Haptic probing: Perceiving the length of a probe and the distance of a surface probed

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Knowing about the properties of objects by wielding them and knowing about the distances of surfaces by striking them with objects as probes are examples of dynamic or effortful touch. Six experiments focused on the invariant mechanical parameters that couple the time-varying states (displacements, velocities) of hand-held rods to the time-varying torques and forces imposed upon them by wielding and probing. There were three major conclusions. First, when a probe is wielded without contact, perceived probe length is a function of the probe's rotational inertia; however, with contact, perceived probe length is affected by the rotational inertia and the distance of the point of contact from the probe's center of percussion. Second, when a surface is struck with a probe, perceived surface distance is affected by the probe's rotational inertia and the angle of inclination of the probe at contact. Third, under seemingly identical conditions of probing, either probe length or surface distance can be perceived selectively without confusion. Results were discussed in terms of haptic information, haptic attention, and the dynamics of probing.

A well-known yet ill-understood fact is that when a person uses a hand-held tool or probe to act upon or to explore the environment, he or she feels the contacted environment at the end of the implement, not in the hand (e.g., Gibson, 1966; Katz, 1925/1989; Lotze, 1856/1885; Polanyi, 1958; Simpson, 1976; Vaught, Simpson, & Ryder, 1968; von Békésy, 1967). As described by William James (1890/1950):

The draughtsman's immediate perception seems to be of the point of his pencil, the surgeon's of the end of his knife, the duellist's of the tip of his rapier as it plunges through his enemy's skin . . . and yet the place where the contact is received is in all these cases the skin, whose sensations are sometimes interpreted as objects on the surface, and at other times as objects a long distance off. (p. 38)

For many animals, touching is an indirect mechanical disturbance of the skin mediated by an appendage, and not a direct impression on the skin by an object. Many animals have appendages to the skin (e.g., vibrissae, hairs, claws, horns, and so on) that protrude into the surrounding layout of surfaces and provide a means for obtaining information at some distance from the skin (Burgess, 1974). The aforementioned well-known fact, implicated in human tool use (e.g., sticks, clubs, rakes, screwdrivers, pliers, etc.) and implements of sport (e.g., tennis rackets,

baseball bats, golf clubs, etc.), is probably an extension of this perceptual capacity found in other animals.

The haptic subsystem of particular significance to probing with a hand-held implement is referred to as *effortful* or *dynamic* touch (Gibson, 1966). Effortful or dynamic touching refers to situations in which muscular effort (in conjunction with stimulation of skin and joints) is especially involved in perceiving the properties of objects and adjacent surface layout (Gibson, 1966). When a rod is held firmly about one end and wielded (that is, shaken, twisted, whipped back and forth, etc.), the awareness one has of properties of the rod's dimensions is based on effortful or dynamic touch. A large number of experiments have been directed at perceiving the length of a hand-held rod by dynamic touch (Burton & Turvey, 1990, 1991; Carello, Fitzpatrick, Domaniewicz, Chan, & Turvey, 1992; Solomon & Turvey, 1988; Solomon, Turvey, & Burton, 1989a, 1989b). These experiments show that for uniformly dense cylindrical objects, perceived length is (1) a linear function of actual length with a slope approximating 1 and an intercept approximating 0, and (2) governed by the moments of the cylindrical object's mass distribution. When a rod is wielded, the second moment of the mass distribution (moment of inertia) is the significant mechanical quantity; when it is held steady, with hand and rod movement minimized, the first moment (static moment) also proves significant. The findings on perceiving the extent of a cylindrical object by wielding are of significance to the present research. In what follows, a summary of the major experiments and results is provided.

Perceiving the Length of a Wielded Rod

One could engage in a variety of behaviors in order to perceive the length of an object by means of the haptic

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perceptual system. Investigators have used finger span (wedging the object between two fingers), temporal sweep (tracing the surface of the object from one end to the other), and cutaneous extent (impressing the object on the skin) to assess perceiving length manually (Durlach et al., 1989). We have elected, instead, a procedure that entails gripping the object at one end—in the fashion of a hammer, tennis racket, and the like. In the experimental arrangement for investigating the haptic ability to perceive the distance to the tip of a visually occluded hand-held object, the subject freely wields the rod held firmly in the hand, by three-space motions about axes in the right wrist, with the right forearm resting on the armrest of a chair. The rod, the arm, and the wielding activity are occluded by a curtain. On the other side of the curtain, the subject can see a surface perpendicular to the ground. The surface can be moved freely by the subject, with the use of the left arm, toward or away from the subject's position. For a given hand-held rod, the subject's task is one of magnitude production—position the surface so that it is aligned with the tip of the hand-held rod that the subject can wield but not see.¹ The subject is free to wield and to adjust the surface for as long as is needed to reach a confident judgment.

In the original experiment using the above procedure (Solomon & Turvey, 1988, Experiment 1), subjects wielded seven rods ranging from 0.31 to 1.22 m. The mapping from actual length to perceived length was highly linear (and was so for all subjects with all r^2 's in the vicinity of .99), with slight overestimation at the shorter lengths and slight underestimation at the longer lengths. Similar results were obtained whether the movement was in front of the body to the right of midline or across the body to the left of midline (Solomon & Turvey, 1988, Experiment 1 vs. Experiment 3), to the side of the body parallel to the lateral plane, with the palm up or down (Solomon et al., 1989a), and when amplitude and frequency of movement were restricted (Solomon & Turvey, 1988, Experiment 4). Rod length, however, cannot be the variable of relevance to the haptic subsystem because only mechanical variables constructed with the dimension of mass—such as torque, kinetic energy, moment of inertia, and so on—affect the tissues of the haptic subsystem during wielding. Length per se is not a mechanical variable.

In another experiment, a weight was added to otherwise uniform rods at three positions (Solomon & Turvey, 1988, Experiment 5). For a rod of a given length, the moment of inertia, I , of the rod about axes parallel and perpendicular to the ground (i.e., the rod's resistances to rotational acceleration about these axes) increases as the location of the added weight increases in distance from the axis of rotation. The experiment showed that perceived length was neither a single-valued function of actual length nor a single-valued function of the total mass of the rod plus the added weight. Perceived length was, however, a single-valued function of I .

The magnitude of I about any arbitrary axis is equal to the moment of inertia about a parallel axis through the center of mass (I_c), plus the mass (m) of the body times the square of the distance (a) between the two axes. That is, $I = I_c + ma^2$. The preceding is the parallel axis theorem. An important corollary of this theorem is that I is least when the axis of rotation is through the center of mass (CM)—that is, when $ma^2 = 0$. If perception of a rod's length is tied to I , then a rod grasped at and swung about its CM should be perceived as shorter than the same rod grasped at and swung about a position other than CM. A typical experiment testing this hypothesis (e.g., Solomon et al., 1989a, Experiment 1) used rods of three different lengths held at $\frac{1}{4}$ length, $\frac{1}{2}$ length, and $\frac{3}{4}$ length. For each axis of rotation, the subject's task was to judge how far he or she could reach with the distal end of the rod if it were held at its proximal end. Subjects met the requirements of the task successfully and ordered their judgments in accord with I as given by the parallel axis theorem; they did so whether the rod was wielded horizontally or vertically, with an overhand or underhand grip. The theorem not only identifies that an axis of $\frac{1}{2}$ yields the smallest I but that the I values for axes at $\frac{1}{4}$ and $\frac{3}{4}$ are identical. The fact that subjects could distinguish accurately among the three rods when held at $\frac{1}{2}$ length (i.e., at CM) has other important consequences. It rules out any hypotheses about CM or center of oscillation (CO) as the basis of perceived length (Solomon & Turvey, 1988; Solomon et al., 1989a). When held at CM, the distance a from the axis of rotation to CM is identical, and practically zero, for the three different rod lengths. The axis-to-CO distance is given by I_c/ma and, therefore, is undefined when the axis and CM coincide.

The cited experiments and others of a similar nature have pointed unequivocally to rotational inertia as the mechanical quantity of relevance to perceiving the extent of a hand-held object by wielding. The only factors that can affect an object's resistance to rotational acceleration are the shape of the body and the distribution of mass in the object. Consider again the rotational configuration of a uniform slender rod of mass M and length L . With respect to an axis perpendicular to the rod and passing through its mass center, $I = ML^2/12$. With respect to an axis passing perpendicularly through one of the rod's ends, $I = ML^2/3$. A change in the axis of rotation is thus seen as a change in the configuration of the body. Furthermore, if the axis passes through a point that partitions the rod into the ratios of a and b ($a + b = 1$), then the rod can be considered as composed of two pieces of lengths aL and bL . It is easily shown that I for the single piece of length L about the given axis is equal to the sum of I_a and I_b , the respective moments of inertia of the pieces aL and bL as defined with respect to the axis passing through a piece's end. Similarly, if a metal disk is attached to the uniform rod, the distribution of mass is altered and $I = I_{\text{rod}} + I_{\text{disk}}$, where the component moments of inertia are calculated according to the parallel axis theorem. Both

of the preceding facts demonstrate the principle that a system of forces acting on a body can be equated with a single force acting on the body about a suitable base point.

