

## THE MANUAL RESOLUTION OF VISCOSITY AND MASS

**G. Lee Beauregard**

Department of Biomedical Engineering  
Boston University  
Boston, MA

**Mandayam A. Srinivasan**

**Nathaniel I. Durlach**

Department of Mechanical Engineering and  
Research Laboratory of Electronics  
Massachusetts Institute of Technology  
Cambridge, MA

### ABSTRACT

Psychophysical experiments measuring human resolution in manually discriminating viscosity and mass were performed while the associated force and displacement variations over time generated by the subjects were simultaneously recorded. The experiments were performed on a computer controlled electromechanical device called the Linear Grasper. For viscosity the Just Noticeable Difference (JND), a measure of human sensory resolution, was found to be 13.6% for a reference viscosity of 120 Ns/m. For mass, the JND was approximately 21% for a reference mass of 12 Kg. Motor performance data indicated that subjects applied average mean grasping forces ranging from 3.5 to 9.5 N with squeeze velocities of 35 mm/sec to 80 mm/sec in viscosity discrimination experiments and accelerations of 350 to 700 mm/sec<sup>2</sup> in mass discrimination experiments. Analysis of the motor performance data indicated that in both discrimination experiments, the subjects' average mean applied force increased with stimulus intensity, while the average mean grasping velocity decreased with stimulus intensity in the viscosity discrimination experiments and the average mean grasping acceleration decreased with stimulus intensity in the mass discrimination experiments. This study is part of an ongoing research program to better understand human haptic perception of physical properties of objects and to provide human factors data for the improved design of haptic interfaces for virtual environments and teleoperation.

### INTRODUCTION

This research is part of an ongoing effort concerned with the manual perception of physical properties of objects. Previous work has explored the manual resolution of length, constant force and mechanical compliance (Durlach et. al., 1989; Pang et. al., 1991; Tan et. al. 1992; Tan et. al, 1995). The present work

is concerned with the manual resolution of the fundamental mechanical properties of viscosity and mass along with an investigation of the relationship between the associated sensory and motor abilities of the haptic system. The overall goal of these studies is to measure the human ability to discriminate and identify objects manually and to gain a deeper understanding of the underlying sensorimotor mechanisms. It is hoped that these quantitative investigations of the human haptic system will not only facilitate the development of haptic interfaces better matched to the capabilities of the human operator but also benefit the design of autonomous robots that must make use of manual sensing and manipulation.

In the first paper of this series, Durlach et al, (1989) explored the manual resolution of object length and reported that the Just Noticeable Difference (JND) increased monotonically from approximately 1 mm at a reference length of 10 mm to 2.4 mm for a reference length of 80 mm. In the second paper, Pang et al, (1991) found that the JND for a constant resistive force to be roughly 7% over a range of reference forces and fixed displacements. The ability to manually discriminate compliance has not been found to be so consistent. Over a series of fixed squeezing distances, Tan et al, (1992) measured compliance JND to be about 8%, but when possible terminal force and mechanical work cues were partly disassociated by randomly varying the squeezing distance, JND increased to 22%. Furthermore, when mechanical work cues were totally eliminated and terminal force cues were reduced, compliance JND was as high as 99% (Tan et al, 1995). This paper reports the results of viscosity and mass discrimination experiments based on the same experimental paradigm and apparatus used in the force and compliance discrimination experiments.

Jones and Hunter have also performed a series of experiments to measure the perception of force, stiffness, viscosity and limb movement using a contralateral limb-matching procedure with

the forearms (Jones, 1989; Jones & Hunter, 1990; Jones & Hunter, 1992; Jones & Hunter, 1992b; Jones & Hunter, 1993). They reported differential sensory thresholds of 7% and 8% for force and limb movement respectively. In analyzing thresholds for stiffness and viscosity, they found significant loss in perceptual resolution compared to that for force. Their results showed an average differential threshold of 23% for stiffness and 34% for viscosity. The magnitude of the reference stiffness ranged from 0 to 6260 N/m and reference viscosity values varied from 2 Ns/m to 1024 Ns/m in their experiments. They hypothesized that the loss in resolution was because force cues had to be integrated with limb position and velocity information.

In mass discrimination experiments carried out zero-gravity conditions, Ross et al. (1984), reported that the subjects' Weber fractions for mass were approximately double their Weber fractions for weight (0.083 - 0.153) obtained for the same objects in an 1-G environments. In related studies involving the perception of the moment of inertia, investigators have reported differential sensory thresholds ranging from 28% (Kreifeldt and Chuang, 1979) to 113% (Ross and Benson, 1986).

