The American Society of Mechanical Engineers

Reprinted From
DSC—Vol. 42, Advances in Robotics
Editor: H. Kazerooni
Book No. G00751—1992

MANUAL RESOLUTION OF LENGTH, FORCE, AND COMPLIANCE

Hong Z. Tan, Xiao Dong Pang, and Nathaniel I. Durlach
Research Laboratory of Electronics
Sensory Communicaton Group
Massachusetts Institute of Technology
Cambridge, Massachusetts

ABSTRACT

This paper summarizes some of the work we have done over the past few years on manual resolution of the object properties length, force, and compliance. The work on length resolution was published in Durlach et al. (1989). The work on force resolution (with fixed displacement) was published in Pang et al. (1991). The work on force resolution (with roving displacement) and on compliance resolution (with fixed and roving displacement) has not been published before. We found that the just-noticeable-difference (*JND*) for length is roughly 1.0 *mm* for the reference length 10 *mm* and increases to 2.4 *mm* when the reference length increases to 80 *mm*. The force *JND* (with fixed displacement) is 5-10% of the reference force and essentially independent of reference force, displacement, and initial finger span. The compliance *JND* (with fixed displacement) is 5-15% of the reference compliance and roughly independent of displacement. Roving displacement substantially increases the *JND* for both force and compliance discrimination.

INTRODUCTION

The general purpose of this work is to characterize, understand, and model the human's ability to recognize and manipulate objects manually. We want to achieve this goal both as an end in itself and as background for the design of improved robots and human-machine interfaces. Although the specific object properties that are important in a given task will depend upon the detailed nature of the task, the properties of length, force, and compliance are clearly fundamental.

We used the finger-span method to study length discrimination, and active finger motion to study force and compliance discrimination. All our experiments involve both cutaneous and proprioceptive sensory systems. Additional information about our work on the resolution of length and force (but not compliance), including comparisons with previous results, can be found in Durlach et al. (1989) and Pang et al. (1991).

METHODS

Experimental Apparatus

The apparatus used in the length-resolution experiments is shown in Figure 1. A vernier caliper with a digital readout was modified to accept two rectangular pads defining the length to be estimated and against which the thumb and forefinger were placed in order to make the estimate.

The apparatus used in force and compliance resolution experiments is shown in Figure 2. The apparatus had two parallel plates, one was fixed and a second could be moved along a linear track perpendicular to the plates. The subject grasped the two plates between the thumb and the forefinger (with the thumb on the movable plate) and squeezed the movable plate toward the fixed plate. The control algorithm was designed so that the force resisting the squeeze was either constant over the displacement (for force discrimination experiments) or increased linearly with the displacement (for compliance discrimination experiments). Two methods of terminating the push were employed. In one case (denoted MW: mechanical wall), the push was terminated by a rigid stop (i.e., for all practical purposes, the resistance force increased to infinity at the terminal span). In the other case (denoted EC: electrical cliff), the mechanical wall was replaced by an electrical cliff (i.e., the resistive force dropped to approximately zero at the terminal span).

Psychophysical Methods

All experiments used a single-interval forced-choice discrimination paradigm with trial-by-trial correct-answer feedback. For each experiment,

(a) there are two admissible signal sources S_1 (the reference: L_0 for length, F_0 for force, and C_0 for compliance) and S_2 (the reference plus increment: $L_0+\Delta L$, $F_0+\Delta F$, and $C_0+\Delta C$);
(b) there are two admissible responses R_1 and R_2;
(c) on each trial, the experimenter presents S_1 or S_2 randomly with equal a priori probabilities;
(d) the subject is instructed to respond R_1 when the signal arises

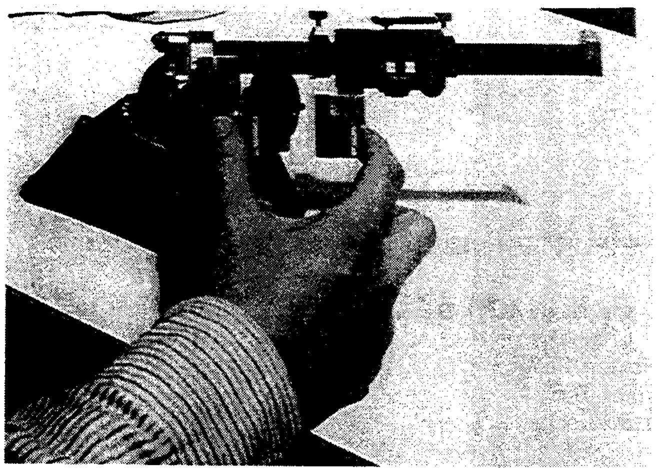

Figure 1. The apparatus used to measure manual length resolution.

