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Inductive Coupling of Hearing Aids and Telephone Receivers

RICHARD G. STOKER, Ph. D.[a]
MARILYN FRENCH - ST. GEORGE, Ph. D.
JODY M. LYONS, M.S.

The Pennsylvania State University

Abstract—The present investigation sought to determine the effects of hearing loss, signal level, telephone receiver type, and telecoil location on the aided word-discrimination abilities of hearing impaired subjects using electromagnetic coupling of their hearing aids to the telephone.

As expected, significant deterioration in discrimination scores was observed with increasing hearing loss. In addition, significant improvement in discrimination scores was observed, for all subject groups, as the signal level increased from 80 dB SPL to 105 dB SPL.

Of the four receiver conditions, the U1 and BARC receivers resulted in the best discrimination scores. Also, the results suggest that the U1 and BARC receivers are indeed equivalent in terms of word discrimination scores.

Finally, the telecoil location in individual hearing aids appeared to have little influence on the speech discrimination capabilities of the subjects in this study. However caution must be used in interpreting that result, since subjects were allowed to adjust the telephone handset position to maximize the signal level in any given condition. This occasionally resulted in inappropriate handset locations for conventional telephone use.

INTRODUCTION

Previous work (1, 2, 3) has shown that a hearing impaired telephone user tends to discriminate speech transmitted through a telephone better when using magnetic (induction) coupling of telephones to hearing aids than when using acoustic coupling. Even though many hearing aid users do not use their magnetic (or "T switch") mode, and many hearing aids are manufactured without telecoils, magnetic coupling to the telephone has proved to be highly effective for a substantial percentage of the hearing impaired. Despite the many potential benefits of telecoil pickup for telephone-hearing aid coupling, no reliable data exist which confirm any advantage or disadvantage for the many shapes, sizes, and sensitivities of the telecoils found in today's hearing aids.

Recent regulatory rulings have responded to pressure from advocacy groups which insist that magnetic coupling is "best" by requiring magnetic "compatibility" of telephones and hearing aids. Telephone suppliers are now generally being required to provide receivers which are "compatible" with telecoils.

Research Questions — The research presented here addresses four major questions:

[a]Address reprint requests to: Richard G. Stoker, McGill University School of Human Communication Disorders, Beatty Hall, 1266 Pine Ave., West, Montreal, Quebec H3G 1A8, Canada.

1. Is there an optimal size, location, or sensitivity for hearing aid telecoils when used with telephone receivers?
2. What is the range of speech recognition performance experienced by hearing aid wearers using telecoil-equipped hearing aids with three commercially available telephone receivers: the Bell System Standard (U-1), the Balanced Armature Receiver with Coil (BARC) and the Aprel Dynamic?
3. Does an Acoustic-Magnetic Coupler (Northern Telecom) used with a low-flux receiver produce speech recognition scores comparable to those obtained with the U-1 or BARC receiver?
4. Is the Balanced Armature Receiver, when equipped with a supplementary field coil, equivalent to the Standard U-1 receiver in terms of hearing impaired user performance?

METHODS AND MATERIALS

Telephone Receiver Conditions

The telephone receivers used in the investigation were of three types: U-1 (Standard Bell System ring armature type); BARC (a balanced armature receiver with supplementary flux coil made by Northern Telecom); and Dynamic, a low-magnetic-flux receiver made by Aprel Acoustics.

The U-1 receiver has been in service since 1951 and provides, in the immediate vicinity of the receiver case, a relatively strong magnetic field that can be detected by a telecoil-equipped hearing aid.

The BARC is a modified version of the BAR (balanced armature receiver). The BAR is functionally equivalent to the L-type receiver used in the United States; the BAR and the L-type produce very little magnetic flux and are generally unsuitable for inductive coupling. Therefore, the BAR has been modified by the addition of a supplementary coil which generates a magnetic field, to make the magnetic flux of BARC functionally equivalent to that of the U-1. However, this presumed equivalence has never been demonstrated by testing with hearing aid users.

A fourth receiver-condition tested in this investigation was the use of the Acousto-Magnetic Coupler (Northern Telecom) used in conjunction with the Aprel receiver (which itself has relatively low magnetic output). Such couplers are designed to convert acoustic energy to magnetic, to enable inductive coupling with nonmagnetic receivers.