Since all active manual interactions, including those in sensory dominant tasks, involve the human motor system, we are also interested in characterizing the motor behavior used by our subjects during the discrimination process. Particularly we are interested in measuring and quantifying the applied forces, velocities and accelerations used by subjects during the experiments. In addition to providing useful human factors data, this information is expected to provide additional insight into the process of manual discrimination since sensory and motor abilities together govern manual resolution under active touch conditions.

## EXPERIMENTAL APPARATUS

The apparatus used in the experiments is shown in Figure 1. It is the same apparatus utilized by Pang et. al. (1991) in force discrimination experiments and Tan et. al. (1995) in compliance discrimination experiments. The device, called the Linear Grasper is a computer controlled electromechanical device that can exert bi-directional forces along a linear track. Subjects interact with the apparatus by grasping and squeezing two parallel aluminum plates with their thumb and forefinger which results in the travel of one of the plates along the linear track towards the plate whose position is fixed. In response to this motion of the plate, the Linear Grasper was programmed to produce a resisting force proportional to velocity in the viscosity discrimination experiments and acceleration in the mass discrimination experiments. Finger motion was halted when the moveable plate pushed by the thumb came into contact with a mechanical stop placed at a fixed distance along the linear track.

Force, position, velocity and acceleration were measured by sensors attached to the moveable finger plate assembly. The force sensor was a BLH semiconductor strain gage, the position sensor was a noncontacting FLDT by Sunpower, the velocity sensor was an inductive type sensor from Transducer Systems and the acceleration was measured with an piezoresistive type accelerometer from IC Sensors. The output signals from all the

sensors were signal conditioned and sampled through a 12-bit Metrabyte A/D converter at 1 KHz by an IBM compatible 80486DX personal computer. The force signal had a resolution of  $\pm 0.05$  Newtons, the position signal had a resolution of  $\pm 0.06$  mm, the velocity signal's resolution was  $\pm 0.05$  mm/sec and the resolution of the acceleration signal was approximately  $\pm 4.0$  mm/sec<sup>2</sup>.



Figure 1: The Linear Grasper

Control software utilized the appropriate velocity or acceleration signal to determine a corresponding output force depending on whether viscosity or mass was being simulated. A calibrated control signal, with a resolution of  $\pm 0.04$  Newtons, was then supplied back to the actuator mechanism of the Linear Grasper through a 12-bit Metrabyte D/A converter and a Techron DC power amplifier. The force/current gain of the motor was constant for the stroke range needed to perform these experiments. Within this stroke range, the motor could be modeled as a second order linear system up to 200 Hz with a strong resonance near 50 Hz. In addition to the programmed force, a frictional force was also present during both sets of experiments, but was always less than 0.5 Newtons.

## EXPERIMENTAL PROCEDURE

Three subjects took part in each experiment with none of the subjects participating in both viscosity and mass discriminations. All subjects, ages 19-23, were right handed with no known hand disorders and used their dominant hand to perform the grasping tasks. All subjects underwent training runs of 1024 trials to ensure that they were comfortable with the device and the experimental procedure.

The emphasis of this study was to explore the relationship between discrimination and motor performance. Thus even though the number of subjects was small, all subjects completed a large number of trials (> 4000) to ensure an adequate amount of motor data (in terms of applied forces, velocities and accelerations) and discrimination data was acquired.

The viscosity and mass discrimination experiments used a one-interval, two-alternative forced choice paradigm. Since subjects were asked to discriminate viscosity or mass, it was possible that their interpretation of the instructions might differ. In order to minimize such differences, trial-by-trial correct response feedback was given to the subjects. During a trial, subjects were presented with one of two possible stimuli. One of the stimuli was the *reference* (e.g.,  $B_0$ ) and the other was the *comparison*, equal to the reference minus an increment (e.g.,  $B_0 - \Delta B$ ). The value of the increment was constant within an experimental run of 64 trials. For each trial, both stimuli had an equal a priori probability of occurring. Upon completion of a trial, the subjects were required to indicate which one of the two stimuli they felt was presented by typing 1 for the larger stimuli or 2 for the smaller stimuli. After the selection was made for each trial, the subjects were provided with correct response feedback.

For each value of the stimulus increment, numerous experimental runs were performed, typically resulting in several hundred trials per subject. The increment was equal to either 10, 20, or 30% of the *reference* in the viscosity discrimination experiments or 10, 20, 30, or 40% of the *reference* in the mass discrimination experiments.