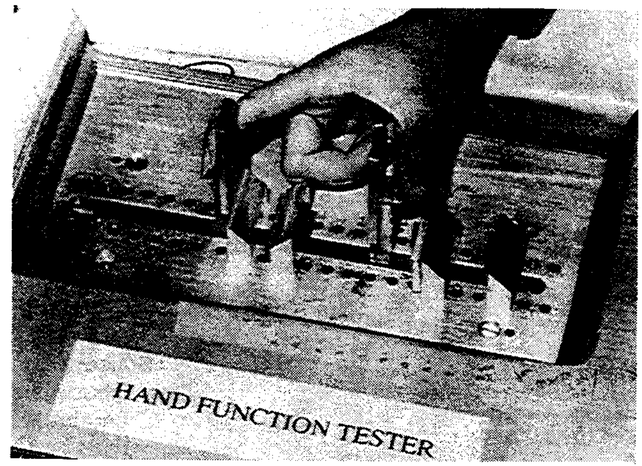

Figure 2. The electromechanical device used to measure manual force and compliance resolution.

from source S_1, and R_2 when the signal arises from source S_2;

(e) the subject is told the correct answer after each response.

Appropriate measures were taken to eliminate possible visual and/or auditory cues from the experimental apparatus. Each experimental run consisted of roughly 60 trials and each experiment employed three or more subjects.

The force and compliance discrimination experiments used both fixed-displacement and roving-displacement paradigms. With the fixed-displacement paradigm, the pushing distance D was kept constant throughout an experimental run. With the roving-displacement paradigm, one of several predetermined D was selected with equal *a priori* probability for each trial. The subject's task was still to discriminate F_0 from $F_0+\Delta F$ (in the case of force discrimination), or C_0 from $C_0+\Delta C$ (in the case of compliance discrimination), despite changes in D from trial to trial. Both the MW and the EC termination methods can be used with fixed-displacement experiments. Only the EC termination method can be used with roving-displacement experiments. Early results comparing the MW and EC termination methods (using the fixed-displacement paradigm) showed that the choice of method had essentially no effect on performance. In general, we used MW for the fixed-displacement paradigm and EC for the roving-displacement paradigm.

Data Processing

All the discrimination data were processed in the same way. For the single-interval forced-choice discrimination paradigm we used, it is assumed that

(a) Each signal presentation results in the generation of a perceptual variable X.

(b) X is a scalar random variable, referred to as the "decision variable", with statistics that are dependent on the stimuli S_1 and S_2, and are described completely by the conditional probability density functions $p_x(X/S_1)$ and $p_x(X/S_2)$. In particular, the statistics are independent of the a priori probabilities and payoffs, and the trials of the experiment are statistically independent.

(c) The probability density functions $p_x(X/S_1)$ and $p_x(X/S_2)$ are Gaussian with means M_1 and M_2 and variances $\sigma_1^2=\sigma_2^2=\sigma^2$.

(d) There exists a fixed cut-off value Q (the "response criterion") on the X axis.

(e) The subject responds R_1 if and only if $X<Q$, and R_2 if and only if $X \geq Q$.

A 2x2 stimulus-response matrix was obtained from each run with the entries indicating the number of times S_i was presented and the subject responded R_j (i,j=1,2). This matrix was processed to obtain estimates of the sensitivity index d' and the response bias β (e.g., see Berliner & Durlach, 1973).

d' is defined as the difference between the means divided by the square root of the variance:

$$d' = (M_2 - M_1)/\sigma, \qquad (1)$$

and β is defined as the deviation of the response criterion (Q) from the midpoint between the two means $[(M_2+M_1)/2]$ divided by the square root of the variance:

$$\beta = [Q-(M_2+M_1)/2]/\sigma. \qquad (2)$$

The condition $\beta=0$ corresponds to unbiased response behavior and, given such behavior, the condition $d'=1$ corresponds to approximately 75% correct performance. Generally speaking, the values of d' in our studies were found to be roughly proportional to the increment being discriminated. Thus, for example, in the force experiments, the values of d' were found to be roughly proportional to the force increment ΔF, or, for fixed reference force F_0, to the fraction $\Delta F/F_0$. Given this proportionality, performance can be summarized by the proportionality constant

$$\delta' = d'/(\Delta F/F_0) \qquad (3)$$

averaged over $\Delta F/F_0$. If the just-noticeable-difference (the *JND*) is defined by the performance threshold $d'=1$ and denoted $(\Delta F)_0$, then $(\Delta F)_0/F_0$, the just noticeable difference in percentage [denoted *JND*(%)] is simply the reciprocal of average δ'.

