Analysis of a synthetic Tadoma system as a multidimensional tactile display

Hong Z. Tan, William M. Rabinowitz, and Nathaniel I. Durlach
Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139

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The Tadoma method is a means of speech reception based on tactile monitoring of the articulatory process. A "synthetic" Tadoma system, involving an artificial face with six facial actions, has been developed as a first-order approximation to the natural Tadoma system. Experiments were conducted to explore the information-transmission characteristics of the synthetic Tadoma system in terms of the four facial movements it incorporates: upper lip in–out, lower lip in–out, lower lip up–down, and jaw up–down movements. Discrimination experiments showed that the just-noticeable difference associated with each movement is about 9% of the reference displacement. One-dimensional (1-D) absolute identification experiments produced, on the average, 1.6 bits of information transfer. Four-dimensional (4-D) identification experiments produced information transfers in the range of 3–4 bits. Of the four dimensions considered, performance on the lower lip up–down movement was most affected, and performance on the jaw up–down movement was least affected, by simultaneous roving movements on the other dimensions. As a result of the interaction among the movement channels, the sum of the 1-D information transfers exceeds the 4-D information transfer. However, the sum of the 1-D information transfers obtained from tests with roving parameters is approximately equal to the 4-D information transfer (possibly exemplifying a "generalized information-transfer additivity law"). In general, both the discrimination and identification results appear unexceptional and, hence, the reception of facial movement information by itself does not appear to account for the extraordinary success of the Tadoma method.

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INTRODUCTION

The study of tactile communication of speech serves several purposes. First, for those who are both blind and deaf, such study will help make possible the use of another sense modality for speech communication. Second, the study will lead to more insight into how the tactile sense works. Finally, the study will improve our basic understanding of speech communication.

Recent work has demonstrated that well-trained deaf–blind people can perceive speech through tactile monitoring of the articulatory process at nearly normal rates (see Norton *et al.*, 1977; Reed *et al.*, 1982b; Reed *et al.*, 1985). In this method, referred to as Tadoma, the person receiving speech places his or her hand on the face and neck of the talker and, in the absence of auditory and visual input, monitors actions associated with the speech-production process to understand speech. In the typical hand position, the thumb rests across the middle of the lips and the fingers fan out across the face and neck.

The Tadoma method is superior to any artificial tactile display of speech that has been studied to date. Some characteristics of Tadoma that might be responsible for its exceptionally good performance are:

(1) A face is a "rich" multidimensional tactile display;

(2) the display directly represents the articulatory process;

(3) the hand is an exceptionally sensitive body part for tactile perception; and

(4) its users were taught the method intensively over several years.

The synthetic Tadoma system (see Reed *et al.*, 1985, for details), a first-order approximation to the natural Tadoma system, was built to facilitate the study of cues used by Tadoma readers. The display portion of the synthetic Tadoma system (the artificial face) is a plastic anatomical model with six facial actions that can be computer controlled. The specific actions included are:

(1) upper lip in–out movement (UIO);
(2) lower lip in–out movement (LIO);
(3) lower lip up–down movement (LUD);
(4) jaw up–down movement (JUD);
(5) laryngeal vibration; and
(6) oral airflow.

Each of these actions can be controlled independently. The four facial movements (UIO, LIO, LUD, and JUD) are effected by position-controlled servomoter systems. The LIPS[1] are rubber tubes that are driven by flexible metal cables attached to the middle of the two LIPS. The JAW movement relative to the skull is effected via a rotational joint constructed in the vicinity of the condylar process.

Leotta (1985) and Leotta *et al.* (1988) evaluated the synthetic Tadoma system (with all six actions) by comparing speech-segment discrimination performance on the synthetic system to results obtained from natural Tadoma. Although some deficiencies in the synthetic system were revealed, results with the synthetic system and those with natural Tadoma were generally similar, supporting the idea that the essential features of a real talking face have been realized in the synthetic system (Leotta *et al.*, 1988).

Our present study begins to examine the extent to which the face is, in fact, a "rich" multidimensional tactile display. More specifically, we evaluate performance using the four movement channels: UIO, LIO, LUD, and JUD. All of these dimensions were studied separately and jointly with respect to information transmission using elementary, static, nonspeech stimuli. In subsequent research, we intend not only to include vibration and airflow, but also to examine rates of information transmission using dynamic, nonspeech stimuli.

