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Evaluation of a Cochlear Prosthesis Using Connected Discourse Tracking[a]

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Abstract—A multichannel cochlear prosthesis was evaluated using the method of Connected Discourse Tracking. Data were obtained from five subjects over a 10-week period. Significant learning effects were obtained both with and without the prosthesis. The method of orthogonal polynomials was used to obtain a statistically precise fit for each learning curve. The curves differed both in terms of shape and average rate of learning. The two best subjects showed substantial improvements, reaching tracking rates in excess of 90 words-per-minute. A method for representing prosthesis-based improvements, which takes learning effects into account, is developed and discussed.

INTRODUCTION

The evaluation of sensory aids is a multifaceted problem for which there are rarely if ever any simple solutions. Several levels of evaluation are possible, ranging from a determination of whether the device does what it is intended to do in an engineering sense to whether the device is measurably effective in improving communication ability or even the overall quality of life. Improvement in communication ability is of particular interest in the evaluation of sensory aids for the hearing impaired, as it is the primary design objective of most such devices.

At present, there is no standardized procedure for evaluating overall communication ability. There is, however, a growing trend toward the use of Connected Discourse Tracking (CDT) as an experimental tool in the evaluation of communication aids. The technique is now widely used in assessing the effect of a cochlear prosthesis on communication ability, and it has also been used in the evaluation of tactile aids: see, for example, Parkins and Anderson, 1983 (1), and Pickett, appearing in this issue (2).

Given the growing importance of connected discourse tracking, it is important to examine the characteristics of the technique. This paper provides an analysis of one version of the connected discourse tracking technique as used in the evaluation of cochlear prostheses.

METHODS

The method of CDT was developed by DeFilippo and Scott, who described it in 1978 (3). The technique was intended for both training and evaluation, but in practice is much more widely used for the latter application. The essence of the procedure is that a talker

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(sender) reads from a prepared text, and the listener (receiver) is required to repeat back what is said. Every word must be repeated correctly. If an error is made, the sender repeats what was said, or alternatively, may either paraphrase the material, use synonyms, or prompt the sender with additional cues. The average rate at which the test material is comunicated, in words per minute, is used as a measure of relative communication efficiency.

Not all research groups use the procedure as originally proposed. The original version required that every word be repeated back correctly. That presents problems when a single word or phrase is especially difficult, since an excessive amount of time may be spent ensuring that this particular segment of the passage is transmitted correctly. The concern here is that average tracking rate for a passage with a few particularly difficult segments will be much less than that for a comparable passage without any unusually difficult segments.

In order to circumvent the above problem, several research groups have modified the tracking procedure so as to include limits on how often an item may be repeated, or on the maximum time allowed for any single segment of the test material.*

The procedure used in the present study was, first, to repeat any segment in which the subject made an error. If this did not succeed, the segment was paraphrased in simpler English; if this did not succeed, the word or phrase causing the problem was spelled out, phoneme-by-phoneme. This last step was particularly time consuming and could take as long as 1 minute of the 10-minute-maximum test session.

The tracking procedure is subject to several sources of variability. These include individual differences in tracking ability between senders as well as between receivers, and also variations in the interaction between senders and receivers. Data on individual differences of this type show variations on the order of 30 percent of the tracking rate as reported by McConkey et al. in 1985 (4).

Tracking rates also vary as a function of the complexity of the test material. For example, Sherrick and Cholewiak reported in 1985 that they had obtained an increase of 20 to 30 percent in tracking rate by going from particularly difficult prose (Tolstoy's War and Peace) to grade-level material.** It is relevant to note, however, that the ratio of tracking rate with the sensory aid to that obtained without the aid was roughly constant for all of the materials considered.

A third problem is that of learning and adaptation. Persons exposed to the tracking procedure for the first time usually find the method relatively difficult, but with some training most subjects soon learn various stratagems that enable them to increase their tracking rate significantly. This of itself is not surprising, since the tracking procedure was initially designed for training as well as for evaluation and has its roots in a teaching technique commonly used at schools for the deaf. Erber and Greer described it as a "communication strategy used by teachers at an oral school for the deaf" in 1973 (5). Moog in 1975 also made the point (6). However, it is important to separate improvements in tracking rate that result from the use of a sensory aid from the improvements that result from the subject's experience with the tracking procedure itself.