Weber's law states that the *JND*(%) is constant over the reference value. Thus, for example, in the force experiments, Weber's law means that $(\Delta F)_0/F_0$ is constant over different values of the reference force F_0. It was found that the length discrimination results violate Weber's law; thus they are expressed in terms of the *JND* $(\Delta L)_0$ as a function of reference length L_0.

When the bias β is negligible compared to d', the *JND* results completely characterize the data. Such was the case with data from the length discrimination experiments and from the force and compliance discrimination experiments with fixed displacement. The bias data from force and compliance discrimination experiments with roving displacement are not negligible and seem to be a function of displacement D. These bias data are shown below.

RESULTS

Discrimination Of Length

The dependence of the length JND $(\Delta L)_0$ on reference length L_0 is shown in Figure 3[1]. The different symbols represent data for four different subjects and for the average over subjects. The curvilinear fit is given by

$$JND(mm) = (L_0 / 4.3)[-0.250 \log L_0 + 0.598]. \quad (4)$$

The RMS deviation of the average data from this curve is 0.003 *mm*. Overall, the length JND $(\Delta L)_0$ is roughly 1.0 *mm* for the reference length 10 *mm* and increases monotonically to 2.4 *mm* when the reference length increases to 80 *mm*. These data clearly violate Weber's law. The JND $(\Delta L)_0$ is not linearly proportional to the reference length L_0: $(\Delta L)_0/L_0$ was 8.1% for L_0=10 *mm*, 4.6% for L_0=40 *mm*, and 2.8% for L_0=80 *mm*. Moreover, the data, as well as Eqn.4, suggest that $(\Delta L)_0$ approaches a constant.

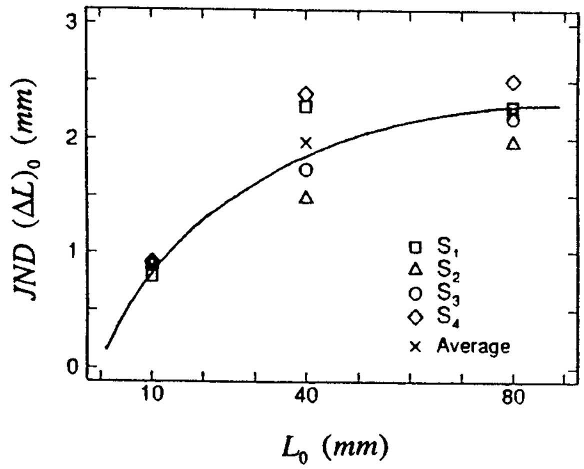

Figure 3. Dependence of the JND $(\Delta L)_0$ on reference length L_0. The different symbols represent data for the different subjects and for the average over subjects. The curvilinear fit is given by Equation 4.

Discrimination Of Force (Fixed D)

The results on the dependence of the force $JND(\%)$ on the reference force F_0, the initial finger-span S, and the pushing distance D, are shown in Figures 4-6[2]. According to the data shown in Fig.4, the force $JND(\%)$ is roughly independent of F_0, and thus satisfies Weber's law, over the range $2.5 \leq F_0 \leq 10.0$ *Newton* . According to the data shown in Fig.5, the force $JND(\%)$ is roughly independent of S over the range $45 \leq S \leq 125$ *mm*. According to the data shown in Fig.6, the force $JND(\%)$ is roughly independent of D over the range $5 \leq D \leq 30$ *mm* for MW termination. The data obtained using the EC termination are similar to those in Figure 6.

In general, we can say that the force $JND(\%)$ is essentially independent of all the parameter variables tested and lies in the range 5-10%[3].

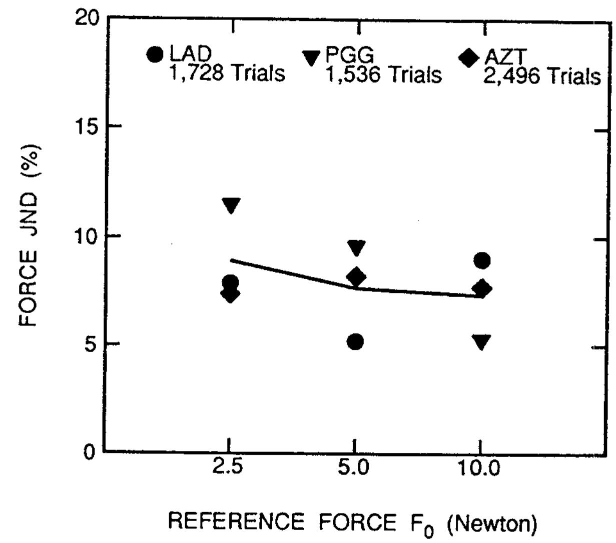

Figure 4. Force $JND(\%)$ versus reference force F_0. Solid line connects means of data points. Pushing distance D was 20 *mm*, initial finger-span S was 105 *mm*, and termination was by mechanical wall (MW). Average JND is 8%. The horizontal axis is logarithmic. Subjects and number of trials for each subject are specified on the graph.