We reported above experiments in which subjects held and wielded a uniformly dense rod at positions intermediate between its two ends with the purpose of perceiving the rod's total length ("how far could you reach with it if you were to hold it at its proximal end?"). As noted, they performed the task successfully, with perceived total rod length tracking the rod's moment of inertia about the axis of rotation as computed through the parallel axis theorem. In one experiment in the series conducted by Solomon and Turvey (1988, Experiment 9), rather than having to perceive the total length of the rod, subjects had to perceive the length of rod that extended beyond where the rod was grasped ("how far could you reach with the portion of the rod forward of the hand?"). This task was also performed successfully; partial rod lengths were distinguished reliably, with perceived length tracking the moment of inertia of the rod fraction. Presumably, in the partial task, the activity of wielding an unseen rod must distinguish the torques and motions of the partial rod from the torques and motions of the rod as a whole. The implication of the experimental results just noted, therefore, is that the haptic subsystem can decompose a torque into component torques and decompose a moment of inertia into component moments of inertia.

Experiments have been conducted in which both the rotational configuration and the mass distribution have been manipulated to address directly this decomposition capability of the haptic subsystem (Solomon et al., 1989b). On each trial, a visually occluded rod was wielded by the subject at a position intermediate between its two ends. The position was either $\frac{1}{2}$ or $\frac{3}{4}$ of the rod's length. On two thirds of the trials, a weight was attached to the rod, at a point either above or below its center of gravity and not coincident with the hand's position. In the first experiment, the subject's task was to perceive the distance reachable with the portion of the rod extending beyond the position of the grasp. In the second experiment, the subject's task was to perceive the distance reachable with the entire rod if it were held at its proximal end.

With respect to the first experiment, if the haptic subsystem can partition the rod into its component moments of inertia, then for a rod of length L , the perception of $L/2$ should be the same for the unweighted rod and for the rod with the weight attached at $L/8$; the perception of $L/4$ should be the same for the unweighted rod and for the rod with the weight attached at $L/8$. That is, the perception of the partial lengths forward of the position of the hand should be unaffected by the increase in moment of inertia brought about by adding a metal disk below the position of the hand. Similarly, if the haptic subsystem can separate the moments of inertia above and below the fixed point, then for the rods with a weight added above the axis of rotation at $\frac{7}{8}L$, the lengths of $L/2$ and $L/4$ should be perceived as longer than when the rods are unweighted. The three basic conditions of the experiment, with respect to the presence and position of the added

weight, can be referred to as Condition N (for none), Condition $1/8$, and Condition $7/8$. The following outcomes were expected, therefore, under the decomposition-of-the-moment-of-inertia hypothesis: (1) When the added weight is below the fixed point (the grasp), it should not affect the perception of the length above the grasp—that is, we expect the equality, Condition $1/8 = \text{Condition N}$; (2) when the added weight is above the fixed point, it should affect the perception of the length above the grasp—that is, we expect the inequalities, Condition $7/8 > \text{Condition N}$ and Condition $7/8 > \text{Condition } 1/8$; and (3) the perceived distances reachable with rods held at $L/2$ should be longer than the perceived distances reachable with rods held at $\frac{3}{4}L$.

Very different outcomes were expected for the second experiment: (1) A rod held at $L/2$ should be perceived as longer when weighted than when unweighted (because its total moment of inertia is greater by the parallel axis theorem), and similarly for a rod held at $\frac{3}{4}L$ —that is, we expect the inequalities, Condition $7/8 > \text{Condition N}$ and Condition $1/8 > \text{Condition N}$; (2) the distances reachable with rods held at $L/2$ should be perceived as shorter than when held at $\frac{3}{4}L$ (because, at $L/2$, the moment of inertia is least by the parallel axis theorem); (3) position of weight should have no differential effect for rods held at $L/2$ (because of same moments of inertia by the parallel axis theorem) but should have a differential effect for rods held at $\frac{3}{4}L$ (because of different moments of inertia by the parallel axis theorem).

The results of the two experiments were in agreement with expectation. In the first experiment, perceived reaching distance was a function of the moment of inertia of the amount of rod forward of the grasp about an axis through the proximal end of the rod segment. In the second experiment, perceived reaching distance was a function of the moment of inertia of the entire rod about the given axis of rotation intermediate between the rod's ends. The subjects in the experiments were able to perceive either the extent of the whole object or the extent of a part. The contrast between the two experiments is striking, given that they differed only in the instructions to the subjects (see also Burton & Turvey, 1991).

The Inertia Tensor and Object Properties

Investigations of the perception of a variety of object properties on the basis of wielding have shown a consistent dependence on the object's pattern of different resistances to rotational acceleration in different directions—a pattern that is quantified by the inertia tensor $\mathbf{I}$. In the 3×3 matrix representation of $\mathbf{I}$, the resistances to the tangential component of rotational acceleration about the three axes are quantified by the diagonal terms (moments of inertia), and the resistances to the normal component of rotational acceleration are quantified by the off-diagonal terms (products of inertia). As summarized above, perceived length of a rod or a rod segment is a function of the rod's or rod segment's moments of inertia (Solomon & Turvey, 1988; Solomon et al., 1989a, 1989b). Perceived orientation of a branch perpendicular to the stem

of a rod seems to be a function of the object's principal axes or eigenvectors (Turvey, Burton, Pagano, Solomon, & Runeson, in press). Perceived shape can be expressed as a function of the ratio of the maximum principal moment to the minimum principal moment (Burton, Turvey, & Solomon, 1990).

Haptic Probing

Investigations of the haptic perception of a surface layout by probing have found the probe's rotational inertia to be an important but not exclusive influence (Barac-Cikoja & Turvey, 1991; Chan & Turvey, 1991). Not surprisingly, the conditions of contact also matter, and elaborating upon this observation will be the major purpose of the present article. To set the stage, a brief summary of the findings on haptic probing is provided.

To study haptic awareness of the separation between surfaces by probing, experiments can be designed in which the participant is seated holding an occluded rod in the right hand and using it to strike the inner surfaces of two occluded perpendicular blocks. With the left hand, a visible pair of blocks is adjusted in separation until the gap between them matches that perceived haptically between the struck blocks. Using the foregoing experimental arrangement, Barac-Cikoja and Turvey (1991) manipulated aperture size, magnitude of angular displacement Θ (with the rotation point O in the wrist always on the bisector of the angle), distance b of the point of contact with the surfaces from the axis of rotation, hand-rod mass m , location of the hand-rod's center of mass a , and moment of inertia I_{yy} of the hand-rod about O . (Thinking of a rod parallel to the ground, the z -axis is its longitudinal axis, the y -axis is vertical and perpendicular to z , and the x -axis is horizontal and perpendicular to z .) Analysis of the patterning of forces resulting from exploratory striking revealed a collective quantity $\lambda = \sin(\Theta/2) [1 - (2a/b) + (ma^2/I_{yy})]$ that was—for a given rod, aperture, and distance—invariant over muscular forces and resultant torques. In the course of seven experiments, Barac-Cikoja and Turvey (1991) found that haptic perception of aperture size was not unique to aperture size but varied with distance, angle, and probe properties. It was, however, specific to λ ; this parameter predicted successfully the interdependent effects of angular displacement, distance of surfaces, and the mechanical properties of the implement. Finally, differences among swinging the rod from the wrist, elbow, or shoulder submitted to the same analysis, incorporating mechanical properties of the arm-as-implement (Barac-Cikoja, 1988).

A commonplace challenge for the unsighted is to perceive by probing the vertical distances of surface arrangements that lie underfoot. An experimental design for investigating this haptic capability has the subject tap a horizontally aligned surface with a probe (such as a rod) through vertical motions that are roughly parallel to the sagittal plane. The probe and the surface are occluded, and white noise presented through headphones eliminates acoustic information. Reports of the surface's vertical distance are communicated by adjusting a visible pointer until

it is aligned with the perceived location of the surface. Using this experimental procedure, Chan and Turvey (1991) manipulated the length, mass, rotational inertia, center of mass, and shape of the probe, together with surface distance and angle of probing. Perceived vertical distance was systematically related to actual vertical distance and was found to be specific to a particular relation among probe moment of inertia, the contact distance from the probe's center of percussion, and the inclination at contact of the probe to the surface. The same relationship was obtained whether the probe was primarily vertical (and rocked, slid, or tapped against the surface) or primarily horizontal (and hammered against the surface). Chan and Turvey (1991) also observed that the probe length and the distance probed were independently perceivable.

The results of the experiments of Barac-Cikoja and Turvey (1991) and Chan and Turvey (1991) confirm the impression identified in the opening paragraphs that touch can function successfully as a distance sense: Haptic probing with a hand-held implement reveals distal surface layout. In both series of studies, the potential contributions of sounds engendered by striking were recognized. Pilot work showed that the pattern of relations observed by Barac-Cikoja and Turvey were the same whether or not the strikes could be heard, and, in each of the seven experiments, padding on the interiors of the struck surfaces was used to minimize sound production. In the Chan and Turvey series, the sounds of tapping in each experiment were masked by noise conveyed to the subject by earphones.

A Dynamical Perspective on Perceiving by Effortful Touch

Analysis of perceiving object properties by effortful touch has been in terms of the object as a dynamical system (Solomon, 1988). In the wielding research, the strategy has been to focus on the dynamics of the object's three-space (rigid-body) motion about a fixed point. For the wielding of a given object on a given trial, the state of the object at any given moment is defined by its displacement (x) and its rate of change of displacement or velocity (v). Muscular forces act on this system to bring about new states, with each new state expressible by a particular pair of x and v values. The rate of change of state as a function of force is expressed, of course, by Newton's third law. Thus, given a state (x , v), the next state is ($x + vdt$, $v + Fdt$), where the force F is given by $F = F(x, v, t)$. The set of state transitions defines the trajectory or behavior of the object. It is to be expected that both within an instance and across instances of wielding to perceive a given property, there will be considerable variability in the object's behavior.