Assessment of information transmission was carried out in two steps. First, discrimination experiments were conducted to investigate the basic resolution of the human tactile sense with respect to the four movements UIO, LIO, LUD, and JUD. Identification experiments were then performed to determine how much information could be received through the movement systems. According to studies by Pollack, Garner, and others (Garner, 1962; Miller, 1956; Pollack, 1973a,b; Pollack *et al.*, 1954), information transfer for unidimensional stimuli is limited to roughly 2 bits. However, by employing several dimensions (as in Tadoma), information transfer can be greatly increased. In general, the amount of information transfer depends not only on the number of dimensions, but on how the different dimensions interact.

I. EXPERIMENTS

Three subjects, HT (the first author), JT, and TH were used in the study. All are hearing and sighted graduate students, and none had previous exposure to the Tadoma method. In all experiments, the subject sat with his/her elbow resting on the table which supported the FACE, and placed a hand on the FACE with the thumb resting (vertically) across the middle of the LIPS and the fingers fanning out across the CHEEK (the typical hand position of Tadoma users). In tests with two intervals per trial, the hand was kept on the FACE during the interstimulus intervals (except in the preliminary discrimination tests). The subject was positioned to look away from the FACE so that the movements could not be sensed visually. Also, the subject wore earmuffs (and ear plugs when necessary) to eliminate possible auditory cues from the FACE.

The artificial face was normally set in a reference or neutral position. This position is defined such that the JAW and the lower LIP are fully up (MOUTH closed), and the upper and lower LIPS are fully in (no protrusions). All movements began and ended in this state and were under computer control. The maximum displacements were 6–7 mm for UIO, LIO, and LUD, and 24 mm for JUD.[2]

The waveforms used to drive the FACE were computer-generated displacement steps composed of a 300-ms constant portion and 150-ms (Hanning) transition portions at the beginning and the end of the waveforms. The 600-ms waveform was then scaled in amplitude to produce desired displacements. All waveforms differed only in their scaled amplitudes.

All experimental runs started with an informal training period. The subjects could start the experimental run when they felt ready. Each run consisted of 100 trials. Trial-by-trial feedback was always provided.

The four FACIAL movements will be referred to as "displacements," "movements," "parameters," "channels," or "dimensions" interchangeably. The terms "target" and "background" shall be used to clarify the different roles the four movements play in an experiment.

A. Discrimination experiments

All discrimination experiments used the symmetric 2I-2AFC (two-interval, two-alternative forced choice) paradigm. For each reference displacement D, three incremental displacements ΔD were used. Each subject completed two runs for each $(D, \Delta D)$ pair. Thus each subject completed six runs (600 trials) for each reference. The order in which these six runs were performed was randomized individually for each subject. Performance was characterized for each of the three $(D, \Delta D)$ pairs by forming the appropriate 2×2 matrix (pooled from two runs) and estimating the sensitivity index d' and response bias β. The response bias β was found to be sufficiently small to be ignored (less than 10% of the corresponding d'). As found in many other studies of sensory discrimination (e.g., Durlach *et al.*, 1989), the dependence of d' on the increment ΔD for a fixed reference displacement D could be well described by a straight line through the origin. Thus the performance for a fixed D can be summarized by the slope $\delta' = d'/\Delta D$ of the straight line (i.e., the sensitivity per mm). The δ' was estimated by averaging the three $d'/\Delta D$ ratios obtained above. The just-noticeable difference (jnd), defined by the performance criterion $d' = 1$, is given by $\text{jnd} = 1/\delta'$. All the results for the discrimination experiments are presented in the form of the Weber fraction jnd/D.

1. Preliminary discrimination experiments

It was not clear at first whether a subject should keep his/her hand on the FACE throughout the whole experimental run (simulating what the Tadoma users do) or only touch the FACE briefly when the facial feature was in the desired position. The purpose of the preliminary study was to compare these two methods. Only subject HT participated in this study.