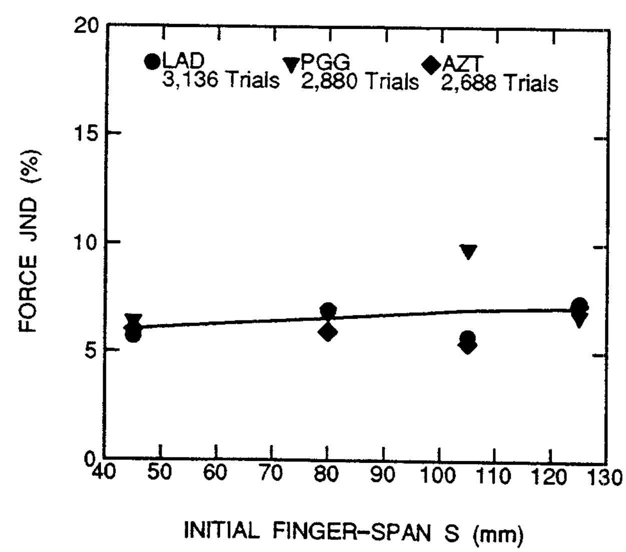

Figure 5. Force $JND(\%)$ versus initial finger-span S. Solid line connects means of data points. Reference force F_0 was 5 *Newton*, pushing distance D was 10 *mm*, and termination was by mechanical wall (MW). Average JND is 7%. Subjects and number of trials for each subject are specified on the graph.

---

[1] To examine how performance improved with practice, we examined the dependence of the proportionality constant $\delta' = d'/\Delta L$ on session number. Specifically, for each subject and each value of L_0, we computed the normalized quantity $\delta'/\overline{\delta'}$, where δ' was computed for each session and $\overline{\delta'}$ was the average of δ' over the total number of sessions. Out of the four subjects tested, only the subject using the nondominant hand showed significant improvement with session number. (For further details, see Figure 2 in Durlach et al., 1989.)

[2] In order to examine the variability of the d' estimates, we compared the variance of our empirical d' measurements (based on 64-trial runs) with the variance derived from an appropriate computer simulation of a Bernoulli process (for details, see Table B1 in Pang et al., 1991). The ratio of the experimental standard deviation to the simulated standard deviation, averaged over 4 values of $\Delta F/F_0$ and 3 subjects for one set of parameter values (F_0=5 *Newton*, S=105 *mm*, D=20 *mm*, MW, $\Delta F/F_0$=5%, 10%, 15%, and 20%), was 1.16. In view of the long time period over which these data were collected, we regard these data as supportive of our assumptions that the trials were independent and constituted a Bernoulli process with time-invariant statistical characteristics.

[3] It is possible, of course, that detailed statistical tests might show a small statistically significant dependence in these data. However, at this stage of our work, we are only interested in large (scientifically significant) effects; we do not care whether effects that are small in magnitude are statistically significant.

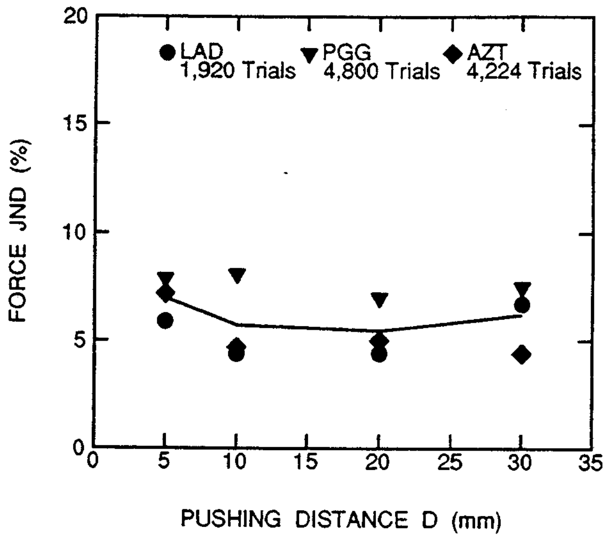

Figure 6. Force *JND(%)* versus pushing distance *D*. Solid lines connect means of data points. Reference force F_0 was 5 *Newton*, initial finger-span *S* was 105 *mm*, and termination was by mechanical wall (MW). Average *JND* is 6%. Subjects and number of trials for each subject are specified on the graph. Similar results were obtained for termination by electrical cliff (EC).