In summary, the four receiver conditions included in the study were (i) U-1, ring armature (Standard Bell-System), (ii) BARC, balanced armature with coil (Northern Telecom), (iii) Low Flux Dynamic (Aprel Acoustics), and (iv) Acousto-Magnetic Coupler (Northern–Telecom) plus the Aprel receiver (Fig. 1).

Hearing Aids

Three hearing aids were selected for each of three hearing-loss categories from a list of 85 aids evaluated. In general, the selection of the hearing aids for testing purposes was pragmatic, based on hearing aids contained in stock. Within this constraint, aids were selected which represented a range of telecoil locations, types, and orientations (Table 1).

Subjects

Twelve subjects in each of the following hearing loss categories were selected from the clinical population of the Audiology Clinic at The Pennsylvania State University:

1. Moderate (precipitous): thresholds between 0 and 25 dB HL from 250 Hz to 1000 Hz, with a precipitous drop in HL at 2000-to-4000 Hz (slope 25 dB/octave).
2. Moderate (gradual): thresholds between 10 dB and 40 dB HL at 250 Hz, with gradual slope (10–20 dB/octave) to 4000 Hz.
3. Severe: thresholds between 40 dB and 85 dB from 500 Hz to 4000 Hz with no threshold differences greater than 15 dB HL between any two octave frequencies over that range.

Experimental Design

The experimental protocol used for this evaluation may be described as a three-factor repeated measures design, with three factors nested in each of three hearing-loss groups. The three factors are: (i) signal level with five levels, (ii) telephone receiver type with four levels, and (iii) hearing aid telecoil configuration with three levels.

Test Materials — Recordings were made of the four forms of the NU 6 word lists. These have been shown to be equivalent for telephone listening tasks and to discriminate well between different classes of hearing impairment: see Stoker et al., 1981 (4). Four randomizations of the four 50-word forms of the NU 6 were prepared and half-lists of these were used to evaluate subject performance. This meant that 32 ($4 \times 4 \times 2$) separate test lists were available for presentation to the subjects.

Instrumentation — Recordings of the word lists were presented to the subjects in groups of 10, using the equipment diagrammed in Figure 2. Testing was completed in a sound treated room. Re-

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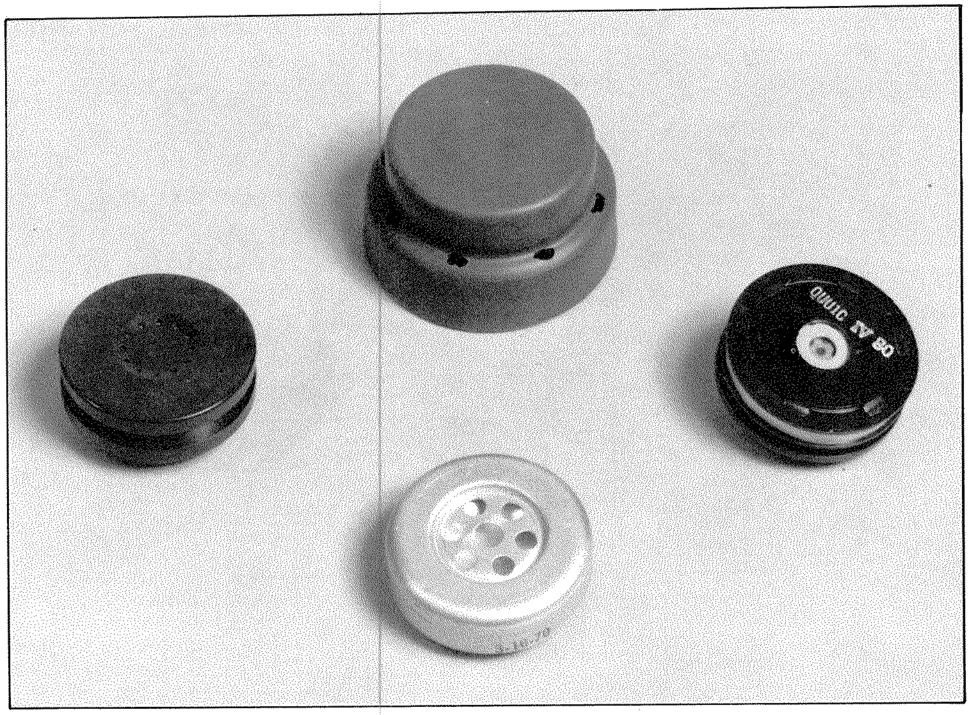