The preceding characterization is conventional Newtonian mechanics. An important feature of the standard mechanical construal is the division of system and environment; the system is characterized by states (x_i , v_i), the environment is not, and, once a system has been defined, everything remaining defines its environment. Forces are part of the environment. It is important to note that the

above function for force includes implicitly a number of constants or parameters (independent of states and time). These express the specific way in which a system is coupled to the forces imposed upon it by its environment. It is the parameters (rotational inertia, mass, coefficient of elasticity, coefficient of friction, etc.) that convey upon a system its specific identity independent of whatever radical changes occur in the system's states (Rosen, 1988). In attempting to perceive the spatial features of an object by wielding about axes in the wrist, the dynamical system is object-with-fixed-rotation point. Rotational motions about a fixed point of the kind characteristic of wielding about a joint follow from $N = I \cdot d\omega/dt + \omega \times (I \cdot \omega)$ (see Euler's equations, Goldstein, 1980). In wielding a given object, the torque N , angular velocity ω , and angular acceleration $d\omega/dt$ will vary from moment to moment. In contrast, I remains invariant. As noted above, research has shown that perceptions are a function of I ; perceived length goes as the moments, perceived orientation goes as the products, and perceived shape goes as a ratio of moments. The implication is that effortful touch is attuned to the invariant parameters of the object's dynamics rather than to the varying states and torques. A particularly relevant experiment is that reported by Solomon and Turvey (1988, Experiment 3): Over different controlled frequencies of wielding with fixed amplitude (and, therefore, different states and torques), perceived rod length was exactly the same function of the rod's rotational inertia.

In sum, a strategy for understanding effortful touch seems to be as follows: (1) define the system, (2) identify the parameters that couple the (muscular and other) forces impressed upon the system to the system's states, (3) determine, for the given property of hand-held object or adjacent surface layout, the parameter or parameters that constrain fully the perception, and (4) provide a reasoned basis for the relation between the pertinent parameter(s) and the perception.

In the present article, the preceding strategy is applied to two comparisons. One comparison is between perception of probe length by wielding and perception of probe length by wielding in such a way as to contact an adjacent surface (a comparison in which the dynamical systems in the two cases are different). The other comparison is between perception of probe length and perception of surface distance, both under conditions of wielding with contact (a comparison in which the dynamical systems in the two cases are the same). When contacting a surface by wielding a rod through motions about axes in the wrist, the system is rod(with fixed rotation point)-and-constraining surface. The forces imposed upon this system are muscular forces and contact forces (shocks, impulses) and the parameters are constants of the rod (such as I) of the surface (such as elasticity, which was not manipulated explicitly in these experiments) and of the configuration of rod and surface at contact (such as angle). For the second comparison, that of probe length and surface distance under conditions of contact, there is evidence to suggest that although the dynamical system is the same in the two cases—namely, rod(with fixed rotation point)-

and-surface—the pertinent parameters are not (Chan & Turvey, 1991, Experiment 9). A major goal of the present research is to determine the parameters, or complexes of parameters, that differentially constrain these two perceptions.

EXPERIMENT 1

Experiment 1 assessed perception of the extent of a hand-held rod under two different conditions of dynamic touching: wielding the rod freely in the air versus wielding the rod horizontally back and forth such that its tip scrapes against a vertically aligned surface at a distance approximately equal to the rod's length.

When a rod is wielded, there is a tissue deformation pattern associated with the three-space motion of the rod. As noted, there is considerable evidence to suggest that aspects of this time-dependent deformation pattern are constrained invariantly by the time-independent rotational inertia of the rod. Under conditions of wielding, perceived length of a thin rod appears to be fully constrained by the rod's maximal moment of inertia. Because of the symmetry of a rod, two of the three moments of inertia about an axis in the wrist (those associated with rotation vertically and horizontally) are equal, and the third (the moment of inertia about the longitudinal axis through the length of the rod) is the least.

When a wielded rod makes repetitive contact with an environmental surface, another source of tissue deformation is defined. Over and above the torques producing and resulting from the three-space motion of the rod, there are brief forces generated on surface contact. These impulse forces or shocks, like the torques of wielding, must affect the deformation pattern of the limb's tissues. Short-duration deformations produced by contact are superimposed on the relatively long duration deformation patterns induced by wielding. These impulse forces of contact will vary from contact to contact but will have an effect on the rotation point in the wrist that is proportional to the distance of the contact point from the center of percussion. When an object is struck a sharp blow at its center of percussion, no momentum is transferred to the rotation axis; it is the "sweet spot" of the bat or racket (relative to that center of rotation). The position of the center of percussion from a given axis is given by the moment of inertia I about the axis divided by the static moment (mass $\times$ distance from pivot point to center of mass). If a rod is struck at its end perpendicularly to the longitudinal axis, then there is a distance P defined by the rod length minus the center of percussion. For a given rod, P will be a parameter; although the forces of contact and the resultant displacement and velocity changes at the rotation axis will vary from tap to tap, they will be coupled to each other by this constant. Consequently, we might expect P to be of relevance to perceiving probe properties under conditions of wielding with contact, scaling the force felt at the rotation point to the contact impulse. Chan and Turvey (1991) found that, for the probing of horizontally aligned surfaces beneath the hand, perceived probe

length was expressible through the power function, perceived length (in centimeters) = $1.6I^{0.21}P^{0.06}$. If this function represents a general dependency, then we can expect to observe a similar scaling relation under the different conditions of the present experiment, conditions that entail a different surface orientation, different orientation with respect to gravity, different muscle synergies, and different torques.

Method

Subjects. Eight undergraduates at the University of Connecticut volunteered to participate as one way of fulfilling a course requirement.

Materials. Three wooden rods were cut from dowels, 1.27 cm in diameter. The rods were 61, 76, and 91 cm in length. A 60-g cube-shaped mass with a central hole slightly larger than the dowel circumference was positioned on each rod at $\frac{1}{4}$ from an end. The moment of inertia of the cube about the vertical axis through its center of mass was $.0003 \text{ kg} \cdot \text{m}^2$. Holding the rod with the added mass close to the hand (at $L/4$, where L is rod length) produces a smaller moment of inertia (I) than does holding the rod with the added mass far from the hand (at $\frac{3}{4}L$). There were, therefore, six probes distinguished by I . Their values are listed in column 3 of Table 1. The corresponding six values of P , the distance between the point of contact at the distal tip of the probe and the probe's center of percussion are provided in column 4.

Apparatus. A chair with a right-sided armrest abutted the front of an L-shaped floor-to-ceiling styrofoam occlusion screen. A subject sat in the chair and put his or her right hand through an opening in the screen so that the forearm was supported by the armrest. This fixed the center of rotation (in the wrist), which is necessary to calculate I . A cloth flap covered the opening and the wrist. Rods placed in the hand were thus hidden from view. Perceived length was indicated by using a rope-and-pulley system to adjust a vertical $10 \times 25 \text{ cm}$ marker affixed to a table to the left of the screen, in full view of the subjects. The marker's position (in centimeters) was read off a tape measure that could not be seen by the subjects. (The maximum traverse of the marker was 183 cm.) For contact trials, a $48 \times 94 \times 80 \text{ cm}$ cardboard box was placed behind the screen so that its front surface was coincident with the tip of the rod. The experimenter adjusted this position for the different rod lengths. The entire arrangement is shown in Figure 1.

Procedure. One end of a rod was placed in the participant's right hand, and he or she was told to maintain a firm grip (that is, moving the rod relative to the hand by movements of the fingers was prohibited). On welding trials, the instruction was to shake the rod freely in the air; on contact trials, the instruction was to swing the rod so as to scrape its tip against the front surface of the box (this was most frequently, but not exclusively, done in the horizontal plane). The subjects were allowed to explore for as long as they needed. Presentation of the different lengths, inertias, and exploratory styles was ordered randomly within a block. There were four blocks of 12 trials each. On each trial, participants were told which

Figure 1. (Top) The probe to be welded and the surface to be struck were occluded from the subject's view. (Bottom) The report apparatus, visible on the subject's left, was adjusted with a rope and pulley.

exploratory style to use and were asked to adjust the marker (moving it back and forth if desired) so that it coincided with the location of the distal end of the rod. Every trial began with the marker at the position nearer the observer. Pilot experiments had established that there was no difference as a function of the starting position (near or far) of the report board. In addition, pilot research showed that perceived extent was not altered by the elimination of auditory information.² For the comfort of the subjects, white noise and earphones were not used.

Before the experimental session, the subjects performed four practice trials, without feedback about the accuracy of their performance. The lengths of the practice rods were different from those used in the experimental session. Before the practice, the subjects were shown the surface hidden behind the screen (at an arbitrary distance). The subjects were not informed about the number and lengths of the rods until after completion of the experiment.