Discrimination Of Compliance (Fixed *D*)

According to the data shown in Fig.7, the compliance *JND* is roughly independent of D over the range $15 \leq D \leq 35$ *mm* and lies in the range 5-15%[4].

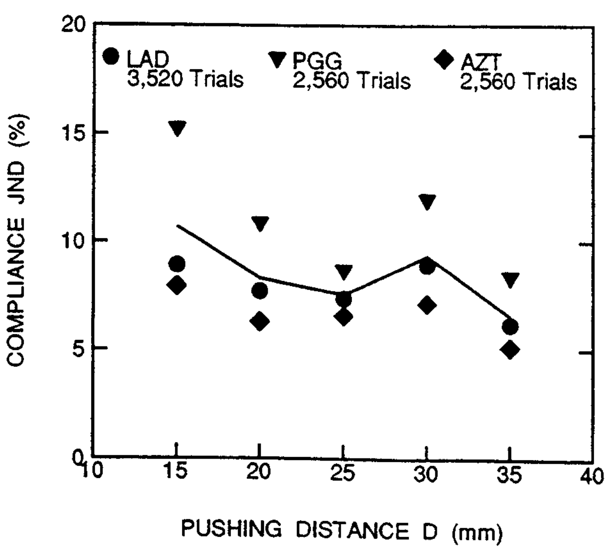

Figure 7. Compliance *JND(%)* versus pushing distance *D*. Solid lines connect means of data points. Reference compliance C_0 was 4 *mm/N*, initial finger-span *S* was 105 *mm*, and termination was by mechanical wall (MW). Average *JND* is 8%. Subjects and number of trials for each subject are specified on the graph.

[4] In order to examine the variability of the d' estimates, we again compared the variance of our empirical d' measurements with the variance derived from a Bernoulli simulation. The ratio of the experimental standard deviation to the simulated standard deviation, averaged over 4 values of $\Delta C/C_0$ and 3 subjects for one set of parameter values (C_0=4 *mm/N*, D=25 *mm*, S=105 *mm*, $\Delta C/C_0$ =5%, 10%, 15%, and 20%), was 1.24.

The Effect Of Roving *D* On Compliance And Force Discrimination

In the compliance discrimination tests with fixed *D*, it is possible for the subject to discriminate compliance by merely discriminating terminal force. In order to eliminate this possibility, further compliance discrimination tests were performed with roving *D*. The values of roving *D* were 15, 20, 25, 30, and 35 *mm*.

Roving *D* was found to have a strong degrading effect on the ability to discriminate compliance (see Fig.8). Whereas the average compliance *JND* for the fixed-displacement experiment was 8% (comparable to the force *JND*), the average compliance *JND* for the roving-displacement experiment was 22%.

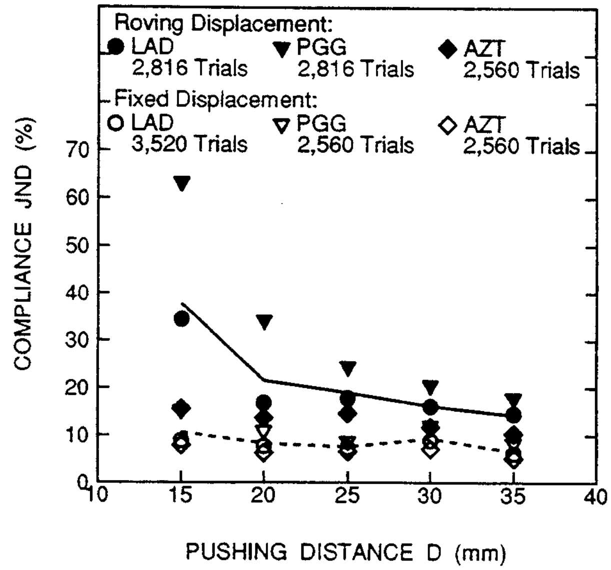

Figure 8. Compliance *JND(%)* versus pushing distance *D*. Filled and open symbols indicate data points from roving- and fixed-displacement experiments, respectively. Solid and dashed lines connect means of data points from roving- and fixed-displacement experiments, respectively. For both experiments, reference compliance C_0 was 4 *mm/N*, initial finger span was 105 *mm*. Average *JND*s are 22% and 8% for roving- and fixed-displacement experiments, respectively. Subjects and number of trials for each subject are specified on the graph.

In view of the strong effect of roving *D* that we found for compliance discrimination, we then also examined the effect of roving *D* for force discrimination. The values of roving *D* were 10, 20, and 30 *mm*. (New data were collected using the fixed-displacement paradigm for comparison). As was the case for compliance discrimination, the degrading effect of roving *D* on force discrimination was substantial (see Fig.9).