FIGURE 1
The four receiver types used in the inductive coupling study: (a) U-1 Standard Bell System Ring Armature; (b) BARC (Balanced Armature with Flux Coil, Northern Telecom); (c) Dynamic Low Magnetic Flux Receiver, Aprel Industries; and (d) Acousto-Magnetic Coupler, Northern Telecom.

TABLE 1
Summary of telecoil characteristics of nine hearing aids used in the study

Subject group	Hearing aid	Location in case	Orientation in space*	Core Construction	Construction Type & dimensions
1	Unitron 905	Medial/dorsal	vertical	metal-wire	round, 10.5 × 1.5 mm
1	Danavox 7355	Medial	30 deg from vertical	metal-tab	squared, squat 6 × 4.8 mm
1	Seimens 24E–SL–PC	Medial/dorsal	vertical	metal-wire	round 17 × 1.5 mm
2	Fidelity F–39	Inferior/ventral	10 deg from vertical	metal-wire	round 8.5 *X* 2.2 mm
2	Seimens 272–AGC1	Medial/dorsal	vertical	metal?-tab	squared, long 17 × 1.5 mm
2	Unitron EIP	Medial/dorsal	10 deg from vertical	metal-tab	rounded 14 *X* 1.1 mm
3	Phonic Ear 801C	Inferior	**	metal?	square, may be epoxy enclosed 6.5 × 8.5 × 1.5
3	Philips HP8276	Superior/ventral	15 deg from vertical	metal-wire?	rounded cylinder 11.5 × 3 mm
3	Zenith Vocalizer 400	Superior	45 deg from vertical	metal?-tab	squat, encased cylinder 8 × 3 mm

*with reference to the long axis of the body
**not discernable due to construction

