Experimental Validation of a Psychophysical Conjecture on a Simplified Model of the Haptic Perceptual Channel

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Abstract

Detection of softness by tactile exploration in humans is based on both kinesthetic and cutaneous perception, and haptic displays should be designed so as to address such multimodal perceptual channel. Unfortunately, accurate detection and replication of cutaneous information in all its details is difficult and costly. In this paper we discuss a simplified model of haptic detection of softness, whereby only information on the rate of spread of the contact area between the finger and the specimen as the contact force increases is transmitted. We provide a rather thorough set of psychophysical tests, to support the feasibility (in at least some contexts) of a reduced-complicacy display of haptic features.

1. Introduction

In order to discriminate the compliance of objects by tactile exploration, humans often use fingers to squeeze or indent their surfaces. In such a probing operation, the operator elicits a variety of touch–related, or *haptic*, sensorial information, which can be broadly divided in two main functional categories (see e.g. [1], [2]): kinesthetic information, which refers to geometric, kinetic and force data of the limbs, as e.g. position and velocity of joints, actuation forces, etc., and is mainly mediated by sensory receptors in the muscles, articular capsulae, and tendons; and cutaneous (or properly tactile) information, referring to pressure and indentation distributions, both in space (on the skin) and in time, which is mediated by mechanoreceptors innervating the derma and epidermis of the fingerpads.

Both kinesthetic and tactile information are crucial to the human capability of discriminating materials by softness: several psychophysical experiments have clearly demonstrated that use of the kinesthetic channel alone reduces human capability of haptic discrimination dramatically (see [3] and [4]). At the present state of the art and technology, however, only few haptic systems have been implemented that convey cutaneous tactile information ([5, 6, 7, 8]). The need for miniaturization, simplicity, economy, and ruggedness of many applications indeed make the display of tactile information a hard task to implement.

In this paper we discuss a psychophysical conjecture, presented first in [9], concerning a much simplified form of tactile information sensing, transmitting, and displaying, called the Contact Area Spread Rate (CASR) model, and present a rather thorough set of psychophysical experiments that validate the CASR conjecture.

2. The CASR conjecture

The psychophysical conjecture concerning a simplified model of the haptic information channel (with respect to the task of softness discrimination) that goes under the CASR acronym [9], was motivated by the observation that, in the haptic exploration of objects by humans, not all the richness of cutaneous sensorial information seems actually to be necessary to discriminate softness of different materials, which is our ultimate goal in this research. In fact, it likely seems that the actual *shape* of the contact zone between the finger and the object is not by far as relevant as the *area* of the zone itself. More precisely, the conjecture was advanced that a large part of haptic information necessary to discriminate softness of objects by touch is contained in the law that relates overall contact force to the area of contact, or in other terms in the rate by which the contact area spreads over the finger surface as the finger is increasingly pressed on the object (the so–called Contact Area Spread Rate — CASR).

Among the advantages of using the CASR model for tactile information processing, one of the most notable is that sensors and actuators can be realized very simply and robustly. Basically, the CASR model of haptic information includes only information on the resultant contact force, and on the total contact area, i.e. two signals whose treatment poses little problems for what concerns both connector harnessing and processing. While force measurement devices are rather standard, some possible implementations of devices for measur-

Robotics Research — IX
J. Hollerbach and D. Koditscheck, eds.
Springer–Verlag, Berlin (GE)

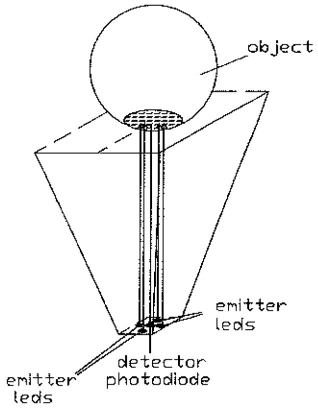

Figure 1: The optoelectronic CASR sensor used in our experiments.

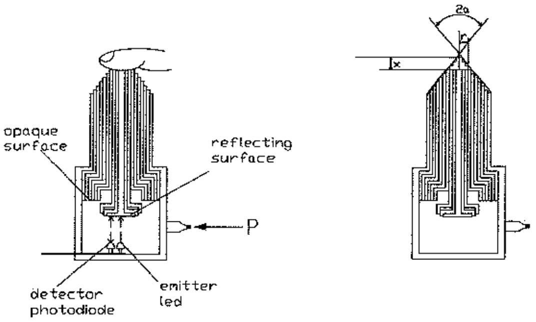

Figure 2: Description of the CASR display.

ing and displaying the total are of contact have been considered and implemented in our laboratory. Those used in the validation experiments reported below are succinctly described in the next section.