The Work Hypothesis

In an attempt to understand the effects of roving *D* using existing data, we reprocessed the data using a "Work Hypothesis": we assumed that the subject responded "bigger force" or "smaller compliance" when the work required to push the metal bar through the given displacement was greater than some fixed criterion value of work. To the extent that this hypothesis is correct (i.e., that the subject was choosing a response on the basis of work rather than force or compliance), one would expect to obtain a higher d' by scoring the responses as correct or incorrect on the basis of work rather than force or compliance. (The implications of this hypothesis for response bias are considered below.)

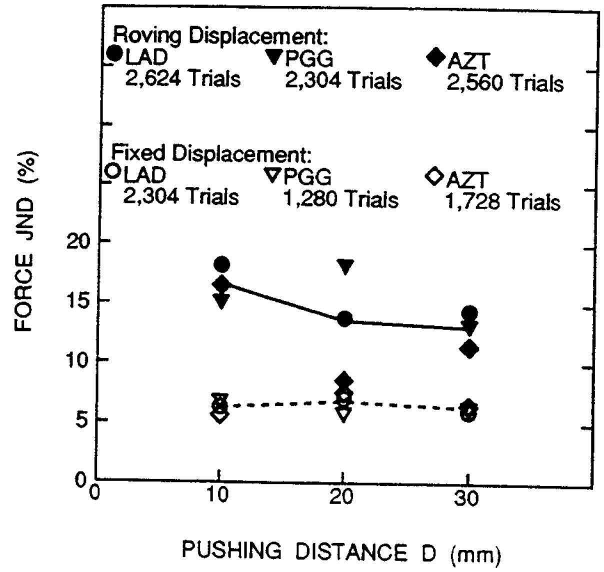

Figure 9. Force *JND(%)* versus pushing distance *D*. Filled and open symbols indicate data points from roving- and fixed-displacement experiments, respectively. Solid and dashed lines connect means of data points from roving- and fixed-displacement experiments, respectively. For both experiments, reference force F_0 was 5 *Newton*, initial finger span was 105 *mm*. Average *JNDs* are 14% and 6% for roving- and fixed-displacement experiments, respectively. Subjects and number of trials for each subject are specified on the graph.

For the compliance discrimination experiments, the Work Hypothesis states that the subject responds C_0 when $W > W_T$, and $C_0 + \Delta C$ when $W \le W_T$, where $W = D^2/(2C)$ is the work associated with the manual squeezing action and W_T is the criterion value of work. For simplicity, we assumed that W_T was chosen by the subject to bisect the total work range in the experiment.

If a subject discriminated perfectly using compliance as cue, d' based on compliance would be ∞ and d' based on the Work Hypothesis would be 0.36. If a subject (partially) based his/her response on work, then d' based on the Work Hypothesis should be higher than 0.36.

Table 1 shows the data reprocessed according to the Work Hypothesis in terms of d' as a function of $\Delta C/C_0$. For comparison, corresponding pooled data are also shown. These data are the same as those plotted in Figure 8, except that they're pooled over D.

Table 1
Results of compliance discrimination experiments reprocessed using the Work Hypothesis. Corresponding pooled data are shown for comparison. Reference compliance C_0 was 4 *mm/N*.

$\Delta C/C_0$	d' Work Hypothesis			d' Compliance Data Pooled Over D		
	LAD	PGG	AZT	LAD	PGG	AZT
10%	1.63	0.79	0.77	0.26	0.28	0.63
20%	1.47	0.93	0.89	0.86	0.81	1.38
30%	1.60	0.61	0.82	1.05	1.13	2.10
40%	1.41	0.91	0.90	1.65	1.25	2.39

The d's from subject LAD using the Work Hypothesis are higher than those without the Work Hypothesis (except for $\Delta C/C_0 = 40\%$). This supports the hypothesis that work, instead of compliance, was the variable being discriminated. This hypothesis is also supported by the approximate constancy of d' over the variation in $\Delta C/C_0$, because the range of W is essentially constant for the different $\Delta C/C_0$ values[5]. PGG's and AZT's results with the Work Hypothesis are significantly larger than 0.36, but do not support the Work Hypothesis as strongly as those of LAD.

For force discrimination experiments, the Work Hypothesis states that subject responds F_0 when $W < W_T$, and $F_0 + \Delta F$ when $W > W_T$, where $W = F \cdot D$ is the work associated with the manual squeezing action and, again, W_T is chosen to lie in the center of the work range. If a subject discriminated perfectly using force as cue, d' based on the Work Hypothesis would be 0.61.