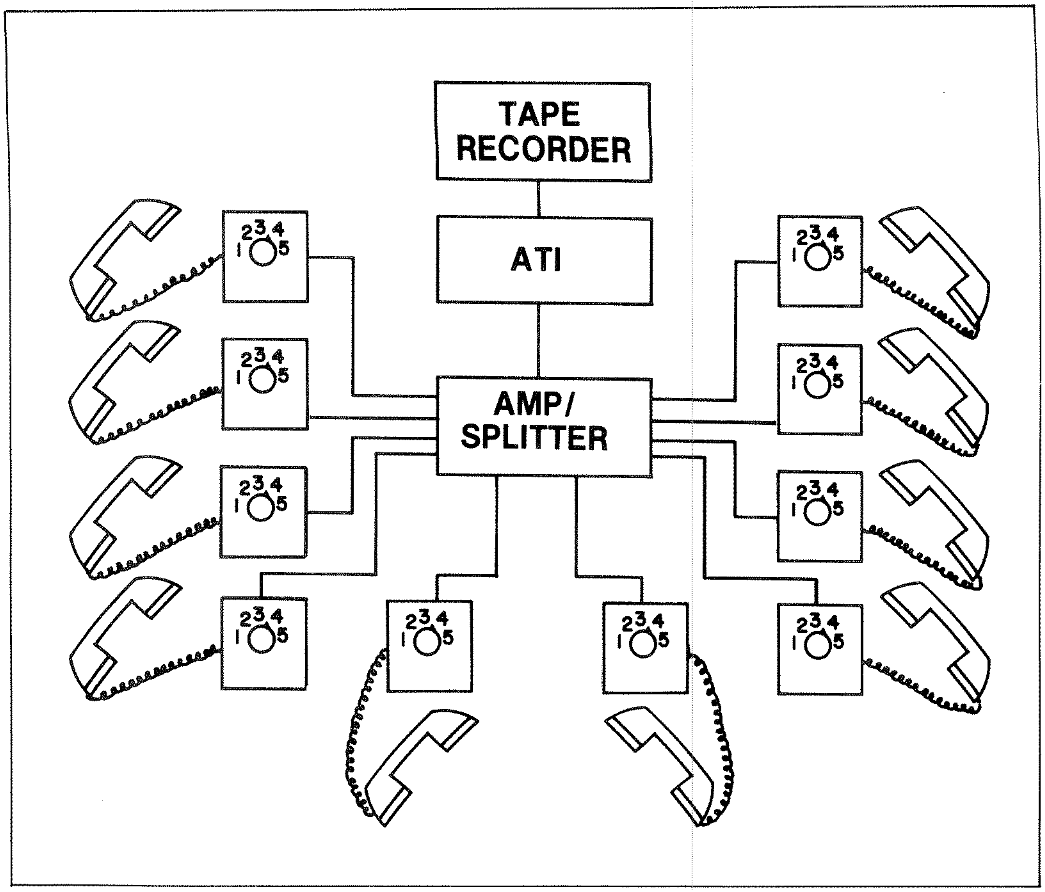

FIGURE 2
Block diagram of the testing apparatus showing the 10 testing positions, tape recorder, audiometer/telephone interface (ATI); the signal amplifier and splitter which delivered the signal to the testing stations where 5-output-level line attenuators allowed the investigators to approximate the sound level likely to be encountered using a typical phone line.

cordings were played on a cassette deck (Toshiba PC2460) and routed through an audiometer/telephone interface (ATI Mark III) that had been adapted to accept direct input from the tape deck as described by Stoker in 1982 (5). The resulting signal was amplified and split by an amplifier/splitter (Fairchild 601) and delivered to 10 individual listening stations where line attenuators (Prince-Phelps) were located.

Each individual listening station was adjusted to produce output levels of 80, 85, 90, 95, and 105 dB SPL at 1000 Hz. Listening station calibration was performed using a sound level meter (B & K 2603) connected to an artificial ear (B & K 4152). The average output level at 1000 Hz from a "typical" phone line is approximately 85 dB SPL (5).

The room used for testing was equipped with incandescent lighting for this project, as fluorescent lighting was shown to materially interfere with the reception of the telephone signal by magnetic inductance.

Procedure — Prior to initiation of the experimental trials, a pure tone audiogram was obtained from each subject. The subject was then fitted with one of the three hearing aids designated for their hearing loss category. Hearing aid adjustments and the volume control were adjusted to provide individual subjects with amplification most suitable for their hearing losses. A reading of "The Grandfather Passage" was then played through two speakers at 90 degrees and 270 degrees of azimuth. The signal level was adjusted (using a 1000-Hz calibration tone set at peak speech levels) to be 65 dB SPL at the center of the listener's head.

Subjects wore a compressed foam earplug in the nontest ear. They were instructed to adjust the volume control of the hearing aid to a comfortable hearing level (MCL); the volume control setting and other hearing aid control settings were then noted on the data form. These settings were replicated later when the subject switched the aid to the "T"

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setting for the telephone listening portion of the study. This procedure was repeated for each of the three hearing aids assigned to the subject's group.

Subjects from all three hearing-loss categories were randomly assigned to one of four testing groups. Each testing group was tested three times for 1 hour each time. The seating pattern for each test session was randomly devised without replacement, so that no subject would sit in the same listening carrel more than once.

As subjects arrived for the experimental trials, they were fitted with one of the three test aids they had each previously evaluated. A compressed foam earmold was used by all subjects for all evaluations, to reduce variability due to earmold type. A closed earplug of the same material was placed in the nontest ear. Once the subjects had been seated at their testing positions, the testing procedure was begun. An individually randomized schedule was devised for each subject; this randomized receiver types (4 types) with volume levels (5 levels), resulting in 20 trials per testing session (an individual subject wore the same hearing aid for all 20 trials). The test sentences were presented in random order, with all 10 subjects hearing the same sentences, but at various loudness levels and using different telephone receivers and hearing aids.

Subjects were instructed from a typed set of standard instructions. They were told to write the words they heard on an answer sheet provided. They were also encouraged to guess if they were unsure. Subjects were instructed to move the telephone receiver until they had located a position which effected the best listening level for them. This provision resulted in some receiver placements which were unusual (i.e., the telephone handset was placed at a 90-degree angle from the medial plane of the head, in one instance).