On the positive side, the tracking procedure has extremely good face validity. Almost all of the standardized tests developed to evaluate communication ability typically concentrate on how well specific components of the speech signal (words, phrases, sentences) are comprehended, but do not take into account the interactive dynamics of a real conversation. The tracking method thus stands out from conventional evaluation procedures because it allows the interaction between talker and listener to play an important role in the evaluation process. It is this good face validity that accounts for the widespread use of the tracking procedure. There is, however, a need to determine the potential precision of the procedure—this is related to learning how to identify and control the many sources of variability. These problems are addressed in this paper in the context of evaluating a multichannel cochlear prosthesis.

Obtaining Tracking Rates with a Cochlear Prosthesis

Five subjects have thus far[c] been fitted with the Nucleus multichannel prosthesis as part of the NYU Medical Center Cochlear Prosthesis Project. In its normal mode of operation, the Nucleus system picks up the speech signal acoustically, processes it electronically to extract important speech features (voice fundamental frequency, second formant frequency), and delivers this information in coded form to a 22-electrode array implanted in the cochlea. The coding is such that only one electrode pair is

*J.A. Reath: personal communication, 1985.

**Sherrick, C.E., and Cholewiak, R.W.: personal communication, 1985.

[c]As of October, 1984.

stimulated at a time. The region of the cochlea being stimulated signals the second-formant frequency. Periodic pulsive stimulation is used, the pulse rate of stimulation being proportional to the voice fundamental frequency. Aperiodic stimulation is used for voiceless sounds, thereby signalling frication. For more detailed information on the cochlear prosthesis see Clark et al., 1983 (7). For further information on the subjects reported on here and the surgical procedures involved, see Cohen et al., 1985 (8).

Each of the five subjects who have been implanted with the prosthesis have undergone intensive training and testing. Included in the battery of tests is the connected discourse tracking procedure, which is administered at weekly intervals for both the aided and unaided condition. In the unaided lipreading (LR) condition the talker's face is clearly visible and the subject must repeat what the sender says using lipreading cues only. The aided condition (LRA) is identical except that the prosthesis is used in addition to lipreading. The test material consists of approximately fifth-grade reading material. The same test material was used with each subject.

Each test lasts 10 minutes, and the average number of words per minute repeated by the subject over this time period is used as the measure of tracking rate.

In order to reduce the various sources of variability noted earlier, each subject served as his own control. All other experimental variables (e.g., test material, sender, tracking strategy) were held constant. The primary variable of interest was the relative change in tracking rate obtained by the use of the cochlear prosthesis. In order to facilitate such comparisons, the logarithm of tracking rate was used. The effect of the prosthesis is thus measured in terms of the difference between log(tracking rate with prosthesis) and log(tracking rate without prosthesis)—or, in the following simpler notation:

$$\text{Relative Improvement} = \text{Log}(\text{LRA}) - \log(\text{LR}) = \text{Log}(\text{LRA}/\text{LR}) \quad [1]$$

where LR is tracking rate for lipreading alone without the prosthesis and LRA is the tracking rate for lipreading with the aid of the cochlear prosthesis.

Since logarithms are used, the Relative Improvement is essentially a measure of the ratio LRA/LR. Note that since extraneous sources of variability such as differences in level of test material, or individual differences between senders and listeners, were held constant for each comparison, these variations should either cancel or be reduced considerably in Equation [1]. (Complete cancellation will occur if there is no interaction between the source of variation and the experimental conditions LR and LRA.)

A second important aspect of the data is that tracking rate has been measured at regular intervals (once per week) for both the LR and LRA conditions over an extended period of time (in this case, several months). As a result, it is possible to separate effects of training from the effects of using the prosthesis. The variation in tracking rate over time obtained without the prosthesis can be considered indicative of the effects of training and general familiarity with the tracking procedure. These data provide a useful baseline from which to measure changes in performance. At each point in time, the change in tracking rate in going from the unaided to aided condition provides a direct measure of the effect of the sensory aid.