Results and Discussion

The last two columns of Table 1 present the perceived lengths under conditions of welding with and without con-

Table 1
Perceived Probe Length as a Function of Probe Parameters,
Contact Parameters, and Conditions of Welding in Experiment 1

Length (cm)	Mass		$I \text{ (kg} \cdot \text{m}^2)$	$P \text{ (cm)}$	Perceived Length (cm)	
	Location				No Contact	Contact
61	$\frac{1}{4}$		.009	27	46.1	51.6
76	$\frac{1}{4}$		.015	35	58.8	62.1
61	$\frac{3}{4}$		.020	41	63.9	62.4
91	$\frac{1}{4}$		.023	16	71.7	69.7
76	$\frac{3}{4}$		.032	21	75.8	70.2
91	$\frac{3}{4}$		.048	25	89.8	76.5

tact. The range of responses permitted by the report apparatus was 0–183 cm, whereas the range of perceived lengths was 46–90 cm. Clearly, the subjects' reports of length covered only a small part of the range of reports they could see permitted by the apparatus, suggesting that their reports were constrained by what was felt in the hand rather than by the visible apparatus.

The main result is that the influence of I on perceived length with contact and without contact was different. A 3 (rod length) $\times$ 2 (mass position) $\times$ 2 (exploratory style) analysis of variance (ANOVA) on the individual subject data revealed main effects of length [$F(2,14) = 72.36$, $p < .0001$; with average responses of 56.1, 66.7, and 76.9 cm for the 61-, 76-, and 91-cm rods, respectively] and mass position [$F(1,7) = 48.66$, $p < .0002$; with average responses of 60.0 cm for $L/4$ and 73.1 cm for $3/4L$]. The main effect of exploratory style was not significant [$F(1,7) = 1.34$, $p > .05$], but its influence was apparent in the contact $\times$ length interaction [$F(2,14) = 10.85$, $p < .001$], as well as in the contact $\times$ mass position interaction [$F(1,7) = 15.77$, $p < .005$]. Because rod length and mass position combine to determine a rod's rotational inertia, the interactions confirm that the effect of rotational inertia on the perception of rod length differed between wielding without contact and wielding with contact.

Inspection of Table 1 reveals that certain probes with very different rotational inertias (e.g., .015 kg $\cdot$ m² and .020 kg $\cdot$ m²) were perceived very similarly under conditions of contact and differently under conditions without contact. This is illustrated in Figure 2, which presents perceived length as a function of $\log I$ for both conditions

(the log transform linearizes the I , which contains a squared length term): The functional dependency of perceived length on rotational inertia is less under conditions of contact. The contact function is flatter than is the no-contact function, and more variable. The differences between the probes in the value of P may have been the reason that inertial contrasts did not always translate into perceptual contrasts under conditions of contact. Again referring to Table 1, larger rotational inertia values were countered in these cases by smaller contact values.

Two multiple regressions of perceived length on the independent variables of $\log I$ and P were conducted. As expected, without contact, the r^2 was .995, $p < .0004$, with only $\log I$ significant; with contact, the r^2 was .997, $p < .0002$, with both $\log I$ ($p < .0001$) and P ($p < .006$) significant. (As a further check on the contribution of P to the contact data, the residual of the linear regression of perceived length on $\log I$ was computed and then regressed against P , yielding $r^2 = .910$.) The power function derived from the multiple regression on logarithms of all variables was: perceived length (in centimeters) = $1.8I^{0.24}P^{0.09}$. This scaling relation is similar to that found by Chan and Turvey (1991, Experiment 6: $1.1I^{0.29}P^{0.10}$) in an experiment in which (1) contact with a horizontal surface beneath the hand was made by tapping aluminum probes up and down through rotational movements at the wrist, and (2) sounds were masked by white noise. For the noncontact data of the present experiment, perceived length (in centimeters) = $2.95I^{0.39}$. This scaling is consistent with that reported in previous research on perceiving length by wielding (e.g., Solomon & Turvey, 1988).

Figure 2. Perceived probe length as a function of moment of inertia and contact condition in Experiment 1.

The implication of the present comparison between welding without and with surface contact is that the latter depresses the exponent on I .

EXPERIMENT 2

Experiment 2 extended the conditions of Experiment 1 in two ways. First, contacts with vertically aligned surfaces were made at distances shorter than the probe length (that is, at contact, the rod was at an angle Θ to the ground plane where $0 < \Theta < 90^\circ$). Second, the contacts were achieved through motions in a vertical plane parallel to the subject's sagittal plane. These extensions are important for the following reason: It is important to determine whether or not the parameters constraining probe length perception in one contact configuration achieved through one kind of movement continue to do so in other contact configurations achieved through other kinds of movements. Different probe-to-surface configurations realized through different movements will entail different muscular synergies, different patterns of muscular innervations, different tissues subject to deformation, different patterns of torques, and different patterns of contact forces. In the specific terms of the experimental strategy identified above, the system definition of rod-(with fixed rotation point)-and-surface constraint (at a fixed distance) implies a parameter associated with angle of contact. The significance of this parameter could not be evaluated under the conditions of Experiment 1.

Experiment 2 extended Experiment 1 in yet another way. In order to sharpen the observation that P affects the perception of probe length, rotational inertia was held constant over variations in contact configuration. Specifically, contacts were made with the probe at either 30° or 58.2° to the ground plane. For a fixed point of rotation in the wrist and a surface at a given distance, achieving these contact configurations meant that the rods had to be of two different lengths. By attaching a mass of a certain amount at a far-from-the-hand position on the shorter rod (with the position determined by the parallel axis theorem), the two rods of different lengths could be made identical in resistance to rotational acceleration. At the same time, this manipulation would mean that the center of percussion of the shorter rod would be proportionally further along its length than would the center of percussion of the longer rod. The impulse forces of contact at the rod tip would occur closer to the percussion center in the shorter rod, meaning, simply, that P would be less for the shorter rod. The Appendix describes how the different parameters are affected by these manipulations.

In sum, Experiment 2 permitted an extended evaluation of the role of contact. Welding rods of different lengths but the same rotational inertias should result in the same perceived lengths. Striking a surface at a given distance with such rods, however, should result in different perceived lengths, given that the parameters of contact (angle and distance from center of percussion) differ between the two rods.

Method

Subjects. Six undergraduates at the University of Connecticut volunteered to participate as one way of fulfilling a course requirement.

Materials. There were six wooden rods cut from dowels, 1.27 cm in diameter. The rods were 37.2, 46.3, and 55.2 cm (the *short set*), and 61, 76, and 91 cm (the *long set*) in length. A 60-g mass was positioned on each probe in the short set so that its moment of inertia was the same as the corresponding probe in the long set. Thus, the 61- and 37.2-cm probes had a moment of inertia of .006 kg · m², the 76- and 46.3-cm probes had a moment of inertia of .011 kg · m², and the 91- and 55.2-cm probes had a moment of inertia of .017 kg · m².

Apparatus. The occlusion screen and report board from Experiment 1 were used again in Experiment 2. The front of the box that served as the striking surface was fitted with a 90 × 200 cm sheet of plywood, so that rods would not strike it on an edge (Figure 3).

Procedure. On noncontact (welding) trials, the instruction was to shake the rod freely in the air by motions about the wrist, keeping the forearm in place on the armrest. On contact trials, the instruction was to strike the probe against the surface through a hammering motion restricted to a plane perpendicular to the ground plane (or, synonymously, parallel to the body's sagittal plane). For both welding with contact and welding without contact, the subjects were allowed to explore for as long as they needed.

On a contact trial, the experimenter moved the box so that the plywood surface was 32, 40, or 48 cm from the axis of rotation. The surface was struck with the probe at one of two angles to the horizontal, 30.0° or 58.2° . These were produced by using, respectively, the 37.2- or the 61-cm probe at the closest distance, the 46.3- or the 76-cm probe at the middle distance, and the 55.2- or the 91-cm probe at the farthest distance. On noncontact trials, the surface was moved to a distance beyond the reach of the longest rod.

Presentation of the different surface locations, angles, and exploratory styles was ordered randomly within a block. There were four blocks of 12 trials each. The subjects were given two practice trials, without feedback, before the experiment began. They were also shown the surface behind the screen (at an arbitrary distance) and an example of the kind of object that would be placed in the hand to reduce any concerns they might have about the sincerity of the experimenter's description of the experiment. The displayed probe was a simple rod without added mass of a length not used in the experiment proper.

Results and Discussion

Table 2 shows perceived length with and without contact for the various combinations of L , I , P , and angle Θ . As expected, when rods of different lengths but the same I were welded without contacting adjacent surfaces,

Figure 3. In contrast to the first experiment, surface distance and probe length did not coincide in Experiment 2. The surface was struck with a hammering motion.

Table 2
Perceived Probe Length as a Function of Probe Parameters, Contact Parameters,
and Conditions of Welding in Experiment 2

Length (cm)	Angle (deg)	I (kg · m ²)	P (cm)	Perceived Length (cm)	
				No Contact	Contact
37	58	.006	11.5	35.3	38.0
46	58	.011	11.4	55.2	45.8
55	58	.017	8.9	65.1	55.4
61	30	.006	21.0	36.8	45.3
76	30	.011	26.4	50.0	58.4
91	30	.017	29.7	67.9	68.2

perceived length went as I . But when those same rods contacted a surface, different contact conditions associated with the two variants of a given probe I resulted in different perceived lengths.