3. CASR Equipment

In order to validate the CASR hypothesis, several psychophysical tests were performed using sensors and actuators purposefully designed to convey the CASR information.

3.1. The CASR sensor

Although several kind of CASR sensors can be built using piezoelectric or piezoresistive materials [9], in our experiments we measured total contact area by measuring the variations in the amount of light reflected at an interface, as contact area changes, by optoelectronic means. The optoelectronic CASR sensor used in our experiments is described in fig.1. The surface of the probing finger is realized with a transparent material (Plexiglas), and a LED/phototransistor pair is placed beneath the surface at a distance of few millimeters. The infrared LED emission is scattered over a wide cone, and is partially reflected at the interface of the finger with the outer environment. Reflection is negligible at points of the finger surface not contacting the probed object, while it is relevant at points belonging to the contact area. The phototransistor hence detects a signal roughly proportional to the contact area.

Although the optoelectronic CASR sensor may be somewhat complicate to build in miniaturized scale, it showed accurate enough for our preliminary experiments. For the purposes of the psychophysical tests to be described shortly, we built a CASR sensor of sufficient accuracy by carefully removing possible artifact causes. In particular, the reflective properties of different objects were equalized by spraying equal colors on their surfaces, and spurious sources of light from outside the sensor were shielded accurately.

3.2. The CASR display

The role of a CASR display is to replicate the rate at which the contacting area of the probed material spreads on the surface of the remote probing finger. A possible implementation of such behavior is described in fig.2. The CASR display consists of a set of cylinders of different radii in telescopic arrangement. A regulated air pressure acts on one end of the cylinders. The operator finger probes the other end of the display. The length of the cylinders is arranged so that, when no forces are applied by the operator, the active surface of the display is a stepwise approximation of a cone whose total angle at the vertex is $2a$. When the probing finger is lowered by an amount x, an area of contact A approximately evaluated as $A(x) = \pi x^2 \tan^2(a)$ is established. Correspondingly, the force opposed to the finger is $F(x) = PA(x)$, where P is the pressure established in the inner chamber by the external regulator. An optoelectronic sensor placed within the chamber allows measurement of the displacement x, while a servo pneumatic actuator regulates the chamber pressure based on x and on the desired CASR profile to be replicated.

A laboratory prototype of the CASR display, with 10 concentric cylinders, is shown in fig.3 on the left, while fig.4 shows the experimental characterization of the CASR effect as measured with several different values of constant pressure P. In the operation of the haptic display, pressure in the inner chamber is varied as the display displacement is changed, in such a way as to mimic the CASR function measured on the specimen under exploration. In our implementation, a pneumatic servovalve by Proportion-Air's QB series is employed to this purpose.

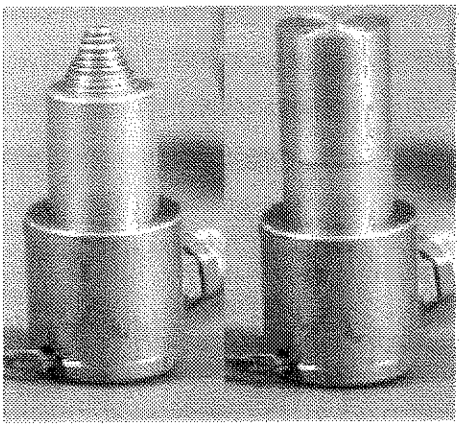

Figure 3: The prototype CASR display on the left and appearance of the kinesthetic display used in the experiments on the right.

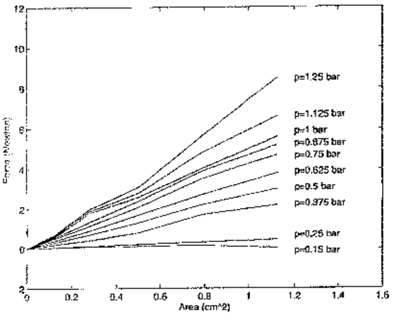

Figure 4: Force/Area response of the prototype CASR display with constant pressure.