RESULTS

The data for the five subjects are shown in Figure 1. Note that tracking rate has been plotted on a logarithmic scale, as shown by the left-hand ordinate. The corresponding values of log (tracking rate) are shown on the right-hand ordinate. Logarithms to the base 10 are used. The subjects are shown in order of relative performance for the aided (LRA) condition, Subject 1 showing the poorest performance. The numbering of the subjects is the same as that used in previous reports on this project (8) and reflects the order in which the subjects received the cochlear prosthesis.

A smooth curve has been fitted to each set of data using the method of orthogonal polynomials (9). This method of analysis is well-suited to observations that are evenly spaced on the independent variable (in this case that independent variable is time, the observations having being taken at regular weekly intervals). One of the properties of the method of orthogonal polynomials is that the complexity of the curve to be fitted is increased systematically until an adequate fit is obtained. This feature of the analysis turned out to be particularly useful, since (as is evident from Figure 1) the subjects showed a variety of learning curves. The simplest curves were obtained for the unaided, lipreading-only (LR) condition. Three of the subjects (No. 1, No. 2, and No. 5) showed no significant change in tracking rate for this condition and the data for these subjects were fitted by a constant, i.e., a horizontal straight line. Two of the subjects (No. 3 and No. 4) showed a

steady increase in LR tracking rate over time, and linear learning curves provided an adequate fit for these data.

For the aided (LRA) condition, all of the learning curves were either linear or showed some curvature. The linear curves were obtained for subjects showing small to moderate improvements (No. 1, No. 3, and No. 4). The two subjects showing relatively large improvements (No. 2 and No. 5) also appeared to approach an asymptote in performance at the high end of their learning curves. This curvature was taken into account by means of a quadratic polynomial for Subject No. 5 and by a cubic polynomial for Subject No. 2. The learning curve for Subject No. 2 was the most complex, since in addition to approaching an asymptote at the high end, the subject also showed a very slow rate of improvement during the early stages of the rehabilitation program. The two effects combined to produce an S-shaped learning curve.

It is not surprising that the more complex learning curves were obtained for the LRA condition. This condition produced substantial improvements in tracking rate, and because these improvements were also large relative to test-retest variability, differences in the shape of the learning curves could be detected statistically. It should also be noted that test-retest variability was less for the LRA condition, thereby adding to the sensitivity of the orthogonal polynomial procedure in uncovering the structure of those particular learning curves. It is believed that the LRA condition was less variable because there were very few occasions in which a subject used up an excessive amount of time on some particularly difficult segment of the test material. In contrast, getting stuck on a difficult segment occurred fairly frequently in the LR condition, particularly for the poorer subjects, thereby increasing the variability of those measured tracking rates.

Interpretation of Results

The measured variability of the tracking data provides a basis for assessing, in statistical terms, the significance of any measured change in tracking rate. The average standard deviation of the log (tracking rate) measurements was 0.081 for the LR condition, 0.044 for the LRA condition, and 0.086 for log(LRA/LR). Note that the variance of log(LRA/LR) was less than the sum of the variances for log(LR) and log(LRA) since these variances were partially correlated. This was presumably because the two measurements of tracking rate were subject to the same sources of intersession variability. In order for a difference in log tracking rate to be statistically significant, this difference should exceed 1.96×0.086 for $p \leqslant 0.05$, assuming a normal distribution and a two-tailed distribution; i.e., it is not assumed a priori that if a significant difference is observed it will necessarily be in one direction only. Although almost all of the measurements to date show log(LRA) to be greater than log(LR), it is not inconceivable that under some conditions log(LR) will be greater than log(LRA).

Expressed mathematically, if

$$\left|\log(\mathrm{LRA}) - \log(\mathrm{LR})\right| \geqslant 1.96 \times 0.086 \geqslant 0.169$$

this difference will be statistically significant at the $p < 0.05$ level.