These observations were corroborated in a 2 (exploratory style) $\times$ 3 (moment of inertia) $\times$ 2 (probe type) ANOVA on the individual subject data. Effects of moment of inertia [$F(2,10) = 33.62$, $p < .0001$] and probe type [$F(1,5) = 18.71$, $p < .01$] were significant, but effect of exploratory style was not ($F < 1$). All of these were involved in significant interactions, however. Exploratory style $\times$ probe type [$F(1,5) = 21.86$, $p < .01$] indicates that the difference between the shorter rods with added mass and inertially equal longer rods with no added mass (or between 30° and 58.2° probe angles) was apparent with striking, but not under conditions of welding without contact; simple effects tests yielded $F(1,5) = 23.69$, $p < .005$, and $F < 1$, respectively. The interaction of exploratory style $\times$ moment of inertia [$F(2,10) = 6.12$, $p < .02$] reveals that the slope of the function relating perceived length with moment of inertia was steeper and less variable for welding without contact ($r^2 = .97$, $p < .001$) than for striking ($r^2 = .68$, $p < .05$). No other interactions were significant ($p > .10$).

Obviously, other sources of constraint are at play under conditions of contact. A multiple regression of perceived length on $\log I$ ($p < .002$) and P ($p < .004$) accounted for 99% of the variance, with both beta coefficients significant. (As a further check on the contribution of P , the residual from the perceived length against $\log I$ regression was regressed on P , yielding $r^2 = .93$.) Finally, given that angle of contact Θ and P were related—larger P values were associated with the larger Θ —a stepwise regression was conducted on all three variables $\log I$, P , and $\cos \Theta$ (the cosine function enhances the linearity). Only $\log I$ and P were entered, in that order.

The multiple regression of perceived length on I and P in logarithmic coordinates yielded the power function: perceived length (in meters) = $2.0I^{0.39}P^{-0.22}$ (with lower and upper 95% limits for the two exponents of 0.27 and 0.51, and -0.33 and -0.11 , respectively). This scaling of perceived length to the mechanical parameters of the task is different from that of the preceding experiment and from that observed by Chan and Turvey (1991, Experiment 9).

The present experiment corroborates (1) the observation of Solomon and his colleagues (Solomon, 1988; Solo-

mon & Turvey, 1988; Solomon et al., 1989a, 1989b) that perceiving the length of a hand-held rod by welding is constrained by the rod's resistance to rotational acceleration, and (2) the observation of Chan and Turvey (1991) that when a rod is so welded as to contact an adjacent surface, the perception of its length is affected by its rotational inertia and the distance of the point of contact from the rod's center of percussion. Chan and Turvey's (1991, Experiment 9) observation was made under conditions in which horizontally aligned surfaces beneath the hand were tapped by means of motions in a plane perpendicular to the body's sagittal plane and brought about by the muscles of the upper arm that rotate the forearm about its longitudinal axis. Their observation is replicated in the present experiment under conditions in which vertically aligned surfaces frontal to the hand were tapped by means of motions in a plane parallel to the body's sagittal plane and brought about by the muscles of the forearm that rotate the hand about the axes in the wrist.

EXPERIMENT 3

Experiments 1 and 2 addressed the first main comparison of interest in the present article: The subjects were asked to perceive a given property—namely, probe length—under conditions in which they imposed muscular forces on two different mechanical systems. The systems in question were (1) rod with fixed rotation point, and (2) rod with fixed rotation point and constraining surface. As emphasized in the introduction, a system's parameters couple the forces imposed on the system to its states (the variables of motion) in a particular system-defining manner. Previous research has suggested that, in effortful or dynamic touch, perception of persistent object and surface properties is linked to the system parameters (rather than forces and states). The parameters of System 1 are a subset of the parameters of System 2. Experiments 1 and 2 showed that, with System 1, perceived probe length is a single-valued function of probe I and that, with System 2, perceived probe length is, within the limits studied, a single-valued function of a product formed by I and P .

In Experiment 3, we examine the second main comparison of interest in the present article: The subjects were asked to perceive two different properties—namely, probe length and surface distance—under conditions in which they imposed muscular forces on the *same* mechanical sys-

tem (i.e., System 2). Precisely, the subjects struck vertically aligned surfaces repeatedly with the purpose of perceiving either the length of the probe or the distance of the surface probed. Chan and Turvey (1991) found that a person could attend selectively to either extent when probing a horizontal surface beneath the hand and that the two kinds of perceiving were constrained by probe and contact parameters in systematically different ways. In Experiment 3, we pursue this finding further, examining surface distance and probe length perception under conditions of striking surfaces aligned vertically.

Method

Subjects. Twenty undergraduates at the University of Connecticut volunteered to participate as one way of fulfilling a course requirement. They were assigned randomly to one of two experimental groups corresponding to the intention to perceive probe length or surface distance.

Materials. The probes were the same rods with added mass used in Experiment 1.

Apparatus. The occlusion screen and report board of Experiment 2 were used.

Procedure. The basic procedure for the condition of striking a distant surface was the same as that of Experiment 2. Depending on the particular combination of probe length and surface distance, angle ranged from approximately 38° to 80° relative to the horizontal, for a total of nine different angles. On a given trial, the experimenter moved the box so that the plywood surface was 18.5, 33, or 48 cm from the axis of rotation. Depending on which group they were in, the subjects were told to indicate probe length or surface distance by adjusting the marker as before (they were unaware that there were two possible instructions). They were given two practice trials, without feedback, before the experiment began.

Presentation of the different lengths, added mass positions, and surface locations was ordered randomly within a block. There were three blocks of 18 trials each. Intention—to perceive surface distance or to perceive probe length—was a between-subject variable.

Results and Discussion

Figure 4 shows mean perceived extent as a function of intention for different probe lengths (top) and different surface distances (bottom). It is important to note that people were able to perform these tasks without confusion: reports of probe length were always in the range of 60–100 cm, whereas reports of surface distance were always in the range of 20–45 cm. A 3 (rod length) $\times$ 2 (mass position) $\times$ 3 (surface position) $\times$ 2 (intention) ANOVA revealed a main effect of intention [$F(1,18) = 59.75$, $p < .0001$; perceived probe length averaged 80.43 cm, and perceived surface location averaged 32.35 cm]. All other main effects were significant [length, $F(2,36) = 50.14$, $p < .0001$; mass position, $F(1,18) = 62.41$, $p < .0001$; surface position, $F(2,36) = 15.13$, $p < .0001$], but they all interacted with intention. It is in those interactions that differing influences on perceived length and perceived surface distance can be seen. Namely, the intention $\times$ rod length [$F(2,36) = 39.04$, $p < .0001$] and intention $\times$ surface position [$F(2,36) = 39.04$, $p < .0001$] interactions (with appropriate simple effects tests) show that perceiving probe length did not depend on surface distance (Figure 4, top) and perceiv-

ing surface distance did not depend on probe length (Figure 4, bottom).

Interactions involving intention and mass position [intention $\times$ mass position, $F(1,18) = 27.00$, $p < .0001$; intention $\times$ surface distance $\times$ mass position, $F(2,36) = 3.50$, $p < .05$] suggest different influences of moment of inertia on perceiving probe length and perceiving surface distance. As shown in Figure 5, regression of perceived probe length on $\log I$ at each surface distance revealed the same linear function, with $r^2 = .94$ ($p < .0001$). In contrast, regression of perceived surface distance on $\log I$ for each surface distance revealed three distinct flat functions, with $\log I$ accounting for a maximum of 12% of the variance. The pattern depicted in Figure 5, obtained with one kind of contact configuration (vertical surfaces in front of the hand with rods held above the hand) was observed by Chan and Turvey (1991) with a different contact configuration (horizontal surfaces below

Figure 4. Perceived probe length (top) and perceived surface distance (bottom) as a function of actual extent in Experiment 3.

Figure 5. Regression of perceived probe length and perceived surface distance on moment of inertia for each surface distance in Experiment 3.

the hand with rods held below the hand). It confirms that perceiving surface distance is dependent on the parameters of the mechanical system of "probe-(with fixed rotation point)-and-surface" in a way different from the perceiving of probe length. To identify this difference more precisely, we examine the role of the contact parameters.

Combinations of the three lengths and three distances produced nine values of Θ . Table 3 shows perceived probe length and perceived surface distance for each angle, averaged over the two mass positions. Simple regressions on $\cos \Theta$ found $r^2(18) = .82$, $p < .0001$, for perceived distance (with perceived extent decreasing with increasing angle), but no similar dependency for perceived probe length [$r^2(18) = .19$, $p > .05$]. Simple regression revealed no dependency of either perceived extent on P (whose values were the same as those listed in Table 1); both regressions exceeded the .05 level.

Multiple regressions revealed the ways in which variables that did not reach significance in simple regressions combined to influence perceived extent. A multiple re-

gression of mean perceived distance on $\cos \Theta$, $\log I$, and P yielded $r^2(18) = .94$, $p < .0001$, with partial F s of 226.2 ($p < .0001$), 32.3 ($p < .0001$), and 2.7 ($p > .05$), respectively. A similar multiple regression for mean perceived length on $\cos \Theta$, $\log I$, and P yielded $r^2(18) = .97$, $p < .0001$, with partial F s of 6.6 ($p < .02$), 340.6 ($p < .0001$), and 6.6 ($p < .02$), respectively. These regressions in logarithmic coordinates yield the following power functions: perceived surface distance (in centimeters) = $1.18 I^{0.17} \cos \Theta^{0.61}$ and perceived probe length (in centimeters) = $4.27 I^{0.31} \cos \Theta^{-0.06} P^{0.07}$. It appears that a person can attend selectively to the tissue deformation consequences of these parameter products.