Response recording — Responses were scored on a whole-word basis. If a word was incorrectly spelled, but recognizable, credit was given for it. A percentage correct score was generated for each list using the words judged to be correct.

RESULTS

An analysis of variance (ANOVA) procedure was used to evaluate the significance of differences in percentage correct scores obtained by subjects using different hearing aids. Three separate ANOVAs were performed on data partitioned by hearing loss category. Significant main effects ($p = 0.01$) were observed for telephone receiver type and volume control setting — but not for hearing aid type. No significant interactions were observed (Table 2).

Since no significant effects were shown for hearing aid type in the previous analysis, the data were averaged across hearing aids within hearing loss category (Fig. 3A). An ANOVA design was used to

TABLE 2
Analysis of variance summary for combined pool of subjects

Source	Sums of Squares	Mean Squares	DF	F ratio	Prob if Asum Met	Prob w/Cons DF Adj
Between subjects' hearing loss	180,057.7	90,028.85	2	26.63	0.000	0.000*
Error	111,549.7	3,380.29	33			
Within subjects' receiver type	18,170.07	6,056.69	3	39.56	0.000	0.000*
HL × R	2,046.49	341.08	6	2.22	0.047	0.124
Error	15,156.79	153.09	99			
Volume setting	53,914.48	13,478.62	4	78.07	0.000	0.000*
HL × V	2,820.94	352.61	8	2.04	0.046	0.146
Error	22,786.87	172.62	132			
R × V	2,221.18	185.09	12	1.86	0.037	0.181
HL × R × V	3,300.18	137.50	24	1.38	0.107	0.264
Error	39,243.53	99.09	396			

*a = 0.01

evaluate the significance of percentage correct scores reported in these combined categories.

Significant main effects ($p<0.01$) were observed for hearing loss category, telephone receiver type, and volume control setting (Table 2).

Tests using Tukey Wholly Significant Difference (WSD), as published by Tukey in 1977 (6), were conducted as a follow-up procedure to evaluate the significance of differences between categorical means within the main effects. These procedures indicated that subjects in the severe hearing loss category performed significantly worse than subjects in the moderate (sloping) group who in turn performed significantly worse than the moderate (precipitous) group ($p<0.05$) (Fig. 3B).

Further, receiver condition 1 (U-1) and receiver condition 3 (BARC) were not significantly different from one another. Conditions 1 and 3 both produced significantly better speech discrimination scores than condition 2 (Dynamic) or condition 4 (Acousto-Magnetic Coupler). In turn, condition 4 produced significantly better scores than condition 2 ($p<0.05$) (Fig. 3C).