Taking antilogs,

$$\text{If either } \frac{\mathrm{LRA}}{\mathrm{LR}} \text{ or } \frac{\mathrm{LR}}{\mathrm{LRA}} \geqslant 1.48$$

then this ratio will be significant at the 0.05 level.

The above leads to a very simple rule, that if use of the cochlear prosthesis produces a greater than 50 percent change in tracking rate, this change will be statistically significant. Note that the above rule applies to single measurements of the tracking rate (using the same version of the tracking procedure as used in this study) for the LR and LRA conditions. If repeated measurements of tracking rate are obtained, the standard error of their average will be smaller and accordingly, a smaller change in average tracking rate will be statistically significant.

Applying the above rule, it is apparent from Figure 1 that significant improvements in tracking rate were obtained for all five subjects in going from the LR to LRA condition Four of the subjects showed a significant improvement at the start of the rehabilitation program while the poorest subject (No. 1) showed a significant improvement at a later stage in the training program.

It is of interest to compare the subjects in terms of their average tracking rates and, in particular, in terms of the relative improvements obtained with the prosthesis. Comparisons of this type, although difficult, are important in that they allow for an assessment of individual differences and the extent to which the prosthesis leads to improved performance across the user population. Such comparisons may also provide, at some future date, a basis for comparing different types of sensory aids.

A difficulty in drawing comparisons across subjects is that, in addition to the large individual differences that are typically encountered, there are important learning effects that need to be taken