The main conclusion to be drawn from Experiment 3 is that when a person strikes a surface with a cylindrical probe, he or she can perceive either the length of the probe or the distance of the surface. These two perceptions are distinct, and they are constrained differently by the parameters of a cylindrical probe striking a surface through motions about a fixed point. We note, however, that although the results of Experiment 3 compare favorably with those of Chan and Turvey (1991, Experiment 9), there are important differences; those investigators found P to be significant to surface distance perception and Θ not to be significant to probe length perception.

EXPERIMENT 4

The purpose of Experiment 4 was twofold. First, it was designed to sharpen the distinction between the roles of probe and contact parameters in perceiving surface distance. To this end, Experiment 4 reproduced the conditions of Experiment 2 (which had been limited to perceiving probe length). Second, it was designed to evaluate the selectivity of perceiving surface distance and probe length as a within-subject manipulation (rather than a between-subject manipulation as had been the case in Experiment 3). Manipulating intention within subjects will permit an evaluation of whether perceiving probe length and perceiving surface distance depend on one another. According to some theorists, percepts can be derived algorithmically from other percepts (e.g., Epstein, 1977, 1982).

Table 3
Perceived Surface Distance and Probe Length as a Function of Probe Parameters and Contact Parameters in Experiment 3

Probe Length (cm)	Surface Distance (cm)	Angle of contact (deg)	Perceived Extent (cm)	
			Distance	Length
61	18	72.3	23.01	69.68
	33	57.2	33.51	68.43
	48	38.1	43.56	66.37
76	18	75.9	23.60	80.37
	33	64.3	31.78	78.78
	48	50.8	41.81	76.70
91	18	78.3	22.75	98.31
	33	68.7	31.18	93.08
	48	58.2	40.00	92.20

The conditions of Experiment 2 reproduced here can be found in Table 4 along with predicted values of perceived surface distance based on the power function from Experiment 3. The predicted pattern of overestimations at 58° and underestimations at 30° was sought in the data of Experiment 4, together with an effect of intention (perceive surface distance vs. perceive probe length) and an interaction between intention and angle. Experiment 3 had shown that, in contrast to perceived surface distance, perceived probe length increased with Θ .

Method

Subjects. Six undergraduates at the University of Connecticut volunteered to participate as one way of fulfilling a course requirement.

Materials and Apparatus. Probes and surface arrangement were the same as in Experiment 2.

Procedure. The basic procedure was the same as that in Experiment 2, with the exceptions that (1) all trials involved surface contact and (2) the subjects were instructed to perceive either probe length or surface distance. In contrast to Experiment 3, the instruction/intention manipulation was within subjects. The subjects were given two practice trials, without feedback, before the experiment began. They were also shown the surface behind the screen (at an arbitrary distance) and an example of the probes that would be placed in their hands in order to clarify the experimenter's description of the experiment and to reduce the subjects' uncertainty about the nature of the experiment. The displayed probe was a simple rod (without added mass) of a length not used in the experiment proper. Actual variations in probe lengths, designs, and surface distances were not known by the subjects before the experiment.

Results and Discussion

Mean perceived surface distances are provided in column 5 of Table 4. The fit to the predicted values was evaluated by a linear regression ($r^2 = .98$, $p < .002$). The pattern of perceived surface distances agreed with that expected from the outcome of Experiment 3. Clearly, with Θ fixed and I varying, perceived distance varied; likewise, with Θ varying and I fixed, perceived distance varied. Multiple regression of mean perceived distances on the two parameters yielded $r^2 = .98$, $p < .002$, with $\cos \Theta$ significant at $p < .002$, and $\log I$ significant at $p < .007$. Mean perceived lengths are provided in the last column of Table 4. Given that I was constant over Θ , the longer length perceptions at the larger angle imply the contribution of contact parameters. Including P in a multiple regression with $\log I$ yielded $r^2 = .94$, $p < .01$,

with both parameters significant ($p < .01$ and $p < .01$, respectively). A check on Θ 's contribution through a stepwise regression was conducted; only $\log I$ and P were entered by the analysis. A related check on P 's contribution to perceived surface distance was also conducted; the stepwise regression entered only $\cos \Theta$ and $\log I$.

To buttress the conclusions drawn on the basis of the regression analyses, a 2 (intention) $\times$ 3 (moment of inertia/surface distance) $\times$ 2 (angle/probe type) ANOVA was conducted on the individual subject data. The conjunctions of conditions express the facts that I increased as surface distance increased and probes without an added mass were associated with the smaller angle (see Experiment 2 and introduction to Experiment 4). The ANOVA revealed a significant effect of intention [$F(1,5) = 23.67$, $p < .005$] and of moment of inertia/surface distance [$F(2,10) = 19.67$, $p < .001$]. The effect of angle/probe type was not significant [$F(1,5) = 1.20$, $p > .05$], but its influence was apparent in the interaction with intention [$F(1,5) = 86.06$, $p < .001$], which revealed an opposite pattern for perceived surface distance and perceived probe length. The steeper angle/unweighted probes yielded longer perceived lengths than did the flatter angle/weighted probes, whereas the steeper angle/unweighted probes yielded shorter perceived surface distances than did the flatter angle/weighted probes. No other interactions were significant.

The regression analyses coupled with the ANOVA make clear that the subjects performed very differently under the two instructions. They were able to selectively perceive surface distance and probe length, corroborating the results from the between-subject design of Experiment 3 and the earlier experiment of Chan and Turvey (1991, Experiment 9) that used a within-subject design. As with these preceding experiments, it appears that the two perceptions are constrained differently by the parameters of the dynamical system comprising rod (with fixed rotation point) and contacted surface. The larger implication is that the patterns of tissue deformation engendered by these parameter configurations can be attended to selectively. An alternative view might contend, however, that the percepts are coupled—for example, probe length is first perceived and then surface distance is derived algorithmically from the initial percept (e.g., Epstein, 1977, 1982). Following Epstein (1977), partial correlations were calculated to evaluate the relationship between the two

Table 4
Perceived Surface Distance and Perceived Probe Length as a Function of Probe Parameters and Contact Parameters in Experiment 4 Together With Predictions of Perceived Surface Distance From Experiment 3

Angle (deg)	I (kg $\cdot$ m ²)	P (cm)	Predicted Distance	Perceived Extent (cm)	
				Distance	Length
58	.006	11.5	33.5	29.7	48.1
	.011	11.4	37.1	37.0	57.8
	.017	8.9	39.9	38.0	62.4
30	.006	21.0	45.0	42.9	51.0
	.011	26.4	50.2	47.6	68.6
	.017	29.7	54.1	53.3	70.1

percepts when their mutual relationship to the mechanical variables was taken out. The partial correlation between perceived surface distance and perceived probe length was not significant ($r = -.26, p > .10$, when perceived length was the "conditioning" or mediating percept; $r = .012, p > .10$, when perceived distance was the conditioning percept). In contrast, partialing out the appropriate conditioning percept left relatively undiminished significant relationships between perceived extent and the mechanical variables ($r = .979, p < .001$, for perceived distance; $r = .882, p < .02$, for perceived length). In sum, it seems that the selective perceptions observed in Experiment 4 were based on the mechanical parameters characterizing the dynamical system and not on percept-percept couplings.

Turning finally to the power functions derivable from the multiple regression in logarithmic coordinates, we have perceived surface distance (in centimeters) $= 1.47 \cos \Theta^{0.64} I^{0.23}$ (with lower and upper 95% limits on the exponents of .44 and .85, and .09 and .22, respectively) and perceived probe length (in centimeters) $= 2.70 I^{0.28} P^{0.13}$ (with lower and upper 95% limits on the exponents of .17 and .43, and $-.01$ and .28, respectively). The power function found here for perceived surface distance is comparable to that found in Experiment 3. The power function of Experiment 4 for perceived probe length compares favorably with that reported by Chan and Turvey (1991, Experiment 9) and that of Experiment 1. Recall that a contrary function described the data of Experiment 2, data obtained under the same striking conditions as those of Experiment 4. The contrasting high positive I exponent and negative P exponent of Experiment 2 may reflect a feature of our experimental sampling or a nonlinear aspect of the underlying tissue deformation quantity that is causally constrained by the mechanical parameters.

EXPERIMENT 5

A feature common to the outcomes of Experiments 3 and 4 was that, given a surface distance, its perception was larger, the smaller the angle of inclination of the probe to the ground plane (or, conversely, its perception was larger, the larger the angle of contact between probe and surface). One might argue that shallower angles of inclination, smaller Θ s, can be taken as indicators of surfaces at further distances. That is, observers may employ a conscious guessing strategy in order to judge the distance of a probed surface—namely, the more horizontal the probe, the further the surface. This notion of a conscious strategy contrasts with the notion that perceived surface distance is a single-valued function of a particular relation between the parameters Θ and I . Unlike the conscious strategy notion, the function notion would allow that there are conditions in which surfaces will be perceived closer when probe inclinations are shallower. These conditions would occur when the reduction in the contribution of Θ to the parameter complex is overcompensated for by the increase in the contribution of I . To fix this argument, consider the power function describing the perceived surface dis-

tance data of Experiment 4: Perceived surface distance (in centimeters) $= 1.47 \cos \Theta^{0.64} I^{0.23}$. If Experiment 4 were repeated with values of I so chosen that the decrease in $\cos \Theta^{0.64}$ across $\Theta = 30^\circ$ and $\Theta = 58.2^\circ$ was overcompensated for by the increase in $I^{0.23}$, then larger perceived surface distances would be associated with shallower probe angles. For example, if the probe I at $\Theta = 30^\circ$ were $.0014 \text{ kg} \cdot \text{m}^2$ and the probe I at $\Theta = 58.2^\circ$ were $.0071 \text{ kg} \cdot \text{m}^2$, then $\cos \Theta^{0.64} I^{0.23}$ at the two angles would be .202 and .212, respectively, and perceived surface distances would be 29.6 and 31.3 cm, respectively.