As mentioned in the Introduction, the study of static stimuli is the focus of this paper. However, when a subject kept his/her hand on the FACE during a complete movement (from neutral position to desired position, then back to neutral position), he/she was presented not only the static amplitude cue from the steady portion of the stimulus but also a dynamic velocity cue from the transition (i.e., since the transition duration was constant, the movement velocity to and from the steady-state displacement varied in proportion to the steady-state displacement). This potential velocity cue could be eliminated by not allowing contact with the FACE during movement transitions.

Three kinds of stimuli were designed to reveal the possible effect of velocity cues. In scheme 1 (which was ultimately selected for the main experiments), the transition time was held at 150 ms, and the total duration of the waveform was held at 600 ms. The subject kept her hand on the FACE during the whole stimulus; both velocity and amplitude cues were available to her in this scheme.

In scheme 2, the transition time remained at 150 ms, but the total duration of the waveform was increased to 1100 ms. The subject was instructed to rest her four fingertips on the CHEEK BONE of the FACE and hold her thumb vertically in front of the FACE. With this position, the palm did not touch the JAW and no part of the subject's hand could sense any of the four movements. Following the end of the rising portion of the waveform, the word "ON" appeared on the terminal screen, followed by the word "OFF" 300 ms later. The subject was told to place her thumb on the LIPS when she saw the word ON and take it away from the LIPS when she saw OFF. The additional 500 ms was sufficient to allow the subject to remove her thumb from the LIPS without feeling the transition portion at the end of the waveform. (Also, the transition portion at the beginning of the waveform could never be felt.) In this scheme, the subject's thumb touched the LIPS for roughly 300 ms and only the steady-state amplitude cue was available to her.

In scheme 3, the steady-state portion of the displacement was kept at 300 ms (as in scheme 1), but the transition time for the two stimuli was adjusted such that the maximum slopes of the rising and falling portions were equal for both displacements. The subject kept her thumb on the LIPS during the whole stimulus presentation. Here, a possible duration cue (duration of the constant portion of the waveform), as well as an amplitude cue, was available to the subject.

All three of these schemes were tested for JUD discrimination with $D = 6.9$ mm and $\Delta D = 0.8$ mm. Results of these tests show that all three schemes produce essentially the same value of d' (the results were $d' = 1.41$, 1.41, and 1.44 for schemes 1, 2, and 3, respectively). This equivalence indicates that transition velocity is not a major cue for this task. Since the three schemes yielded similar results, we elected to use scheme 1 for all subsequent experiments.

2. Main discrimination experiments

Two types of discrimination experiments were performed. In the first, we applied movements D and $D + \Delta D$ to one channel (the target) and kept the other three channels (the background) at their neutral positions. In the second, the same target displacements were applied, but random displacements were applied independently to the three background channels. These two types of tests are referred to as discrimination with "fixed" and "roved" backgrounds, respectively.

a. Discrimination with fixed backgrounds. The results for the discrimination experiments with fixed backgrounds are summarized in Table I. The results for each channel and each reference displacement D are given in terms of the Weber fraction jnd/D in percent. Since JUD has a much bigger displacement range than the other three channels, more values of D were used.

The intersubject differences are generally small. The Weber fractions averaged across references within each channel vary between 8.3% and 10.6% and average 9.3%. Roughly speaking, the Weber fractions are independent of reference displacements, movement channels, and subjects. This strikingly simple result is important to the design of subsequent experiments and will be referred to later in this paper.

b. Discrimination with roved backgrounds. The displacement on each of the three background channels was chosen independently from four possible levels that included 0 mm and three values that were equally spaced on a logarithmic scale and spanned the whole movement range for the channel (6 mm for UIO, 7 mm for LIO and LUD, and 23 mm for JUD). Before each experiment, the subject was informed of the target channel and told to ignore the three background channels as much as possible. Furthermore, they were instructed to maintain their hand position even though better performance might conceivably be achieved by altering hand position (e.g., when UIO is one of the background channels, lowering the thumb level to that of the LOWER LIP would conceivably eliminate UIO influence and thus improve one's performance on discriminating displacements on the target channel). Maintaining a constant hand position is obviously important for comparisons across experimental conditions.

TABLE I. Results of discrimination with fixed backgrounds. Entries in the table give Weber fractions jnd/D in percent; D is reference displacement in mm.