Table 2 shows the data reprocessed according to the Work Hypothesis in terms of d' as a function of $\Delta F/F_0$. For comparison, corresponding pooled data are also shown. Again, the Work Hypothesis is strongly supported by the fact that (1) the d's from subject LAD using the Work Hypothesis are higher than those without the Work Hypothesis; and (2) these d's are approximately constant (the range of W is, again, almost constant for the different $\Delta F/F_0$ values[6]). PGG's and AZT's results with the Work Hypothesis are less supportive of the Work Hypothesis because they are less than or close to 0.61. Overall, work seems to have played a bigger role in the compliance experiments than in the force experiments. As will be seen below, this is also reflected in the bias data.

Table 2
Results of force discrimination experiments reprocessed using the Work Hypothesis. Corresponding pooled data are shown for comparison. Reference force F_0 was 5 *Newton*.

$\Delta F/F_0$	d' Work Hypothesis			d' Force Data Pooled Over D		
	LAD	PGG	AZT	LAD	PGG	AZT
5%	1.13	0.70	0.38	0.13	0.33	0.38
10%	1.49	0.54	0.76	0.64	0.53	0.82
15%	1.46	0.63	0.28	0.72	0.79	1.39
20%	1.19	0.76	0.68	1.16	1.52	1.88

Response Bias In Compliance And Force Experiments

With the fixed-displacement paradigm, there was negligible response bias β for both the compliance and force discrimination tasks. With the roving-displacement paradigm, however, substantial response bias was found in both the compliance and the force

[5] The ranges of W for the different $\Delta C/C_0$ values were: $W \in [25.6, 153.1]$ *N·mm* when $\Delta C/C_0 = 10\%$; $W \in [23.4, 153.1]$ *N·mm* when $\Delta C/C_0 = 20\%$; $W \in [21.4, 153.1]$ *N·mm* when $\Delta C/C_0 = 30\%$; and $W \in [20.1, 153.1]$ *N·mm* when $\Delta C/C_0 = 40\%$. These ranges were computed as follows. For each $\Delta C/C_0$ value, 5 values of roving D were used for both stimuli C_0 and $C_0 + \Delta C$. Thus 10 values of W were computed for each $\Delta C/C_0$ value. For instance, for $\Delta C/C_0 = 10\%$, the W values were 28.1 & 25.6 *N·mm* (for D=15 *mm*); 50 & 45.5 *N·mm* (for D=20 *mm*); 78.1 & 71 *N·mm* (for D=25 *mm*); 112.5 & 102.3 *N·mm* (for D=30 *mm*); and 153.1 & 139.2 *N·mm* (for D=35 *mm*). Thus, the range for $\Delta C/C_0 = 10\%$ was $W \in [25.6, 153.1]$ *N·mm*. The criterion W_T was chosen to lie between 71 and 78.1 *N·mm*. The ranges of W for other $\Delta C/C_0$ values were computed in a similar way.

[6] The ranges of W for the different $\Delta F/F_0$ values were: $W \in [50, 157.5]$ *N·mm* when $\Delta F/F_0 = 5\%$; $W \in [50, 165]$ *N·mm* when $\Delta F/F_0 = 10\%$; $W \in [50, 172.5]$ *N·mm* when $\Delta F/F_0 = 15\%$; and $W \in [50, 180]$ *N·mm* when $\Delta F/F_0 = 20\%$. These values were computed in the same fashion as those for the compliance data except, of course, that the formula for computing work was different. In the force experiment, work was computed according to the formula $W = F \cdot D$, whereas in the compliance experiment, work was computed according to the formula $W = D^2/(2C)$.

experiments (see Fig.10). These biases depend strongly on the pushing distance D, but were independent of the compliance and force increments ($\Delta C/C_0$ and $\Delta F/F_0$, respectively).