Experiment 5 tested the foregoing prediction by repeating Experiment 4 in the manner suggested. Additionally, by repeating the contrast between perceiving surface distance and probe length as a within-subject manipulation, a further opportunity was provided to evaluate the dependency of these perceivings upon each other.

Method

Subjects. Nine undergraduates at the University of Connecticut volunteered to participate as one way of fulfilling a course requirement.

Materials. Six wooden rods were used without added masses. The six I values were .0014, .0028, and .0037 $\text{kg} \cdot \text{m}^2$ (for the 37.2-, 46.3-, and 55.2-cm rods), and .0071, .0126, and .0196 $\text{kg} \cdot \text{m}^2$ (for the 61-, 76-, and 91-cm rods).

Apparatus. The surface and report board of Experiment 2 were used.

Procedure. The basic procedure was the same as that of Experiment 4, with the same surface distances, probe lengths, and angles of contact. The only difference was that the short set of rods was not weighted to match the moments of inertia of the long set.

Results and Discussion

The tendency for perceived distance to be smaller at the larger Θ witnessed in Experiments 3 and 4 was reversed in Experiment 5, as predicted. The observed mean perceived surface distances were 26.4, 30.5, and 32.3 cm for the $\Theta = 30^\circ$ conditions, and 26.5, 31.6, and 34.4 cm for the $\Theta = 58.2^\circ$ conditions. A linear regression of perceived extent on values predicted by the power formula from Experiment 4 yielded $r^2 = .98, p < .001$. The implication is that subjects' perceptions of surface distance are specific to a relation between the Θ and I parameters of the dynamical system comprising probe (with fixed rotation point) and contacted surface. As additional support for this interpretation, we can note that it predicts an influence of I larger than an influence of Θ for conditions of the present experiment, in contrast to the opposite prediction for Experiment 4. Multiple regression of the mean perceived distances on $\cos \Theta$ and $\log I$ yielded $r^2 = .98, p < .003$, with $\cos \Theta$ and $\log I$ both significant but with the significance values ($p < .003$ and $p < .001$, respectively) and the partial F values (83.81 and 131.56, respectively) favoring $\log I$. In Experiment 4, the corresponding pattern favored $\cos \Theta$ ($p < .001$ vs. $p < .007$, and 130.93 vs. 45.83).

As one might suspect from the degree of fit between observed and predicted perceived surface distance, the power functions of the present and preceding experiments

are closely similar. For Experiment 5, perceived surface distance (in centimeters) = $1.33 \cos \Theta^{0.68} I^{0.23}$ (with lower and upper 95% limits on the exponents of .45 and .91, and .17 and .30, respectively).

In common with the procedures of Experiments 3 and 4, in Experiment 5 the subjects were asked to perceive either surface distance or probe length. That they behaved differently under the two instructions is suggested by several facts: (1) the different magnitudes of the two classes of responses (mean perceived surface distance = 30.3 cm, mean perceived probe length = 48.7 cm), (2) the lack of correlation between the two response measures ($r^2 = .31$, $p > .05$), and (3) a linear dependency of perceived probe length on $\log I$ ($r^2 = .97$, $p < .001$, but no corresponding dependency of perceived surface distance on $\log I$ ($r^2 = .38$, $p > .05$). (Because I and P were very highly correlated [$r = .97$] in this experimental design, as were actual probe length and Θ , multiple regressions with these combinations were ruled out.) Once again, partial correlations showed that the relationships between perceived extent and the mechanical variables were not mediated by the other perceived extent ($r = .99$, $p < .001$, for perceived distance; $r = .97$, $p < .01$, for perceived length). Percept-percept coupling is not to be found in the data of Experiment 5. As in Experiment 4, perceptions were constrained fully by the parameters of the dynamical system comprising probe (with fixed rotation point) and contacted surface.

EXPERIMENT 6

Collectively, the five experiments point to a potentially succinct answer to the question of which parameters constrain the perceptions of surface distance and probe length under conditions in which surfaces are probed through vertical motions about a fixed rotation point: I and Θ constrain surface-distance perception, and I and P constrain probe-length perception. Experiment 6 was conducted to shore up the preceding conclusion, especially with respect to I . A cylindrical probe of a given I can be constructed in an indefinitely large variety of ways. This variety necessitates variety in other probe mechanical parameters (e.g., mass, center of mass, center of percussion, etc.). The question posed by Experiment 6 is whether or not increasing the variety of configurations satisfying a given I exerts any systematic influence on the two perceptions. The significance of an answer to this question lies with eventual efforts to delimit potential higher order parameters to which the perceptions of surface distance and probe length are specific.

Method

Subjects. Twelve undergraduates at the University of Connecticut volunteered to participate as one way of fulfilling a course requirement. They were assigned randomly to one of two experimental groups corresponding to the intention to perceive probe length or surface distance.

Materials. Rods were cut from 1.27-cm-diam dowels, with two each of the same three lengths as had been used in Experiments 4

and 5. As before, the three shortest lengths reached the surface at the flatter angle and the three longest reached the surface at the steeper angle. A short cylindrical-shaped mass was attached to each instance of a given rod length. A 90-g mass was placed at a specific position on the proximal side (near the hand) of one rod's CM, and a 60-g mass was placed at a specific position on the distal side (far from the hand) of the other rod's CM. The positioning of these masses was dictated by the parallel axis theorem under the requirement of producing the same I value for each instance of a given rod length; they were also dictated by the requirement, common to the preceding experiments, of producing the same I value for the two different rod lengths used to strike the surfaces at the two different angles. The consequences of satisfying these requirements were that (1) the I s of the short, medium, and long probes were .008, .012, and .020 $\text{kg} \cdot \text{m}^2$, respectively, and (2) there were four configurations for each I .

Procedure. The basic procedure was the same as that of Experiment 5. Presentation of the moments of inertia/surface locations, angles, and added-mass positions was ordered randomly within a block. There were three blocks of 12 trials each. The subjects were given two practice trials, without feedback, before the experiment began. As in the previous experiments, the subjects were also shown the surface behind the screen (at an arbitrary distance) and an example of the kind of object that would be placed in the hand to reduce any concerns they might have about the correctness of the experimenter's description of the experiment. The displayed probe was a simple rod without added mass of a length not used in the experiment proper. The subjects were told that both probe lengths and surface distances would be manipulated. They were not told about the variation in probe configuration.

Results and Discussion

Mean perceived extents for each probe configuration (averaged over moment of inertia/surface distance) are shown in Table 5. The now-familiar difference between intentions is apparent again, but the influence of probe configuration is not straightforward. A 2 (intention) $\times$ 3 (moment of inertia/surface distance) $\times$ 4 (probe configuration) ANOVA revealed a significant effect of intention [$F(1,10) = 58.34$, $p < .0001$], with distance judgments averaging 39.2 cm and length judgments averaging 67.3 cm (the regression of perceived surface distance on perceived probe length again revealed no relationship, $r^2 = .003$). The effect of moment of inertia/surface distance was also significant [$F(1,20) = 20.55$, $p < .0001$], with average responses of 46.1, 54.1, and 59.5 cm for $I = .008$, .012, and .020 $\text{kg} \cdot \text{m}^2$, respectively. Of particular interest was the effect of probe configuration (the four combinations of angle, added mass, and added mass position comprising a given I). The ANOVA indicated that although probe configuration was not significant ($F < 1$),

Table 5
Perceived Surface Distance and Perceived Probe Length
as a Function of Probe Parameters and
Contact Parameters in Experiment 6

Probe Configuration	Perceived Extent (cm)	
	Distance	Length
30°/60 g	45.0	61.7
30°/90 g	44.0	64.1
58°/60 g	33.3	73.0
58°/90 g	34.4	70.5

its interaction with intention was [$F(3,30) = 6.86, p < .001$]. Inspection of Table 5 suggests that this interaction is, in fact, rooted in a contribution of Θ . This was corroborated in a 2 (intention) $\times$ 3 (moment of inertia/surface distance) $\times$ 2 (angle) $\times$ 2 (added mass) ANOVA, which, in addition to effects of intention and moment of inertia, revealed an interaction of intention with angle [$F(1,10) = 7.26, p < .03$]. This interaction was of the same kind as that found in Experiment 4: Probe length judgments were larger at the steeper angle, and distance judgments were smaller. No other main effects or interactions in either analysis were significant.