	Target channel																		
	UIO			LIO				LUD				JUD							
	D (mm)			D (mm)				D (mm)				D (mm)							
Subject	1.7	5.1	Average	0.3	3.2	6.0	Average	0.1	3.1	6.1	Average	0.4	1.2	1.5	3.3	6.9	14.1	21.3	Average
HT	9.5	9.9	9.7	8.2	9.4	9.4	9.0	7.4	11.5	9.3	9.4	9.0	11.3	10.2	8.4	11.0	8.0	7.3	9.3
JT	9.6	11.6	10.6	6.0	10.0	11.2	9.1	7.2	10.6	9.6	9.1	9.0	9.8	9.4	8.7	6.2	8.2	6.8	8.3
TH	6.4	11.1	8.8	10.1	5.5	9.9	8.5	9.7	10.0	10.4	10.0	11.5	10.0	11.6	11.5	8.9	6.8	8.3	9.8
AVE	8.5	10.9	9.7	8.1	8.3	10.2	8.9	8.1	10.7	9.8	9.5	9.8	10.4	10.4	9.5	8.7	7.7	7.5	9.1

TABLE II. Results of discrimination tests comparing fixed and roved backgrounds. Entries for "roved" and "fixed" are the Weber fractions jnd/*D* in percent, and entries for "ratio" give the values of roved/fixed.

		Target channel and *D* (mm)			
Subject	Background	UIO 1.1	LIO 2.5	LUD 2.3	JUD 6.9
HT	roved	25.7	33.8	···	13.1
	fixed	6.4	6.5	7.0	5.9
	ratio	4.0	5.2	···	2.2
JT	roved	20.3	47.6	···	15.1
	fixed	6.5	7.7	6.9	10.5
	ratio	3.1	6.2	···	1.4
TH	roved	27.5	56.8	···	17.0
	fixed	8.5	9.4	9.3	10.7
	ratio	3.2	6.0	···	1.6
Average	roved	24.5	46.1	···	15.1
	fixed	7.1	7.9	7.7	9.0
	ratio	3.4	5.8	···	1.7

In order to control for possible training effects, we repeated discrimination experiments with fixed backgrounds at the same time that we performed the discrimination experiments with roved backgrounds. For each reference displacement, each subject first completed six runs with roved backgrounds and then six runs with fixed backgrounds. All 12 runs were always completed on the same day.

Only one reference displacement was chosen for each of the four movement channels. The jnd's associated with this reference for both roved and fixed backgrounds show that roving the background substantially degrades resolution (see Table II). The roved/fixed ratios range from 1.4 to 6.2 and average 3.6. This ratio is absent in the table for LUD, because none of the subjects could perform the LUD discrimination task for the roved condition even when the LUD increment was as large as the reference displacement. As can be seen by comparing results in Tables I and II, the fixed-background results show some training effects. For example, subject HT's average jnd/*D* scores in Table I are 9.7% for UIO, 9.0% for LIO, 9.4% for LUD, and 9.3% for JUD, whereas the corresponding scores in Table II are 6.4%, 6.5%, 7.0%, and 5.9%. On the other hand, TH showed very little improvement in performance, and both JT and TH exhibited degraded scores for JUD. Finally, while the average jnd/*D* in Table I is largest for UIO and second smallest for JUD, the corresponding average $\text{jnd}_{\text{fixed}}/D$ in Table II is smallest for UIO and largest for JUD. Thus the improvement in performance is greatest for UIO and least for JUD.

Although the roved/fixed ratios vary across the three subjects, the relative dependence of the ratios on target channel is the same for all of them. The jnd for LUD was most affected by roved displacements, followed by LIO, then UIO, and finally JUD. This ordering appears reasonable in the light of the following observations. LUD displacement can only be felt by sensing the position of the lower LIP on the thumb; however, LIO as well as JUD displacement changes the lower LIP position. When these three displacements occur in a single presentation, subjects are unable to separate out the LUD component. LIO displacement is felt by sensing the lower LIP protrusion. When LUD and JUD displacements are present, the lower LIP touches the subject's thumb at different locations, causing the protrusion to be felt differently. Perception of UIO displacement is relatively well separated from LUD and JUD displacements. However, it is substantially influenced by LIO displacement (e.g., when LIO displacement is substantially greater than that of UIO, the subject's thumb loses contact with the upper LIP on the FACE and performance degrades). Finally, perception of JUD displacement is least affected by the other three displacements because it can be felt by the subject's palm as well as thumb.