A 2x2 stimulus-response matrix generated from each experimental run was utilized to compute a sensitivity index,  $d'$ , and a response bias,  $\beta$  (See Berliner & Durlach (1973) for a more detailed presentation of psychophysical methods). The sensitivity indices from the experimental runs were used to calculate a commonly accepted measure of sensory resolution, the Just Noticeable Difference (JND) for subjects at each fixed squeezing distance. The response bias data was used to determine if subjects were inclined towards selecting a particular response regardless of which stimulus was presented.

Based on preliminary experiments, a reference viscosity,  $B_0$ , of 120Ns/m was presented in the viscosity discrimination experiments and a reference mass,  $M_0$ , of 12 kg was presented in the mass discrimination experiments. These values were chosen to ensure that applied grasp forces would be generally consistent with those used in the earlier force and compliance discrimination experiments. Both discrimination experiments were performed for fixed squeezing distances of 15, 20, 25, 30 and 35 mm, with the initial finger span between the thumb and forefinger of the subjects set at 105 mm. Determining JNDs for this series of fixed displacements would allow us to directly compare the manual resolution of viscosity and mass over the same range of fixed displacement values that were used in the force and compliance discrimination experiments.

## RESULTS

### Viscosity and Mass Discrimination:

In Figures 2 and 3, the results of the viscosity and mass discrimination experiments are plotted with respect to the various fixed squeezing distances. The overall mean JND for viscosity was  $13.6\% \pm 3.0\%$  and for mass the overall mean JND was  $21.0\% \pm 3.5\%$ . The bias results, presented in Table 1, are small for both discrimination experiments indicating that

the subjects were generally unbiased in their responses.

Viscosity and mass JNDs are respectively double and triple the JNDs of 7% and 8% reported for constant force and mechanical compliance when the squeezing distance was fixed (Pang, et al. 1989; Tan, et al. 1992). Thus it appears that sensitivity to physical properties is diminished when force cues must be combined with derivative based displacement cues. This trend is consistent with the earlier results by Jones and Hunter in their contralateral matching experiments involving the forearm, although the differential threshold values for stiffness and viscosity measured by Jones and Hunter are higher than our JND results.

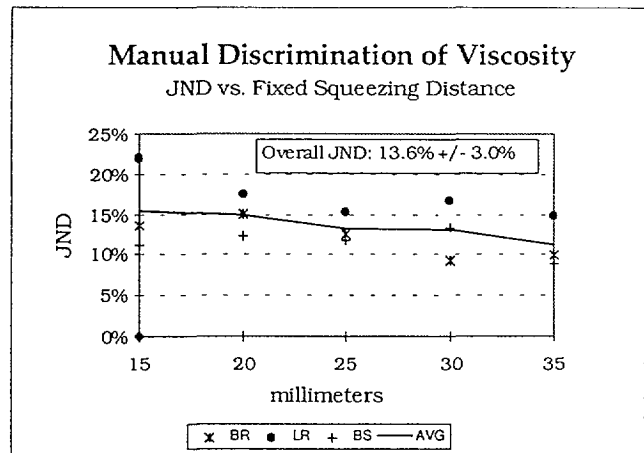


Figure 2: Viscosity Discrimination Results

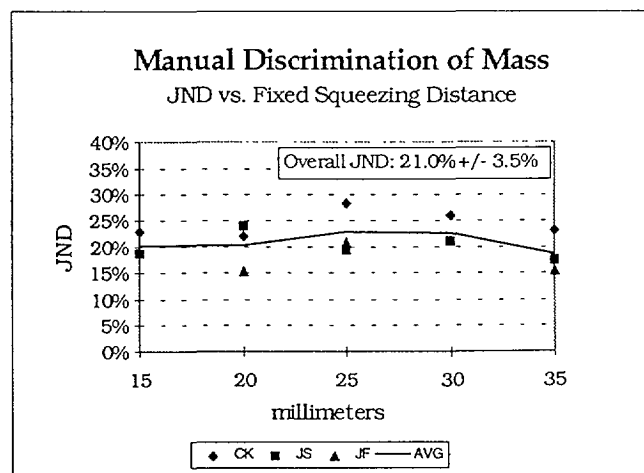


Figure 3: Mass Discrimination Results

### Motor Performance:

Pertinent motor data regarding applied force, squeeze velocity, and acceleration were recorded during the experiments. Summary data plots for the overall averages of these variables are shown in Figures 4-7. These results are based on data sampled every fourth trial over 1600 trials for the viscosity discrimination experiments and over 9344 trials in the mass discrimination experiments. In these plots, force, velocity and acceleration data are plotted against mass and viscosity stimulus