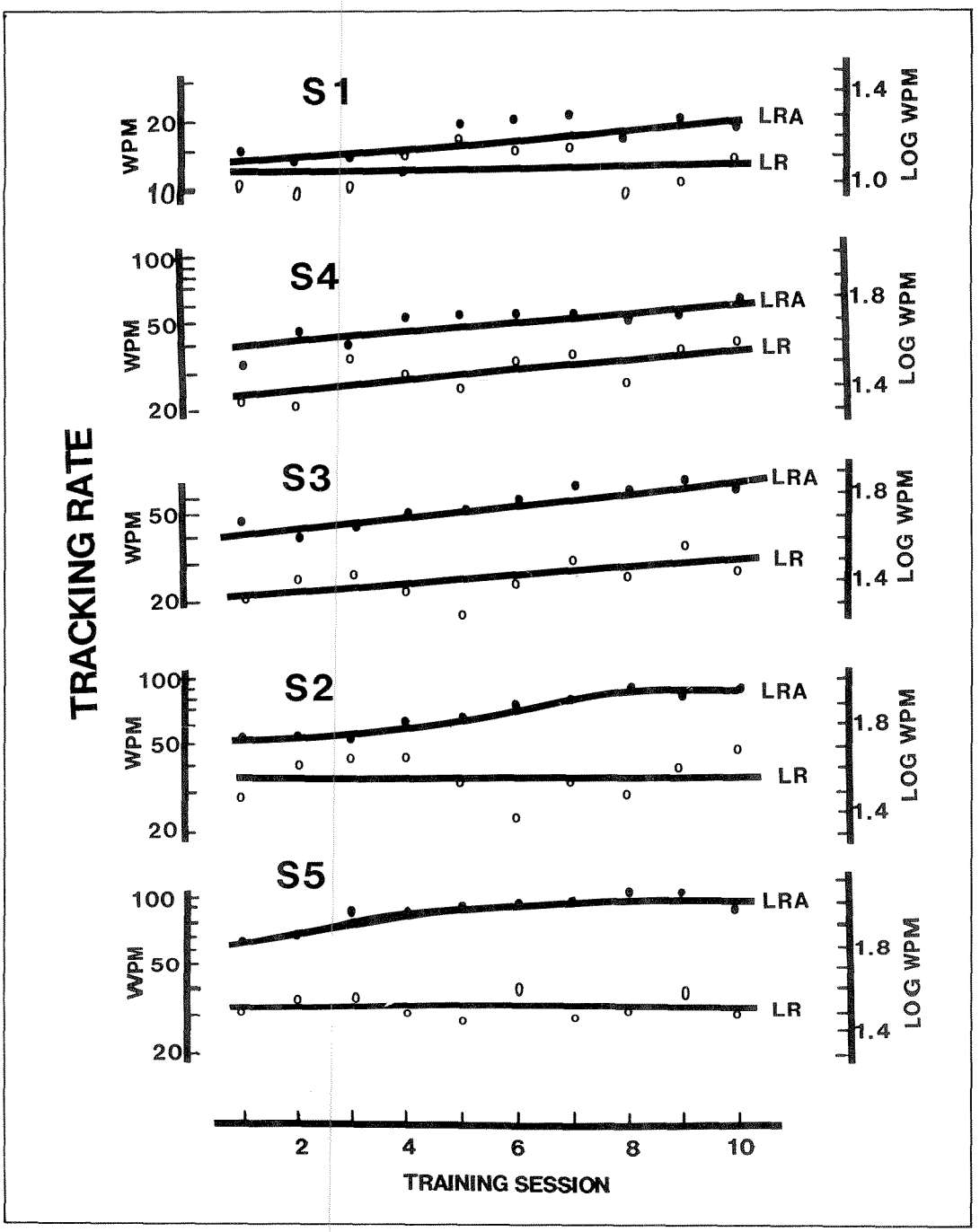

FIGURE 1
Tracking rates obtained for five subjects.

into account. One approach to the problem is to chart relative improvement as a function of unaided (LR) tracking rate. In this way information on both the LR and LRA conditions is included in the diagram (the latter indirectly) while at the same time focussing on the variable of primary interest, log(LRA/LR). Learning effects are indicated by arrows.

Figure 2 shows the data plotted in that way. Each point represents the most recent estimate of both log(LRA/LR) and log tracking rate (LR condition) as obtained from the end points of the fitted curves in Figure 1. The arrows show the direction of continued learning. Thus, for example, the learning curves for Subject No. 1 (Fig. 1) show no evidence of any saturation in learning for the LRA condition while at the same time tracking rate for the LR condition remains

constant. Extrapolation of the data beyond Training Session 10 indicates that the ratio log(LRA/LR) will continue to increase while tracking rate for the reference LR condition will remain constant. An arrow is thus shown for Subject 1 in Figure 2 indicating an expected future increase in log(LRA/LR), but no further change in log(LR). In contrast, the learning curves for Subject No. 4 show continued improvement in log(LR) but not in log(LRA/LR), since the LR and LRA learning curves have essentially the same slope; i.e., both log(LR) and log(LRA) show evidence of continued improvement while the ratio log(LRA/LR) remains constant. Subject No. 3 is the one subject for whom extrapolation of the learning curves showed continued improvement in both log(LR) and log(LRA/LR). The arrow for this subject shows expected improvements along both the log(LR) and log (LRA/LR) axes in Figure 2. Note that although Subjects No. 2 and No. 5 showed by far the largest improvements in log(LRA/LR) during the course of the rehabilitation program, both these subjects showed a saturation in this learning effect after about the eighth training session. Extrapolation of these learning curves beyond the 10th training session indicates no further improvements. Consequently no arrows indicative of continued learning are shown for these two subjects in Figure 2.

How does tracking rate relate to face-to-face communication?—An important practical consideration is the magnitude of the relative improvement needed for effective face-to-face communication. A typical tracking rate for normal hearing persons is 110 wpm reported by McConkey et al. in 1985 (4). That figure serves as a useful upper bound on tracking rates for even the most successful users of a cochlear prosthesis or any other sensory aid. A more realistic target is a tracking rate of 70 wpm; hearing impaired persons who are able to reach this tracking rate require the speaker to repeat what is said about a third of the time. Although slow and frustrating at times, face-to-face conversation between a normal hearing and a deaf person is practical at that rate. The two negatively sloping lines in Figure 2 indicate the relative improvements in tracking rate that are needed to reach these two criteria as a function of the unaided (LR) tracking rate.

Examination of Figure 2 shows that one subject (No. 1) stands out from the rest in terms of relative performance. This subject has by far the lowest unaided tracking rate and shows the smallest relative improvement with the prosthesis. This is the subject with whom difficulties were encountered in the surgical implantation of the electrode array; the prosthesis at present is functioning essentially as a single-channel rather than a multi-channel device. Even with the expected continued improvement in log(LRA/LR), shown by the vertical arrow, this subject is considered unlikely to reach even the lower, practical criterion of a 70-wpm aided tracking rate.