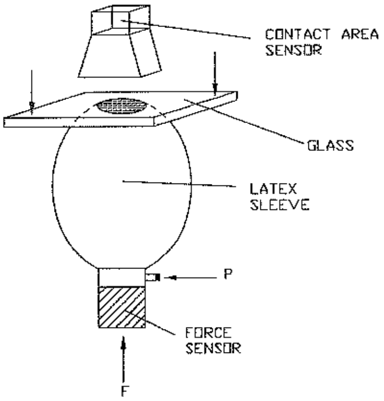

Figure 5: Variable softness device used in psychophysical experiments.

4. Psychophysical validation: experimental results

To validate the CASR conjecture, we devised and executed several psychophysical experiments, which have been conducted in our laboratory with the help of volunteers using the CASR sensing and displaying equipment described above. For comparison purposes, a purely kinesthetic display is used in some experiments. In order to minimize the impact on psychophysical experiments of the different technology and appearance of the kinesthetic display with respect to the CASR haptic display, the former device has been realized by covering the CASR display with a hollow cylinder, whose upper base is flat and rigid (see fig.3 on the right).

4.1. First Experiment: Recognition Rate

The experiment consisted in measuring the capability of 15 volunteers to recognize 5 different items by touching a remote haptic system. Recognition rates using direct exploration, a kinesthetic display, and the CASR paradigm have been compared.

To do so, we collected 5 sets of data corresponding to the contact of a rigid surface with surfaces of decreasing compliance. In order to keep experimental conditions (superficial texture, color, thermal properties of the specimens) as constant as possible in experiments with different items, we used a single device with variable softness (see fig.5). The device consists of an inflatable thick Latex sleeve, of which the apparent softness is varied by changing the internal air pressure.

The first phase of the experiment consisted in pressing a flat glass surface against the upper portion of the sleeve and in gathering, for 5 different levels of inter-

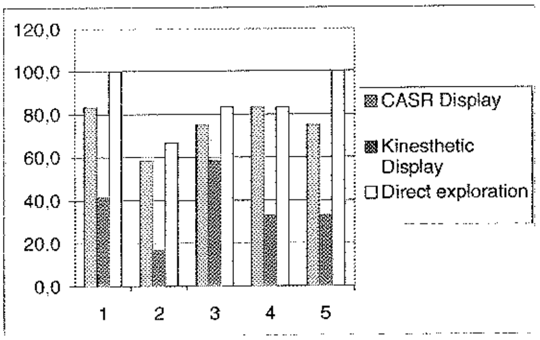

Figure 6: Percentage of successful recognition of 5 different levels of softness by direct exploration, and by remote exploration using the CASR haptic and the kinesthetic displays. Data are referred to 15 subjects, each performing 2 trials on each of the 5 different specimens (for a grand total of 450 trials).

nal pressure in the sleeve, data concerning the contact force (measured by a load cell shown in fig.5), the displacement, and the area of contact (measured by an optoelectronic sensor through the compressing glass).

In the second phase of the experiment, volunteers wearing surgical latex gloves have been allowed to practice in touching the latex sleeve inflated at 5 different levels of pressure, determining as many apparently distinct specimens differing in softness, which were labeled as "item 1" through "item 5". After what was subjectively (by the volunteers) considered a sufficient training, volunteers explored the CASR display described in a previous section, while the display pressure was controlled in such a way that its contact area would spread, in contact with a rigid surface, at the same rate as one of the sample items. Volunteers were asked to guess which item the display resembled best. This procedure was iterated for all items in random order. Analogously, volunteers were asked to explore the kinesthetic display, and report on their associations with different items. The display is controlled in this case so as to replicate the apparent displacement/force behavior of the items. Finally, volunteers were asked to perform recognition of different items by exploration of the original items themselves, presented in random order. Results of the three sets of data concerning correct recognition of different levels of softness are reported in fig.6. It can be observed that recognition using the CASR information outperforms pure kinesthesia, and provides results comparable with direct exploration of items.

4.2. Second Experiment: Consistency of Perception

An experimental protocol was designed to assess the consistency of users' perception from the haptic and kinesthetic displays. By this protocol, volunteers were required to tune (through instructions given to an assistant) the regulation of the air pressure in the inner chamber of the display, while being allowed to comparatively explore one of the specimens and the display itself at their will. The tuning was interrupted when the volunteer was subjectively satisfied with the degree of resemblance of the perception from the display and the specimen, and the perceived optimal tuning parameter (POTP) recorded. The experiment was repeated for different specimens, and using both the CASR haptic and the kinesthetic display. Fifteen volunteers participated in the experiment, each one probing both displays five times.