B. Identification experiments

One-dimensional (1-D) and four-dimensional (4-D) information-transfer characteristics of the FACE for the four movement channels were examined. All identification experiments employed a one-interval absolute identification procedure with trial-by-trial feedback. For each identification test, subjects were informed of the number of alternatives in the stimulus set and received brief training in associating the alternatives with a set of integers in a natural order. Upon receiving a stimulus, the subject was required to respond with the corresponding integer. A stimulus–response confusion matrix was obtained and information transfer (IT) was computed.[3]

1. 1-D identification with fixed backgrounds

In this experiment, we examined IT for 1-D stimuli with fixed backgrounds. Three channels were examined: LIO, LUD, and JUD. Preliminary results showed that the UIO channel yielded results similar to those of the LIO channel. To save time, data on UIO were not completed.

Sixteen stimuli were used for the JUD channel and 14 stimuli for each of the LIO and LUD channels. The displacements of the stimuli included 0 mm and steps that were

TABLE III. Results of 1-D identification tests comparing fixed and roved backgrounds. Entries for "fixed" and "roved" give the information transfer (in bits). Ratio = fixed/roved. The ratio scores for UIO used fixed data from LIO, consistent with the preliminary results (see text).

		Target channel and number of stimuli				
Subject	Background	UIO 14	LIO 14	LUD 14	JUD 16	Average
HT	fixed	···	1.8	1.7	2.0	1.8
	roved	1.4	0.9	0.5	1.4	
	ratio	1.3	2.1	3.7	1.4	
JT	fixed	···	1.8	1.7	1.8	1.8
	roved	1.1	0.9	0.6	1.4	
	ratio	1.7	2.0	3.1	1.3	
TH	fixed	···	1.3	1.3	1.4	1.3
	roved	0.4	0.4	0.2	1.2	
	ratio	3.0	3.5	7.1	1.2	
Average	fixed	···	1.6	1.6	1.7	1.6
	roved	1.0	0.7	0.4	1.3	
	ratio	2.0	2.5	4.6	1.3	

equally spaced on a logarithmic scale (consistent with Weber's law). The maximum displacements were 24 mm for JUD and 7 mm for the LIO and LUD channels. Each subject completed between 1200 and 1500 trials for each channel. The results of this experiment are summarized in Table III (the rows labeled "fixed").

The IT_{fixed} values vary between 1.3 and 2.0 bits and average 1.6 bits. Note that subject TH's values are consistently lower (by roughly 0.5 bits) than those of the other two subjects. For each subject, the ITs are highest for JUD, followed by LIO and LUD. According to the study by Braida and Durlach (1972) in the domain of auditory intensity perception, IT increases as the number of jnd's increases when the range of stimuli includes less than 50 jnd's. The JUD channel has the biggest displacement range among all the movement channels and includes approximately 50 jnd's in its stimulus set. On the other hand, the LIO and LUD channels include only 30–40 jnd's. Thus the relatively high IT for JUD is not surprising.

2. 1-D identification with roved backgrounds

This study parallels the 1-D discrimination study with roved backgrounds. The stimulus set used for the target channel was the same as that used in the 1-D identification experiments with fixed backgrounds. Simultaneous roved displacements were applied to the three background channels. The displacement for each of the background channels was chosen independently from four possible levels, which were the same as those used in the 1-D discrimination experiments with roved backgrounds. Before each experimental session, subjects were informed of the target channel. They were again instructed to ignore the roved movements as much as possible but not to change their usual hand position on the FACE. Each subject completed 1000 or more trials for each of the four target channels. The results of this experiment are summarized in Table III (the rows labeled "roved").

Subject TH's scores are again consistently lower (by an average of 0.5 bits) than those of the other two subjects. More dramatically, his *ratio* scores are about twice as big as those of the other two subjects (except for the JUD channel), indicating that his performance on the UIO, LIO, and LUD channels is greatly affected by roved displacements on other channels. The average IT_{roved} for the LUD channel is 0.4 bits, indicating that the subjects were not able to identify even two stimulus categories in this channel. Referring back to Table II, one notes that performance on the LUD channel in the discrimination task was also substantially degraded by simultaneous roved displacements in other channels. By comparing the order of the ratio scores in Table III with that of the ratio scores in Table II, the results are seen to be consistent in that the LUD channel is most affected, followed by LIO, UIO, and then JUD, by simultaneous displacements in other channels.