Figure 3D depicts an overall increase in scores

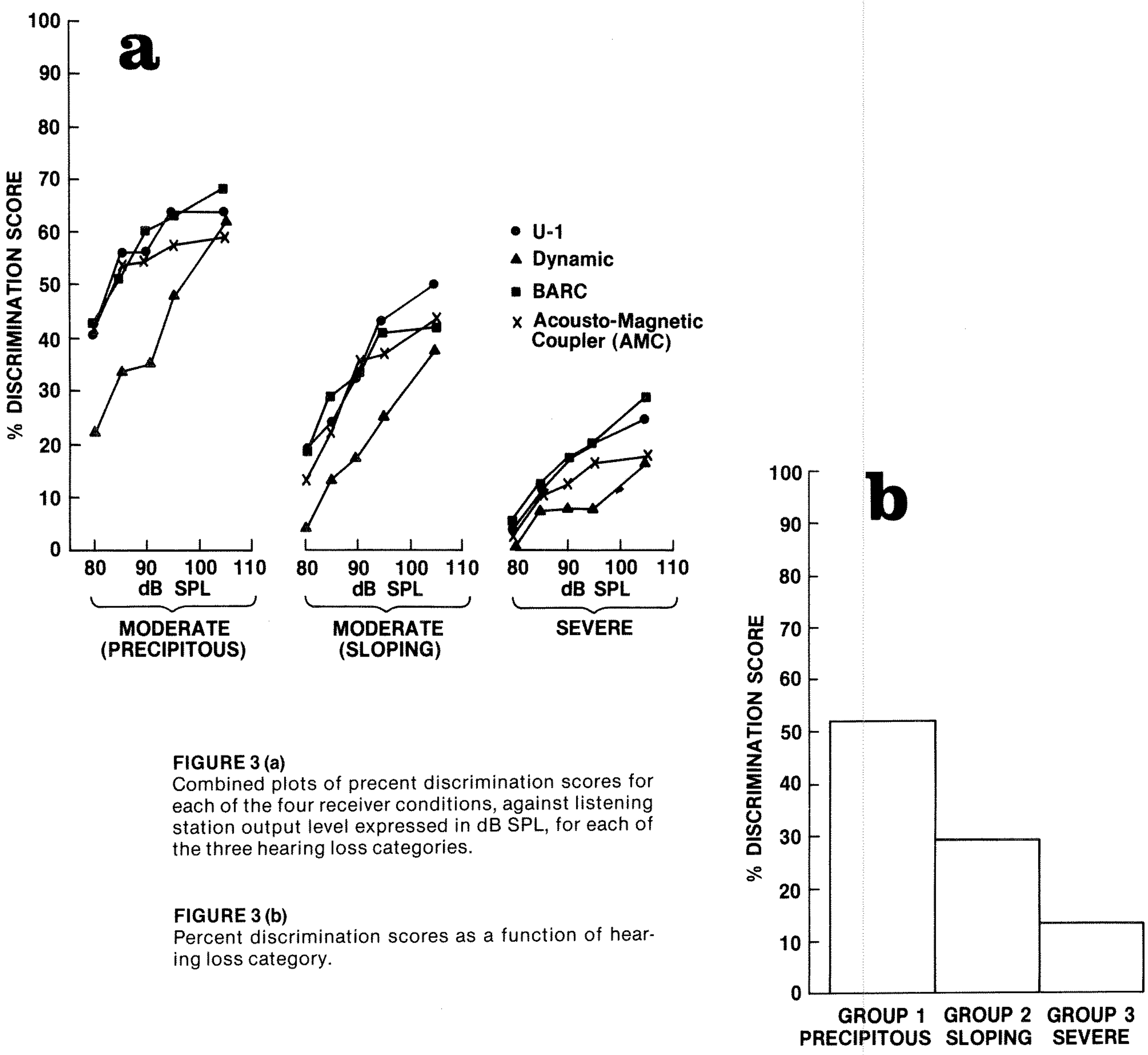

FIGURE 3 (a)
Combined plots of precent discrimination scores for each of the four receiver conditions, against listening station output level expressed in dB SPL, for each of the three hearing loss categories.

FIGURE 3 (b)
Percent discrimination scores as a function of hearing loss category.

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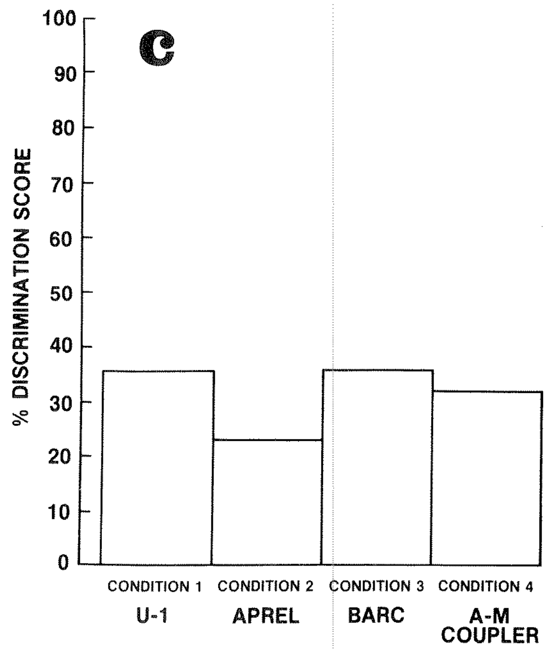

FIGURE 3 (c)
Percent discrimination scores as a function of each of the four receiver conditions tested.