values. The data have been averaged over all subjects and fixed displacements. These results indicate that mean applied force averaged over all subjects ranged from about 5.5 to 7 N in viscosity discrimination and from approximately 4.8 to 5.8N in mass discrimination. For both sets of experiments, the average value of the mean applied force in each trial increased with the stimulus intensity, but with a decreasing gradient. In contrast, average mean velocity values (ranging from 55 mm/sec to 70 mm/sec) and average mean acceleration data (ranging from 450 mm/sec<sup>2</sup> to 700 mm/sec<sup>2</sup>) both decreased with stimulus intensity.

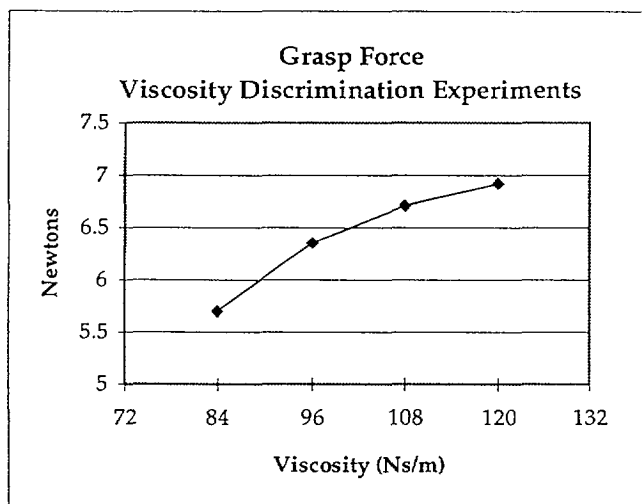


Figure 4: Average Grasp Force vs. Viscosity

A compilation of motor performance data for each subject is presented in Tables 2 and 3 for both discrimination experiments. Both tables present the percent difference between the average mean forces for the reference and the comparison stimuli for each stimulus pair along with the average mean force applied by subjects for the reference stimulus. In addition, Table 2 presents the percent difference in average mean velocity between stimulus pairs in the viscosity discrimination experiments. Similarly in Table 3, the percent difference in average mean acceleration between stimulus pairs in the mass discrimination experiments is presented. In the mass discrimination experiments, results for subjects CK and JF were from data sampled over the course of 3200 trials and the results for JS were based on data sampled over 2,944 trials. In the viscosity discrimination experiments, results for subjects, BS, LR and BR were from data sampled over the course of 576, 576 and 448 trials respectively. In addition to the motor data, the percentage of correct responses for the sampled trials is also shown in the tables.

The data in Tables 2 and 3 indicates that the average force applied varied greatly among the subjects, from approximately 4.2 to 9.6N in the viscosity experiments to 4.2 to 6.7N in the mass experiments. Despite this, there were still many similarities in the subjects' motor performance: (1) The difference in the average mean force for the reference and comparison stimuli was always quite small (less than the force

JND as measured by Pang, et al, 1991) when the percent difference in the mass or viscosity stimuli was below or near the JND, (2) This difference in average mean force generally increased as the difference in stimulus pair increased, (3) The average mean acceleration in the mass experiments and the average mean velocity in the viscosity experiments were always less for the reference stimulus (4) The differences in average mean acceleration and velocity also increased as the difference in stimulus pair increased, and (5) These increases in the percent differences for acceleration, velocity and force were generally correlated with discrimination performance as measured by percent correct.

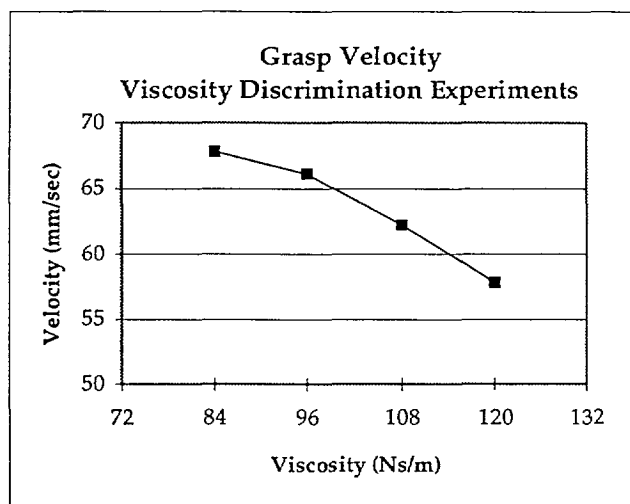


Figure 5: Average Grasp Velocity vs. Viscosity

A preliminary interpretation of these data is that:

- (1) Subjects do *not* discriminate by simply applying a constant force to all stimuli and sensing velocity differences in viscosity discrimination experiments and acceleration in mass discrimination experiments. Because if subjects utilized this strategy then the percent difference in average mean applied force should be less than or equal to force JND for all stimulus pairs, which is clearly not the case.
- (2) Likewise, subjects do *not* appear to discriminate by grasping all stimuli with the same velocity in viscosity discrimination experiments and with the same acceleration in mass discrimination experiments and sensing a corresponding change in the resistive force. This does not appear to be the case because not only is this inconsistent with the velocity and acceleration motor data, but also because viscosity and mass JNDs results are much higher than would be expected if subjects were doing force discrimination.

Since the stimuli are randomly presented in an one interval discrimination task, there is no obvious reason why the percent difference in force has to decrease as the difference in stimuli decreases. Thus, the motor data indicates that subjects use strategies include both force and velocity cues during viscosity discrimination and force and acceleration cues during mass

STIMULUS	SUBJECT	15mm $\beta$	20mm $\beta$	25mm $\beta$	30mm $\beta$	35mm $\beta$
	BR	0.24	0.39	0.33	0.16	0.26
Viscosity	BS	-0.07	0.11	-0.03	0.12	0.11
	LR	0.00	-0.05	-0.03	0.16	-0.01
	JF	0.20	0.07	0.06	0.13	0.20
Mass	JS	0.28	0.10	0.09	0.13	0.17
	CK	0.04	0.01	0.18	0.03	-0.01

Table 1: Response Bias Results For Viscosity And Mass

Subject	$\Delta B/B$	Average Mean Force for the Reference	Percent Difference in Avg. Mean Forces	Percent Difference in Avg. Mean Velocity	Percent Correct
BS	30%	4.23N	16.09%	-19.86%	97.9%
BS	20%	4.30N	8.44%	-14.45%	87.5%
BS	10%	4.30N	5.63%	-4.86%	77.1%
LR	30%	9.60N	18.18%	-16.89%	91.7%
LR	20%	9.60N	9.12%	-13.61%	70.8%
LR	10%	9.30N	-2.35%	-13.72%	52.1%
BR	30%	6.15N	18.16%	-16.91%	58.3%
BR	20%	7.75N	4.12%	-19.85%	78.1%
BR	10%	7.00N	5.03%	-5.52%	58.3%

Table 2: Motor Performance Data During Viscosity Discrimination

Subject	$\Delta M/M$	Average Mean Force for the Reference	Percent Difference in Avg. Mean Forces	Percent Difference in Avg. Mean Acceleration	Percent Correct
JS	40%	6.29N	15.57%	-40.71%	82.81%
JS	30%	6.45N	11.71%	-26.31%	75.96%
JS	20%	6.57N	4.17%	-19.79%	72.92%
JS	10%	6.10N	-2.51%	-13.90%	52.78%
JF	40%	4.16N	11.81%	-46.99%	88.02%
JF	30%	4.26N	14.02%	-22.82%	78.85%
JF	20%	4.28N	2.44%	-21.95%	69.23%
JF	10%	4.21N	0.04%	-11.06%	61.46%
CK	40%	6.36N	12.43%	-45.96%	83.33%
CK	30%	6.42N	9.27%	-29.61%	69.23%
CK	20%	6.49N	5.34%	-18.33%	61.06%
CK	10%	6.68N	2.42%	-8.42%	59.90%