3. 4-D identification

In this experiment, the subject was asked to identify simultaneous displacements in all four movement channels. The number of alternatives used for each channel was four. (Since the IT from a single channel in the roved 1-D tests never exceeded 1.5 bits, four alternatives on each channel were thought to be sufficient.) Thus the total number of alternatives was 256. The four displacement values for each channel were the same as those used for background channels in 1-D discrimination and identification experiments with roved backgrounds. On each trial, the displacement for each channel was chosen independently and with equal probability from its four possible alternatives. Upon receiving the stimulus, the subject responded with an integer between 1 and 4 for each of the four movement channels in the following order: UIO, LIO, LUD, and JUD. The choice of the response order was arbitrary but was kept constant for all the 4-D tests. As usual, trial-to-trial feedback was given. Each subject received about 1 h of training in associating the integers 1–4 with each of the four movements on each of the four channels. A total of 5000 trials was collected for each subject. No obvious improvement from session to session (in terms of IT estimated from each session) was observed.

Three measures of IT were computed from the 4-D data (as in the experiments by Rabinowitz *et al.*, 1987):

(1) The measure IT_{4D} for the whole, unreduced, 256×256 confusion matrix;

(2) the sum, over all four dimensions, of the "pooled projections" IT_{pooled}, where, for each dimension, IT_{pooled} is computed from the 4×4 matrix obtained by pooling results across all complementary variables;

(3) the sum, over all four dimensions, of the "conditioned projections" IT_{cond}, where, for each dimension, IT_{cond} is computed by averaging the ITs obtained from the sixty-four 4×4 matrices conditioned on the combinations of the individual values of the complementary variables.

As discussed in Rabinowitz *et al.* (1987), the extent to which IT_{cond} exceeds IT_{pooled} for a particular channel reflects the degree to which the perception of displacement in the given channel depends on the displacements in the other channels.

The results of the 4-D identification experiment, together with the sums $\Sigma\ IT_{fixed}$ and $\Sigma\ IT_{roved}$ obtained by summing the values of IT_{fixed} and IT_{roved} obtained in the 1-D identification experiments (Table III), are shown in Table IV.[4]

As has often been observed in the past with other types of stimuli, IT_{4D} is considerably smaller than $\Sigma\ IT_{fixed}$ (e.g., see Egeth and Pachella, 1969; Garner, 1962; Rabinowitz *et al.*, 1987). Note, however, that this is not the case for

TABLE IV. Comparison of 4-D and 1-D identification results. Entries are information transfer (in bits). IT_{4D} denotes the bias-corrected 4-D ITs. See text for details.

	4-D			1-D	
Subject	IT_{4D}	$\Sigma\ IT_{pooled}$	$\Sigma\ IT_{cond.}$	$\Sigma\ IT_{fixed}$	$\Sigma\ IT_{roved}$
HT	4.0	3.0	3.6	7.2	4.1
JT	3.0	2.2	2.8	7.0	3.9
TH	2.9	1.7	2.2	5.3	2.2
Average	3.3	2.3	2.9	6.5	3.4

Σ IT$_{\text{roved}}$: Averaged over subjects $\text{IT}_{4\text{D}} \simeq \Sigma\,\text{IT}_{\text{roved}}$. In other words, although the IT in the 4-D experiment falls far short of the sum of the ITs obtained in the *fixed* 1-D experiments, it is roughly equal to the sum of the ITs obtained in the *roved* 1-D experiments. This result is discussed further in Sec. II.

Note also that, for each subject, $\text{IT}_{4\text{D}}$ is greater than $\Sigma\,\text{IT}_{\text{cond}}$, which, in turn, is greater than $\Sigma\,\text{IT}_{\text{pooled}}$. Averaged over subjects, the differences are 0.4 and 0.6 bits, respectively. These differences, like those between the 1-D fixed and 1-D roved tests (in discrimination as well as identification), indicate the existence of substantial dependencies among the various channels.

