type of loss do not appreciably affect spatial judgements, but there may be slight differences seen in the groups for certain spatial positions. Other research has given inconsistent results regarding degree of debility produced by different loss types in binaurally- and monaurally-impaired subjects (Bocca and Antonelli, 1976; Hausler and Levine, 1980; Hausler, Marr and Colburn, 1979; Hawkins and Wightman, 1980; Noffsinger, 1982; Quaranta, Cassano and Cervellera, 1978).

It seems reasonable that progressively greater degrees of loss should concomitantly be seen in greater depth judgements debility, especially if depth judgements are based on changing intensity information being derived from sources at different distances (Inverse Square Law). Because of this, and the loss level classification difficulties alluded to above, we grouped the subjects and analyzed the data in several unequal "n" loss level categories. Level I was not used. For example, subjects CH and DP are respectively on the upper and lower ends of categories (I and III) were considered for one analysis to be in category II, and their results compared to the depth acuity of four Ss clearly in level IV. The outcome of this and other attempts was that no significant effects of any sort were observed. However, Fig. V shows that there were non-statistical differences between the two groups in the above example. That is, there is little difference between their depth appreciation for a 0.5 kHz comparison stimulus, and the milder loss subjects do nearly as well at 2.0 kHz as at 0.5. But, level IV observers were poorer with the higher frequency comparison -- they greatly underestimate the standard's depth when positive directional movements are required and do the opposite for negative movements. Are such differences then possibly spurious effects of group size differences? Individual mean error comparisons neg this possibility. All level IV Ss had larger errors than the two milder loss subjects at every IP except "0".



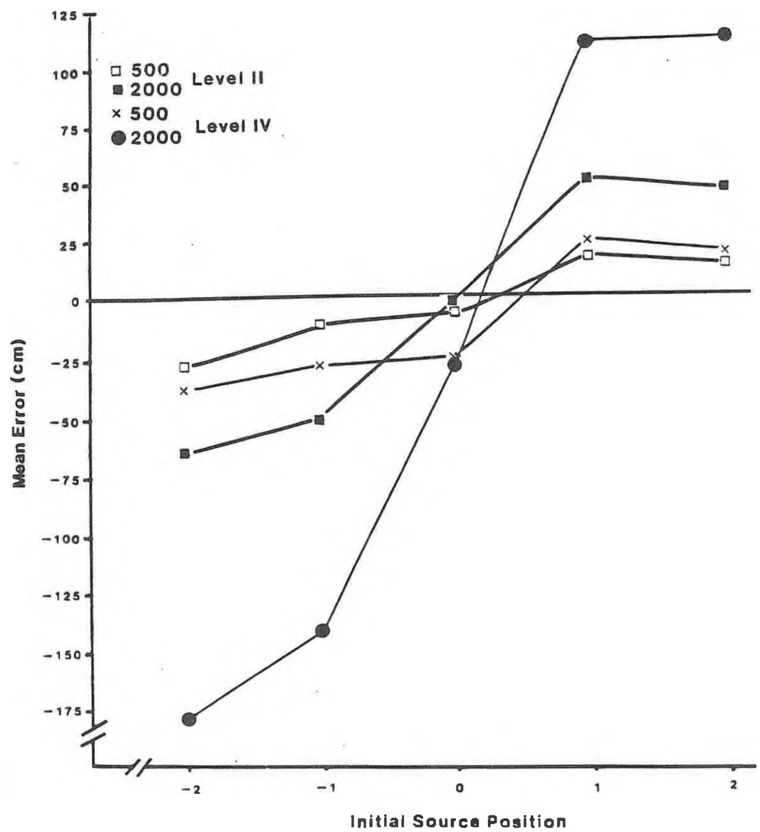


Figure IV: Mean errors (cm) of sensi-neural (SN) and conductively-impaired (C) monaurals for 0.5 and 2.0 kHz sources

Figure V: Mean errors by monaurals of loss level II and IV for 0.5 IV monaurals for 0.5 and 2.0 kHz sources

Finally, we observed no consistent patterns of errors or other relationships between similar etiological and treatment factors and the ability to judge depth. For example, there were no error similarities in the three persons who had early otitis of various forms and subsequent myringotomies. In fact, the closest error scores or accuracy indices were for the neuroma subject whose problem onset and surgical treatment occurred at about 20 years of age, and subject AT whose drug-induced deafness occurred at a very early age. At best, they are both SN's. Because of such apparent lack of concordance, no statistical evaluations were attempted.

DISCUSSION

The absence of loss levels effects was puzzling and yet not entirely unexpected. That is, it is not clear on the one hand why increasing loss levels are not more affected by increased distances and attendant loss in signal strength than they are. It would seem that the combination of high loss level, and much decreased signal strength, especially from the farthest IPs, should have provided considerable performance decrements. In fact, it did for the 2.0 kHz comparison (see Fig. V, level IV). Obviously, the relatively good depth judgement of these Ss at 0.5 kHz however, was enough to conceal any overall levels factor. On the other hand, loss severity (not defined as here) has both been and not been a significant factor in a variety of acoustic tasks (see e.s. Roser, 1966; Hausler, 1979; 1980). Gatehouse and Pattee (1983) however recently reported that binaurally-impaired observers, defined and categorized as here, did exhibit different degrees of localization ability. It could be that monaurals, having one good ear, are not very disadvantaged in judging signal depths of median-sagittal sources, just as they are not at localization (Gatehouse and Cox, 1972).

Is there any way then to explain the apparent, but not statistically poorer performance of the higher loss level subjects when judging depth with a high frequency comparison source? Perhaps the cue lies not in level per se but in loss type. That is, perhaps the fact that three of the four category IV subjects were SN's might be significant since such persons frequently have poorer high frequency resolution. Moreover, SN's have greater difficulty than other loss types in such things as binaural detection, direction, and angle discrimination (Durlach, Thompson, and Colburn, 1981; Colburn, Barker and Milner, 1982; Colburn, 1982); masked thresholds (a spread towards higher frequencies; see Martin and Pickett, 1970 for example); in broadened psychoacoustical tuning curves (e.g., Wightman, McGee and Kraemer, 1977; Zwicker and Schorn, 1978) and additional loudness summation. Recently, Florentine, Buus, Scharf, and Zwicker (1980) renamed several of these factors frequency selectivity and indicated SN's were most impaired on it. However, a loss type supposition is not easily supported here. First, audiometric testing of the three SN's used did not show any greatly reduced thresholds for 2.0 kHz that might have made their abilities to hear such tones suspect. Second, the SN's as a group were somewhat better at judging depth and particularly with 2.0 kHz comparison source than were the conductives (see Fig. IV) deaf. Whether any or several of the other factors listed above might be operating in this depth paradigm and can help explain the results is difficult to determine. In order to try and determine the effects of both loss levels and loss types more clearly, we are currently gathering data with binaurally-impaired subjects.

In summary, there were no statistical depth perception differences obtained for any of the clinical classifications. As far as loss type and impairment side this was deemed reasonable in light of some previous literature. The fact that loss levels did not seem to affect the ability to accurately judge depth was somewhat more puzzling. The data here and past findings suggest that level or degree of loss will, given increased subject numbers and bilaterally impaired observers, prove to be of importance in depth appreciation. Finally, it is also expected that etiological factors in combination with type of and degree of loss will also be found to be correlated with differential ability in depth perception.

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