The average and standard deviation of POTP for each item and display were subsequently calculated. The average POTP was then compared with the experimental tuning parameter (ETP) evaluated by experimentally measuring the CASR diagram, and by choosing the best fit with a curve interpolated from those shown in fig.4. Both the discrepancy between the average POTP obtained with the CASR display and the ETP, and that between the POTP obtained with the kinesthetic display and the ETP, are negligible (no statistically meaningful advantage of the CASR display over the kinesthetic display results by this criterion). However, standard deviations of POTP differ significantly for the two displays, as reported in fig.7. This indicates that perception of similarity of objects by touch is much more consistent using the CASR display than the kinesthetic display.

4.3. Third Experiment: Perceptual Thresholds

Important parameters in the psychophysics of perception are absolute and differential thresholds, i.e. the minimum level of intensity of a stimulus capable of evoking a sensation, and the minimum intensity difference between two stimuli that allows the subject to distinguish between them. In the case of haptic discrimination of softness, absolute thresholds are rather difficult to measure, and not as relevant to applications as differential thresholds. We focussed therefore on the assessment of the latter parameter.

The differential threshold of a perceptual stimulus, or, as it is often called, the *just noticeable difference* (JND), is a figure reflecting the fact that people are usually more sensitive to changes in weak stimuli than they are to similar changes in stronger or more intense stimuli (for instance, one would probably notice a difference in weight between an empty paper

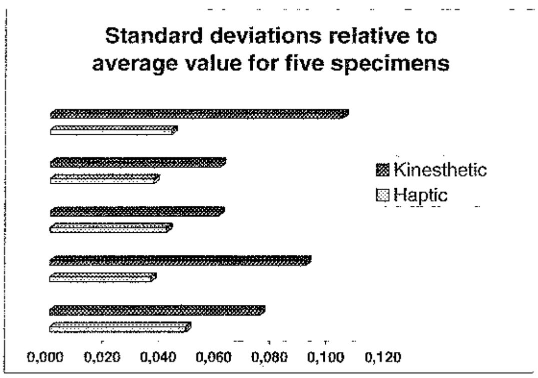

Figure 7: Standard deviations of perceived optimal tuning parameters (POTP) for the CASR haptic and the kinesthetic displays.

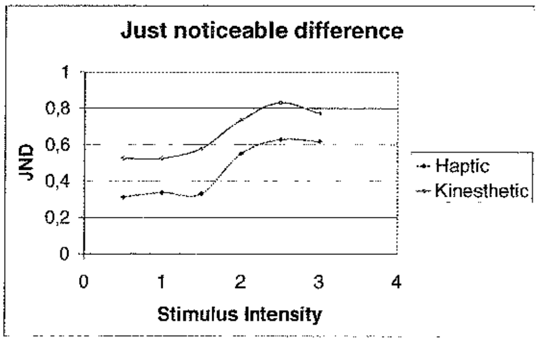

Figure 8: JND versus the intensity of reference standard stimulus for the CASR display and the purely kinesthetic display. Each data point represents the average of 30 trials (2 trials by 15 subjects).

cup and one containing a coin, yet probably a difference between a cup containing 100 coins and one containing 101 would not be noticed). The German psychophysicist Weber suggested the simple proportional law $JND = kI$, indicating that the differential threshold increases with increasing intensity I of the stimulus; the constant k is referred to as Weber's constant. Although more recent research indicates that Weber's law should only be regarded as a rough characterization of human sensitivity to changes in stimulation, it approximates reality well in the middle range of stimuli (the JND tends to grow more slowly in the low and high range of reference stimuli). Average values of Weber's constants are available in the psychophysical literature (see e.g. [10]) for most common perceptual channels, among which the two most relevant to our purposes here is for $k = 0.013$ for diffused tactile stimuli, and $k = 0.136$ for punctual tactile stimuli (this numbers indicate the rapid saturation of receptors involved in punctual tactile perception).

In order to evaluate the JND of the CASR haptic display comparatively with the kinesthetic display, 15 volunteers were asked to touch the same display twice and decide whether or not there was a difference in compliance. The average of the minimum difference in the stimulus (i.e., regulated pressure, hence compliance) that could be consistently detected (less than 10% false responses) by the volunteers, at varying the absolute intensity of the reference stimulus, is reported in fig.8. Both diagrams are pretty much linear in the medium range, where Weber's constant can be evaluated as ca. $k = 0.09$. Though not as good as diffused cutaneous tactile perception, both displays show a slower growth of JND than punctual stimuli. The haptic display allows subjects to discriminate differences in compliance 20% more finely than the kinesthetic display.