In order to examine these dependencies further, we examined the effect of a given displacement in one channel on the IT obtained through each of the other channels.^{5} Overall, we found a tendency for the IT in the other channels to decrease as the displacement in the given channel increased. The most notable example of this tendency occurred when JUD was chosen as the conditioning channel: On the average, the ITs obtained from the other channels decreased by 0.5 bits as the displacement on JUD increased from zero to maximum. In other words, large JAW opening substantially reduced the accuracy in judging the positions of the other channels. These findings indicate that the displacement on one channel can influence not only the bias on the other channel, but also the resolution on that channel.

II. CONCLUDING REMARKS

A. Intersubject differences

According to the results shown in Table I, the three subjects' scores from the initial fixed-background discrimination tests are roughly comparable. Data in Table II, however, show worse performance on the fixed-background test for TH. Apparently, whereas HT and JT tended to improve with practice on these tests, TH did not. The data in Table II also show that the effect of roved backgrounds on discrimination is roughly similar for the three subjects. According to the results shown in Table III, 1-D identification performance is roughly the same for HT and JT, but considerably worse for TH. These results tend to hold for all entries, both fixed and roved, with two exceptions: the substantial superiority of HT over JT for UIO with roved backgrounds and the relatively good performance of TH for JUD with roved backgrounds. Note also that, with the exception of the JUD tests, the effect of roving was considerably worse for subject TH. Finally, according to the results in Table IV, we note that, on the 4-D identification tests, the performance of HT is substantially better than that of JT, which is roughly comparable to that of TH.

Overall, and using the performance of HT as a reference, the most idiosyncratic result for TH is the remarkably poor performance in the 1-D identification tests with roved backgrounds for the three LIP variables UIO, LIO, and LUD (but not the JAW variable JUD). Averaged over these three variables, the IT for TH is only 0.33, whereas it is 0.89 for HT and 0.84 for JT. Note also that this idiosyncratic effect of roving in the 1-D identification tests is much reduced in the discrimination tests; in the discrimination tests, the effect of roving for TH is not much greater than for HT or JT. The most surprising result for JT, on the other hand, is his poor performance in the 4-D identification tests. Whereas the IT in the 4-D tests is much lower for JT than for HT (3 bits compared to 4 bits), the effect of roving in both the discrimination and 1-D identification tests is roughly comparable for the two subjects.

In general, although some of these intersubject differences are substantial, they are by no means exceptional (compare them, for example, to the intersubject differences in Optacon reading discussed by Craig, 1977). Moreover, they do not seriously interfere with the general conclusions of our study. In fact, to the extent that the relations concerning the different tests hold for all the subjects, intersubject variation (e.g., in overall performance) strengthens the conclusions, not weakens them.

Finally, we note that previous work suggests that the performance of experienced Tadoma users would probably not be noticeably better on these tasks than that of normal subjects. According to available data, the remarkable performance of Tadoma users on tests of continuous-speech comprehension is not due to remarkable tactile sensitivity: The performance of the two classes of subjects is roughly the same for resolution of isolated speech segments (Reed *et al.*, 1978 and Reed *et al.*, 1982a).

B. Comparison to other displays

Our results, although limited, suggest that the performance that can be achieved with the movement systems incorporated into the synthetic Tadoma system is not exceptional. The measured ITs, both in the 1-D cases and the 4-D case, are relatively unimpressive (e.g., see, for comparison purposes, the tactual ITs reported by Rabinowitz *et al.*, 1987, and Sherrick, 1985). Also, the Weber fraction appears to be relatively large (or at least not small) compared to other Weber fractions in the tactual sense (e.g., see Durlach *et al.*, 1989; Sherrick and Cholewiak, 1986).