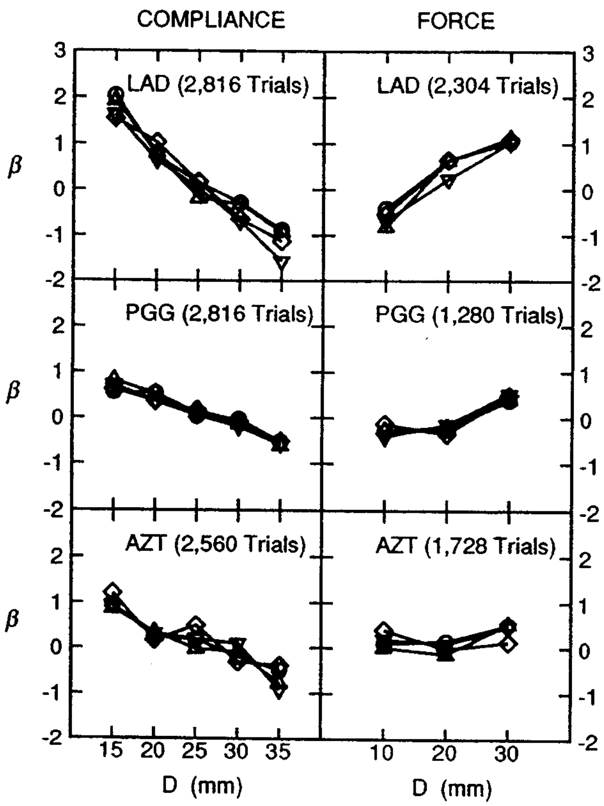

Figure 10. Bias results from compliance and force discrimination experiments with roving displacements. The four symbols in the compliance column are associated with the four $\Delta C/C_0$ values: 10, 20, 30 and 40%. The four symbols in the force column are associated with the four $\Delta F/F_0$ values: 5, 10, 15 and 20%. Subjects and number of trials for each subject are specified on the graph.

The sign of the response bias β is interpreted as follows. For compliance discrimination, a positive β means that the subject tended to respond $C_0 + \Delta C$ too often (i.e., the subject responded as if the object was more compliant). According to Figure 10, when the displacement D was small, the subject tended to judge the object being squeezed as softer. This is consistent with the Work Hypothesis.

For force discrimination experiments, a positive β means that the subject tended to respond $F_0 + \Delta F$ too often (i.e., the subject responded as if more force was exerted on the thumb). According to Figure 10, when the displacement was large, the subject tended to judge the force as greater. This is also consistent with the Work Hypothesis.

Note that, as in our analysis of the d' results, subject LAD's data support the Work Hypothesis more strongly than PGG's or AZT's.

CONCLUDING REMARKS

Our data on length discrimination and on force discrimination using fixed D are similar to those obtained by previous investigators (see the discussions in Durlach et al., 1989, and Pang et al., 1991). Our results on force discrimination using roving D and on compliance discrimination using either fixed or roving D have not been compared to those from previous investigators because we have not been able to find any appropriate previous data for comparison.

A common feature of all our experiments is the involvement of both the kinesthetic/proprioceptive system and the cutaneous sensory system. The issue of how much information is obtained through each of these sensory channels has a long and controversial history, as discussed in Clark & Horch (1986). The experiments reported here do not help separate out these factors.

The fact that our length discrimination data violate Weber's law is not surprising since finger span is only remotely related to underlying physiological parameters such as muscle length, joint position, and skin stretch. (In this connection, it is interesting to note that we have preliminary data indicating that the *JND* in joint position is roughly independent of reference joint position). On the other hand, the invariance of the Weber fraction for force discrimination using fixed displacement is quite remarkable given the number and ranges of variables tested. Of particular interest to us is the invariance of the Weber fraction over the variable D (see Figure 6). Apparently, the extra samples of force information that are available when D is large do not enhance the discrimination. In other words, there is no evidence that the subject integrates the force information over the displacement in these experiments. Unfortunately, our apparatus did not permit these experiments to be conducted for values of D less than 5 *mm*. Obviously, as D approaches zero, the Weber fraction must go to infinity.

Perhaps the most interesting feature of our results concerns the dramatic degradation in performance associated with randomization of D. Because of the large amounts of practice available to our experimental subjects (as indicated on the graphs, thousands of trials were involved), it is difficult to believe that this degradation can be explained solely in terms of training. Clearly, further work is required to understand this degradation.

ACKNOWLEDGMENTS

This work was partly supported by a grant from the National Institutes of Health (Grant No.5 R01 DC00126) and a grant from the Office of Naval Research (Grant No.00014-90-J-1935). We also wish to thank Drs. Mandayam Srinivasan and William M. Rabinowitz for their comments on an earlier manuscript of this paper.

REFERENCES

Berliner, J. E., and Durlach, N. I., 1973, "Intensity perception: IV. Resolution in roving-level discrimination," *Journal of the Acoustical Society of America*, Vol.53, pp.1270-1287.

Clark, F. J., and Horch, K. W., 1986, "Kinesthesia," In L. R. Boff, L. Kaufman, and J. P. Thomas (Eds.), *Handbook of perception and human performance* (Vol.1, chap.13), New York: Wiley.

Durlach, N. I., Delhorne, L. A., Wong, A., Ko, W. Y., Rabinowitz, W. M., and Hollerbach, J., 1989, "Manual discrimination and identification of length by the finger-span method," *Perception & Psychophysics*, Vol.46, pp.29-38.

Pang, X. D., Tan, H. Z., and Durlach, N. I., 1991, "Manual discrimination of force using active finger motion," *Perception & Psychophysics*, Vol.49, pp.531-540.