Table 3: Motor Performance Data During Mass Discrimination

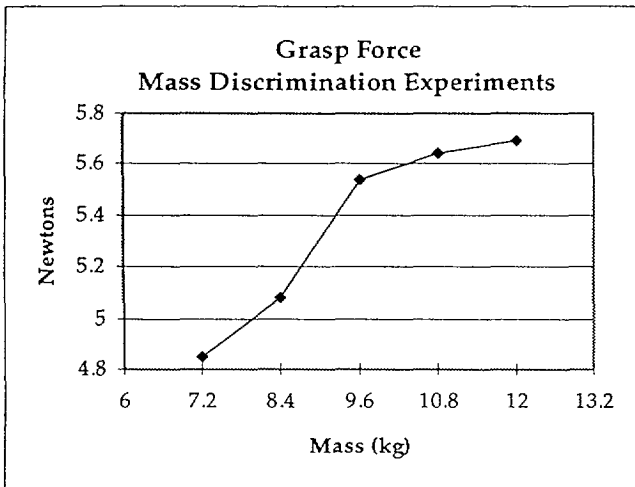


Figure 6: Average Grasp Force vs. Mass

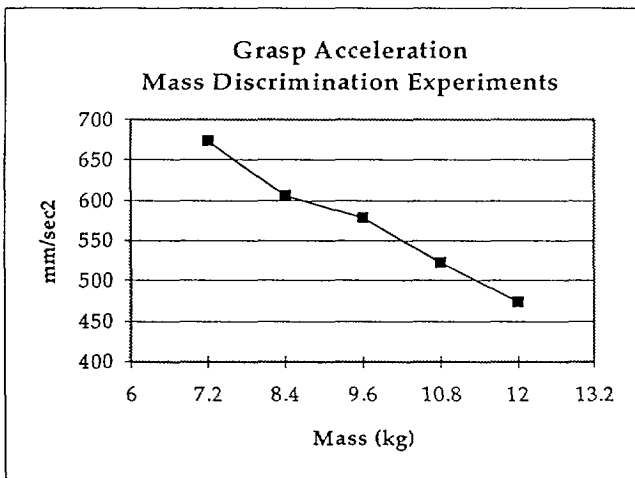


Figure 7: Average Grasp Acceleration vs. Mass

## CONCLUSIONS

The JNDs of viscosity and mass were measured to be about 13.6% for a reference viscosity of 120 Ns/m and 21%, for a reference mass of 12 kg. The values were relatively constant over a series of fixed squeezing distances from 15mm to 35mm. Future research will measure viscosity and mass JNDs at other reference values. Preliminary analysis of motor performance data indicated that subjects use both force and velocity cues during the viscosity discrimination experiments and force and acceleration cues during the mass discrimination experiments. To investigate the relative importance of each of these cues in aiding discrimination, more analysis of the motor data along with experiments to measure velocity and acceleration JNDs are planned.

## ACKNOWLEDGMENTS

The work reported here was supported under ONR grant N61339-93-C-0083.

## BIBLIOGRAPHY

- Berliner, J.E. & Durlach, N.I. (1973). Intensity perception IV: Resolution in roving-level discrimination. *Journal of the Acoustical Society of America*, *53*, 1270-1287.
- Durlach, N.I., Delhorne, L.A., Wong, A., Ko, W.Y., Rabinowitz, W.M. & Hollerbach, J. (1989). Manual discrimination and identification of length by the finger-span method. *Perception and Psychophysics*, *46*, 29-38.
- Jones, L.A. (1989). Matching forces: constant errors and differential thresholds. *Perception*, *18*, 681-687.
- Jones, L.A., & Hunter I.W. (1990). A perceptual analysis of stiffness. *Experimental Brain Research*, *79*, 150-156.
- Jones, L.A., & Hunter I.W. (1992). Differential thresholds for limb movement measured using adaptive techniques. *Perception and Psychophysics*, *52*, 529-535.
- Jones, L.A., & Hunter I.W. (1993). A perceptual analysis of viscosity. *Experimental Brain Research*, *94*, 343-351
- Kreifeldt, J.G. & Chuang M.C. (1979). Moment of inertia: psychophysical study of an overlooked sensation. *Science*, *206*, 588-590.
- Pang, X.D., Tan, H.Z., & Durlach, N.I. (1991). Manual discrimination of force using active finger motion. *Perception and Psychophysics*, *49*, 531-540.
- Ross, H.E., Brodie E. & Benson, A.J. (1984) Mass discrimination during prolonged weightlessness. *Science*, *225*, 219-221.
- Ross, H.E. & Benson, A.J. (1986). The Weber fraction for the moment of inertia. in B. Berglund, U. Berglund, and R. Teghtsoonian (Eds) *Fechner Day 86* (pp. 71-76). Stockholm: International Society for Psychophysics.
- Tan, H.Z., Pang X.D., & Durlach, N.I. (1992). Manual resolution of length, force and compliance. *Winter Annual Meeting of the American Society of Mechanical Engineers: Advances in Robotics*, *42*, 13-18.
- Tan, H.Z., Durlach, N.I., Beauregard, G.L., & Srinivasan, M. A., (1995). Manual discrimination of compliance using active pinch grasp: The roles of force and work cues. *Perception and Psychophysics*, *57*, 495-510.