4.4. Fourth experiment: Psychometric function

The psychometric function is another measure of sensorial resolution widely used in psychophysical studies. The experiment consists of asking volunteers to compare the apparent compliance of the CASR display in two successive trials. During the first trial, the display is regulated to a standard value S of compliance (i.e. of air pressure in the inner chamber), while during the second a different value X is set. Volunteers are asked to decide whether X is harder than S, and the number of positive answers divided by the total number of answers is denoted by $P\{X > S\}$. As X is varied from values lower to values higher than S, the *psychometric function* is obtained as

$$F_S(X) = P\left\{ X > S|_{(S,X)} \right\}. \qquad (1)$$

In the ideal case of an infinitely fine resolution in the sensory channel, the psychometric function would be a step function ($F_S(X) = 0$, $X < S$, $F_S(X) = 1$, $X > S$). A diagram of the psychometric functions obtained with the CASR haptic display and the kinesthetic display is reported in fig.9. It can be observed that the haptic display curve has a steeper slope than the kinesthetic by a 3:2 factor, indicating again a much finer resolution.

4.5. Fifth Experiment: Perceptual Granularity

An experiment was designed in order to assess how fine a graduation of compliance could be perceived by subjects. Volunteers were asked preliminarily to touch

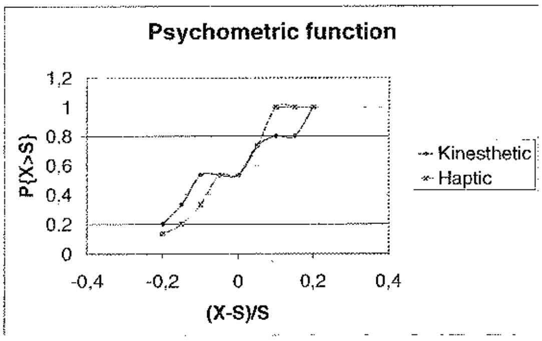

Figure 9: Psychometric function of the CASR display. The reference stimulus S corresponds to an air pressure of 0.5 bar in the displays, i.e. in the middle of the operating range of the devices. Each data point represents the average of 30 trials (2 trials by 15 subjects).

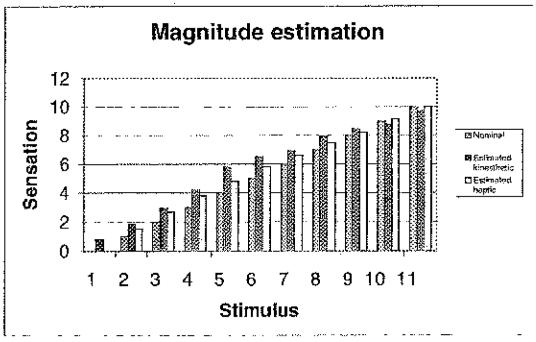

Figure 10: Histogram relative to variations of magnitude estimation. Each data bar represents the average of 30 trials (2 trials by 15 subjects).

the display while it was regulated to a value close to its minimum operating level, and afterwards with the display regulated to its maximum level. The interval between these two values was then divided in ten, and subjects were successively presented with the display regulated to such intermediate levels in random order. Subjects were asked to rank the perceived compliance in a range of 10, with 0 being the minimum and 10 the maximum levels of which they had previous experience. The average rank estimated by subjects is presented in fig.10 for both the haptic and kinesthetic display. It can be observed that the granularity of perception is finer for the haptic display: as an overall measure, for instance, the variance of estimated ranks is 0.3 for the CASR haptic display, and 1.0 fro the kinesthetic display.

5. Conclusions

It has been firmly established in the psychophysical literature that the ability of discriminating softness by touch is intimately related to both kinesthetic and cutaneous tactile information in humans. In replicating touch with remote haptic devices, there are serious technological difficulties to build devices for sensing and displaying fine tactile information. In this paper, we investigated the possibility that a simplified form of tactile data could convey enough information to allow satisfactory discrimination of softness, while allowing practical construction of devices for practical applications. One of these devices is presented in paragraph 3 and has been used to acquire information of different materials necessary to control the haptic display. Results of our psychophysical experiments strongly encourage the CASR conjecture.

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