Of the other four subjects, two are already performing well above that lower criterion and one of these subjects (No. 5) has reached a tracking rate approaching that of a normal hearing person. Although the learning curves for this subject appear to have saturated for the LRA condition, she is now showing measurable tracking rates on the order of 100 wpm **with** lipreading cues, and is able to communicate reasonably well over the telephone. Her tracking rate for audition only (without lipreading and without the prosthesis) is zero in that she is unable to perform the tracking task under those conditions.

The remaining two subjects (No. 3 and No. 4) are performing below the lower criterion of 70 wpm for the LRA condition. Continued learning is evident in both cases and it is considered likely that Subject No. 3 will reach the lower criterion after continued training. Subject No. 4 has further to go to reach that point and is showing expected improvements only along the log(LR) axis, as indicated by the horizontal arrow. Remember that, for this subject, tracking rates for both the LR and LRA conditions show evidence of continued improvement but because the rate of improvement is the same for both conditions, the ratio log(LRA/LR) is remaining essentially constant. It is conceivable that with extensive training this subject will eventually reach the aided tracking rate of 70 wpm.

In assessing relative performance in the context of Figure 2, it is important to bear in mind that the plotted points are subject to experimental error on both axes. This leads to statistical difficulties in fitting curves to such data and in establishing significance levels: see for example Madansky, 1959 (10) and Abrahamson and Levitt, 1969 (11).

It should also be remembered that comparisons along the log(LRA/LR) axis are statistically more powerful, because here the major sources of variability (such as differences in test material or variations between talkers) have only a secondary effect — provided these factors are held constant for both the LR and LRA conditions. Comparisons along the log(LR) axis are much less sensitive, in that these measurements of absolute tracking rate are subject to all of the sources of variability we have mentioned.