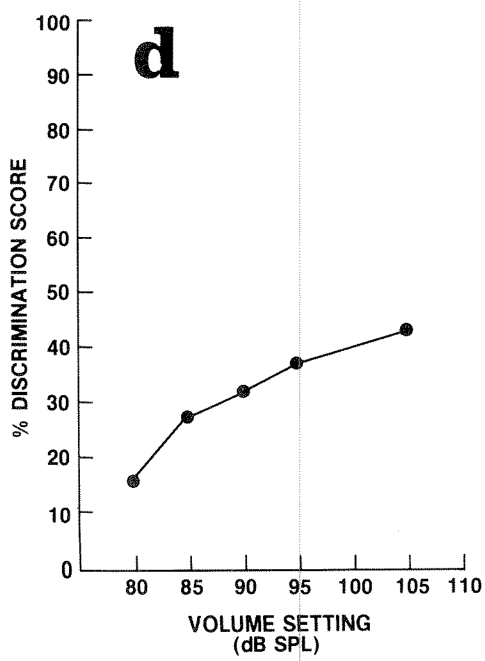

FIGURE 3 (d)
Percent discrimination scores as a function of volume setting (dB SPL).

as a function of volume setting. WDS procedures confirm that each level is significantly different from the others ($p<0.05$).

DISCUSSION AND CONCLUSIONS

At the beginning of this report, four research questions were posed. The results of the study will be discussed, using those questions as a framework.

1. **Is there an optimal size, location, or sensitivity of telecoils?**

The general answer, at least within the sample of hearing aids used here and the experimental constraints, seems to be "no." The results obtained in this study indicate no advantage under any experimental condition or hearing loss category for any of the hearing aids that were considered. Because hearing aid volume level and other adjustments (MPO, frequency response) were set using free field performance as a guide, the data may indicate that all of the telecoils used performed relatively poorly. Another, more likely, explanation is that the freedom of motion allowed subjects in placement of the telephone receiver effectively neutralized any location effects of telecoils, because rotation of the telephone about the axis of the hearing aid case usually allows a listener to locate a region, however small, where the magnetic flux is strong enough to allow reasonably effective coupling. The disadvantage of such manipulation is that it often results in very inappropriate placement of the telephone transmitter, thus making it difficult for a person on the other end of the link to hear, or requiring the hearing impaired telephone user to adopt the awkward strategy of alternating optimum receiver placement with optimum transmitter placement.

2. **What is the range of speech recognition performance experienced by hearing aid users using telecoil equipped hearing aids with three telephone receivers?**

In general, this question is best addressed by consideration of Figures 3A and 3C. Figure 3A represents the data pooled across all hearing groups and volume levels, while Figure 3C presents the same data partitioned only by coupling condition. As Figure 3C clearly indicates, there is no difference in overall performance between the U-1 receiver and the BARC receiver. More interestingly, there are statistically significant differences between the BARC and U-1 performance and that of the Aprel with Acousto-Magnetic Coupler. The poor performance overall of the Aprel receiver was not unexpected because the magnetic flux created by this receiver is significantly lower (about 25 ma/M as opposed to 50 ma/M in the U-1 receiver).

Figure 3A shows that the Dynamic receiver data parallel those collected using the other receiver types. This indicates that the Dynamic receiver produced a signal at the eardrum of the hearing aid wearers which was 15–20 dB softer than that produced by the BARC or U-1 with the same electrical input.

3. **How does the Acousto-Magnetic Coupler compare to the U-1 and BARC?**

Figures 3A and 3C indicate that the Acousto-Magnetic Coupler (AMC) does not perform as well as the U-1 and BARC receivers when used with hearing aid telecoils, particularly at the higher presentation levels. This finding is quite surprising when one considers that the magnetic field produced by the AMC is virtually identical to that produced by the BARC or U-1.

It is likely, however, that in addition to the magnetically transmitted information, air-conducted acoustic radiation emanating from the U-1 (or BARC) receiver also reaches the eardrum of the listener via a transmission path through the earmold and earmold tubing. That would be an important secondary signal transmission path, particularly at the higher signal levels. The rubber cup of the Acousto-Magnetic Coupler would attenuate this secondary airborne transmission path, thus reducing the total signal level at the listener's ear in the case of the AMC.

This suggests that some simple design changes, such as allowing a clearer airborne path to the ear through the coupler, would possibly result in higher user satisfaction with the device.

4. **Are the BARC and U-1 Receivers equal in telecoil performance?**

As documented above, the data show that use of the U-1 or BARC receivers by hearing impaired subjects results in identical average word discrimination scores when their hearing aids are magnetically coupled to the telephone receiver ■

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