It is likely, of course, that, when the movement systems are supplemented by airflow and laryngeal vibration, the IT will increase substantially (perhaps even double). It is also possible that the synthetic Tadoma system has exceptional virtues with respect to certain dynamic properties (such as temporal-order discrimination), so that the information rate for this system is a large multiple of the static IT (e.g., roughly ten times larger). Nevertheless, to date we have not demonstrated any remarkable superiority for this display. If further study fails to reveal such superiority, we will be forced to conclude either that (1) the synthetic system does not capture the essentials of natural Tadoma (despite the preliminary results discussed in Leotta *et al.*, 1988) or (2) the unusually good performance observed with natural Tadoma is not explainable primarily in terms of the "exceptional richness" of the display. As discussed in the Introduction, and quite apart from the established relative superiority of the hand as a tactual receiver (many other tactual communication systems have also used the hand), it is possible that the superior performance evidenced by users of natural Tadoma is due to the direct representation of the articulatory process in the Tadoma method and/or the intensive long-term training received by the Tadoma users. Recent results demonstrating the abilities of well-trained users of tactual signing and tactual fingerspelling (Reed *et al.*, 1987) suggest to us that the latter of these two factors is probably the most important. Perhaps any tactual system that provides an information-transfer rate that exceeds some minimum value X can be used for speech communication if intensive training at an early age is provided. Unfortunately, serious study of this issue requires not only improved methods for estimating X (both the values of X required for different proficiency levels of speech reception and the values provided by the various tactual methods and displays), but also complex and long-term research on training effects.

C. A generalized information-transfer additivity law?

The usual IT additivity law states that multidimensional IT is the sum of the component 1-D ITs when the component variables are independent (precise statements of this law can be found in Ashby and Townsend, 1986). However, in this law, it is assumed that the 1-D ITs are obtained from 1-D experiments in which the complementary parameters are held *fixed*. The results of our experiments are consistent (at least roughly) with the idea that additivity *always* holds, provided only that in the 1-D experiments the complementary variables are roved over the appropriate ranges (i.e., the same ranges that are covered in the multidimensional experiment). In other words, the deficit in the multidimensional IT (relative to $\Sigma\ \mathrm{IT}_{\mathrm{fixed}}$) caused by interaction of the variables is adequately reflected in the difference between $\Sigma\ \mathrm{IT}_{\mathrm{roved}}$ and $\Sigma\ \mathrm{IT}_{\mathrm{fixed}}$. Further discussions of this idea can be found in Durlach *et al.* (1989).

To the extent that further research confirms this proposed generalization, the following implications should be noted. First, according to this law, the potential reduction in IT associated with the more complex response coding in the multidimensional case (e.g., in our experiments, the need to respond with a four-integer vector in the 4-D case) is negligible. The reduced IT in the multidimensional case is due primarily to the characteristics of the *stimulus set.* Second, since it takes many fewer trials to obtain reliable estimates of the component 1-D roved ITs than of the multidimensional IT, the law can be used to save experimental research time.

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[1] We shall use SMALL CAPS to refer to the corresponding parts on the synthetic Tadoma system throughout the paper.

[2] For computer manipulation, the displacements were specified in terms of *counts* (i.e., steps on the optical encoder of each movement channel servomoter). For each of the four movements, a calibration measurement of the displacement (D) in mm as a function of *counts* (C) was approximated by $D = k(C - C_0)$, with $C \geqslant C_0$. The slopes (k) were 0.016, 0.014, 0.015, and 0.036 and the intercepts (C_0) were 130, 20, 46, and 8 for UIO, LIO, LUD, and JUD, respectively. (The nonzero intercepts were the result of backlash in the cable-drive linkages.) In this paper, we specify positions in terms of mm of displacement, as derived from these straight-line fits.

[3] These computations included corrections for the bias that occurs in estimates of IT from limited experimental data (Houtsma, 1983; Tan *et al.*, 1989). For a detailed description of the corrections, see Tan (1988).

[4] The entries in Table IV that have the most uncertainty (because of the large number of confusion-matrix cells relative to the number of trials) are those for $\mathrm{IT}_{4\mathrm{D}}$, the bias-corrected 4-D IT. It should be noted, however, that the true value of the 4-D IT is bounded from below by $\Sigma\ \mathrm{IT}_{\mathrm{pooled}}$ and from above by the uncorrected value of the 4-D IT computed directly from each subject's confusion matrix based on 5000 trials. Averaged over subjects, these bounds are 2.3 and 3.9 bits and the bias-corrected $\mathrm{IT}_{4\mathrm{D}}$ is 3.3 bits. Although the range of these bounds is rather large, we are unaware of any method of reducing this uncertainty short of collecting many thousands of additional trials per subject.

[5] For instance, we examined the effect of a JUD displacement on the IT obtained through the UIO channel by computing the IT for the 4×4 UIO matrix, which pools data from all UIO 4×4 matrices conditioned on the displacement of JUD.

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