An estimate of between-talker variability has

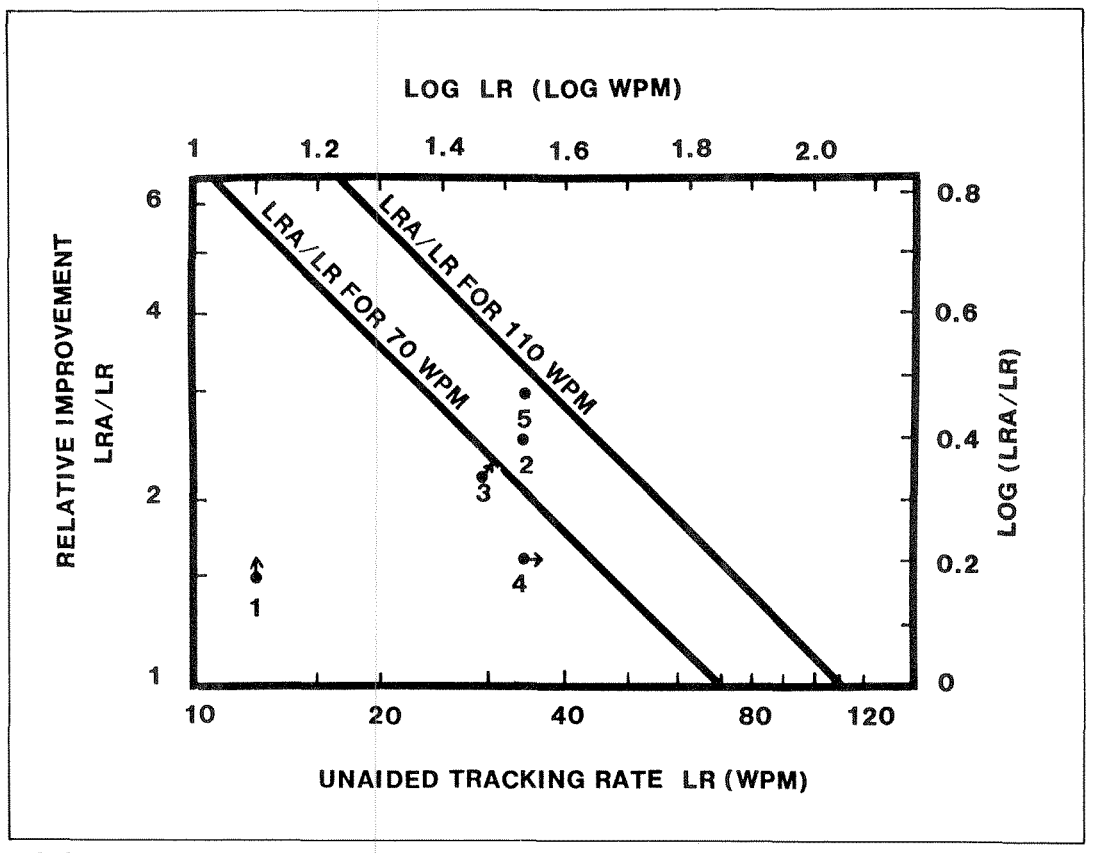

FIGURE 2
Representation of relative improvement and unaided tracking rate (LR) on Log-Log coordinates.

been obtained from McConkey et al. who documented both changes over time and changes associated with different talkers. The standard deviation of between-talker changes (which includes test-retest variability) was found to be 0.13 log(wpm); see reference (4). This is only moderately larger than the estimated standard deviation of 0.081 for log(LR) and 0.044 for log(LRA), as derived earlier.

CONCLUDING COMMENTS

Statistical significance is an important consideration in establishing whether the prosthesis has any effect. But having established that use of the prosthesis produces a statistically significant increase in tracking rate, it is still important to ask whether that measured improvement is of any practical value to the subject. Subject No. 1 showed the smallest improvement and for this subject use of the prosthesis has been of marginal value in improving communication ability. Tracking rate improved from an average of 12 words-per-minute to just under 15 words-per-minute after 10 weeks of training. Both of those tracking rates are well below average, indicating that this subject has considerable difficulty in communicating and that intensive rehabilitation training is needed both to improve lipreading skills and to help the subject make better use of the supplementary cues provided by the prosthesis.

The subject showing the next smallest improvement (No. 2) is able to function at a much higher level than No. 1, with lipreading alone. The relative improvement in tracking rate obtained with the prosthesis, although only slightly larger than that for Subject No. 1, is of much greater practical significance since it has brought her within reach of a practical level of communication for face-to-face conversation. (This subject, interestingly, is showing continued improvement at roughly the same rate for both the aided and unaided conditions.)

The median subject (No. 3) has shown not only a significant long-term improvement in tracking rate for the unaided (LR) condition, but has also shown a large relative improvement with the prosthesis, improvement that has continued to increase signifi-

cantly over the course of the rehabilitation training program. The combined effect of the prosthesis and the rehabilitation training program is such that this subject is now able, albeit with difficulty and not always successfully, to participate in face-to-face conversation with normal hearing persons. Prior to this intervention, she was unable to communicate effectively in that way. How much of the improvement can be ascribed to the prosthesis and how much to the rehabilitation program, per se, is an extremely important and relevant question but one that cannot be answered definitively on the basis of the available data. The two effects appear to have acted "symbiotically," with a net positive result. The importance of intensive rehabilitation training should not be underestimated and careful consideration should be given to assessing the potential for rehabilitation training prior to surgery.

The two best subjects (No. 2 and No. 5) showed substantial learning effects for the aided (LRA) condition but no significant changes in performance for the unaided (lipreading-only) condition. Both of these subjects were relatively good lipreaders to begin with, and the effect of the prosthesis has been such that they are now able to participate effectively in face-to-face conversation with normal-hearing individuals—and with each other. Subject No. 5, in particular, is able to communicate at a rate and accuracy comparable to that of a normal hearing person in a moderately noisy environment (such as at a cocktail party). The impact of the prosthesis for these two subjects has been profound by every available measure. They are now able to participate in the hearing world with relatively little difficulty whereas in the past they depended on the help of a sign-language interpreter ■

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