Although the ANOVAs dismiss probe configuration and promote Θ as the major source of variance in addition to I , it is the case that mean values of P (consequences of how the probes are configured) are coordinate with Θ . Thus, for 30° , mean P was 10.7 cm, and for 58.2° , mean P was 37.8 cm. Stepwise regressions were conducted with perceived surface distance and perceived probe length as the dependent measures and $\cos \Theta$, $\log I$, and P as the independent measures. For perceived distance, the analysis entered only $\cos \Theta$ and $\log I$, in that order; for perceived probe length, only $\log I$ and P were entered, in that order. The same selection and ordering were found when either probe mass or probe center of mass was included in the stepwise regression, a result that enforces the implication of the ANOVAs that probe configuration per se is of limited relevance beyond its determination of I and P . The outcomes of these stepwise regressions corroborate the main findings of the previous experiments. Multiple regressions in double logarithmic coordinates yielded the following power functions: perceived surface distance (in centimeters) = $1.8 \cos \Theta^{0.55} I^{0.31}$ (with lower and upper 95% limits on the exponents of .42 and .67, and .23 and .39, respectively); perceived probe length (in centimeters) = $1.95 I^{0.21} P^{0.10}$ (with lower and upper 95% limits on the exponents of .14 and .28, and .06 and .13, respectively).

GENERAL DISCUSSION

In the present article, we have investigated two characteristic achievements of dynamic or effortful touch: the perception of the extent of an object held in the hand and the perception of the distances of surfaces touched with a hand-held object. Our investigation has been shaped by a general perspective on effortful touch that emphasizes the invariant dynamic parameters that couple, during a given trial, the time-varying states (displacements, velocities) of the probe to the time-varying torques and forces imposed upon the probe. The experiments were directed at the two kinds of dynamical systems that are defined by (1) pure wielding of a hand-held object about a fixed point in the wrist, and (2) wielding a hand-held object about a fixed point in the wrist with surface contact at the furthestmost point of the object.

Three major conclusions can be drawn from the experiments. First, when a probe is wielded without contact,

perceived probe length is governed by the probe's resistance to rotational acceleration; however, when the wielding also involves surface contact, perceived probe length is affected by both I and a parameter of contact (i.e., the distance of the point of contact from the probe's center of percussion). Second, when a surface is struck with a probe, perceived surface distance is affected by the probe's resistance to rotational acceleration and a parameter of contact (i.e., the angle of inclination of the probe at contact). Third, under seemingly identical conditions of probing—striking a given rod against a surface at a given distance and angle—people can attend selectively to either probe length or surface distance without confusion. We will consider each of these conclusions in turn.

The Role of Contact in Perceiving Probe Length

A considerable body of evidence has demonstrated the single-valued dependency of perceiving the extent of a hand-held object on that object's rotational inertia (Solomon & Turvey, 1988; Solomon et al., 1989a, 1989b). The present experiments suggest, however, that additional parameters affect perceiving the extent of a hand-held object when it makes repetitive contact with an adjacent surface. This observation might warrant the conclusion that a person's awareness of the length of a hand-held object is constrained by different parameters in different circumstances. The parameters identified, however, are the measurable mechanical parameters associated with wielding and striking with an implement, parameters that refer directly to the rigid-body motions and contacts but refer only indirectly to the deformable body motions of the tissues of hand and arm. A reasonable hypothesis is that the information for the haptic perceptual system is defined over the patterning of tissue deformations brought about by the play of forces incident to the motions of limbs and cutaneous appendages and to contacts with adjacent surfaces. The patterning of the mechanical energy in the tissue medium would be in the form of different strains and rates of strains in different directions (Chan & Turvey, 1991; Solomon & Turvey, 1988; Turvey, Solomon, & Burton, 1989). Given an appropriate field description of this transforming structured array (cf. field description of optic flow, Koenderink & van Doorn, 1981; Waxman & Ullman, 1985), a single variable might be isolated to which the perception of the extent of a hand-held object was specific. This variable would be invariant over the different conditions in which extent was perceivable by dynamic touch—namely, holding motionless (Burton & Turvey, 1990), wielding (Burton & Turvey, 1990; Solomon & Turvey, 1988; Solomon et al., 1989a, 1989b), and striking adjacent surfaces with a variety of motions (e.g., directed downward, Chan & Turvey, 1991; or directed outward, as in the present research). The latter conjecture is in keeping with the related hypotheses that perception is specific to information and that, for the perception of any given environmental property, there is a single invariant to which that perception is specific (see

Burton & Turvey, 1990; Chan, Carello, & Turvey, 1990; Gibson, 1960, 1966; see also Cutting, 1986, 1991, for a contrasting view).

There was much consistency throughout the experiments of the present series in the scaling of perceived probe length to I and P , with the single exception of Experiment 2. Excluding Experiment 2, the exponent for I ranged between .21 and .32, and the exponent for P ranged between .09 and .13. The observed exponents across experiments were closely similar to those reported by Chan and Turvey (1991, Experiment 9) for a very different contact configuration and probing motion (to reiterate, they obtained an I exponent of .21 and a P exponent of .06) and with the sound of contact masked by white noise. The exponent for I is in the ballpark of the exponents reported previously under conditions of wielding without contact, which tend to be in the range of .2 to .4, with a value in the vicinity of .3 occurring most frequently. Solomon et al. (1989b) have argued that an exponent on I of $\frac{1}{2}$ is to be expected from dimensional considerations of the mapping between the rotational inertia of a homogeneous cylindrical probe and its length. These considerations apply equally to a cylindrical probe wielded without and with contact. However, direct comparison between contact and no contact, as in Experiment 1 of the present series, suggests that contact reduces the exponent on I . If this observation proves reliable, then it should play a role in developing an understanding of the tissue deformation variable to which—by the single-invariant hypothesis advanced above—perceived object extent is specific under all wielding conditions.

Although P has proven valuable in accounting for variance in perceived probe length beyond that accounted for by I , its status as a dynamical parameter is less clear and less secure than that of I . As noted in the introduction, three-space rigid-body motion about a fixed point is expressed by equations of motion in which the coupling role of I (more specifically, of the inertia tensor $\mathbf{I}$) is unequivocal. By comparison, the ascription of such a role to P (viz., coupling the states of the axis to the impulsive forces of contact) is equivocal. Ordinarily, a parameter complex involving mass, center of mass, I , distance from axis to contact point, and so on appears in equations of motion expressing the effects of shocks (e.g., Den Hartog, 1948). Barac-Cikoja and Turvey (1991) identified, from first principles, an invariant complex for perceiving aperture size by striking. Unfortunately, it was not found to apply in the present case of perceiving by dynamic touch (evaluations were attempted in each of the applicable situations of the present series), and contact parameters more principled than P have so far eluded us. In sum, P should be regarded cautiously; at best, it is an indicator of the relevance of contact parameters to the perceiving of probe length when surfaces are struck and it is a motivation for pursuing in more detail, and with more refined conceptions, the dynamics of probing. As intimated above, the anomalous scaling of Experiment 2 may be a measure of how inadequate our understanding is of the contact parameter affecting probe-length perception.

Parameters Affecting Perceived Surface Distance

Turning to the perception of surface distance, it is apparent from the outset that we ought not expect the rotational inertia of the probe and the impulsive forces of contact to play the same roles that they play in probe-length perception. Contact is necessary to the perception of surface distance by dynamic touch; it is not necessary to the perception of probe length by dynamic touch. Furthermore, successful perception of surface distance by probing in the most general of cases would seem to be dependent on the degree to which it is indifferent to the probe's extent. Given the dependence of probe-length perception on I , the foregoing claim amounts to the expectation that I cannot be assuming anything like the role in surface-distance perception that it assumes in probe-length perception. The graphic representation of the data of Experiment 3 (Figure 5) makes it very clear that the two perceivings depend very differently upon I . Every analysis of the data of the present experiments bearing on the issue confirmed that perceiving surface distance was independent of probe length and probe-length perception. In sum, logical considerations and experimental results suggest that probe rotational inertia is contributing to surface distance perception in a manner that is specific to that particular perceptual task.

Despite the apparent forcefulness of the preceding conclusion, there are reasons to be cautious. To begin with, it is at odds with what one might infer from the comparison of the exponents of I in the scalings of perceived surface distance and perceived probe length. The power functions for perceived surface distance were reasonably consistent across the experiments, with the exponent on Θ ranging between .55 and .68 and the exponent on I ranging between .16 and .31. The latter range approximates that for I in the scaling of probe-length perception under conditions of wielding with contact (.21-.32). This similarity of exponents might point to a similarity of roles for I in the two perceptual tasks, or it might not. The argument against equating similar exponents with similar roles is that the method of multivariable power functions, while invaluable to the determination of scaling relations between dependent and independent measures, is not especially illuminating on the manner in which the independent measures link to bring about the scaling. The same scaling may show up for very different physical reasons. (On the positive side, when the underlying dynamical system is known, then it can be seen that the method of multivariable power functions yields a scaling conforming to that prescribed by the equation of the underlying dynamic; see Turvey, Schmidt, Rosenblum, & Kugler, 1988.) A second reason for caution in adopting the above conclusion, however, suggests that the first reason may be on target. Consider the experimental situation in which the lengths of the probes (the distances of the tips of the probes from the hand) are always equal to the distances of the surfaces from the hand, as in Experiment 1. Now probe inclination is a parameter with the fixed value of 0 across conditions and noncontributory to the different distance perceptions across the different conditions. What param-

eters might we expect to govern surface-distance perception under these circumstances? The experiments of Chan and Turvey (1991) found I and P to be the governing parameters, and our analyses of their data show that, in two of the three surface-distance experiments relevant to the issue, the exponents were similar to those found in our research and theirs for probe-length perception. To be specific, in Experiments 6 and 7 of Chan and Turvey, the exponents on I were .25 and .17, respectively, and the exponents on P were .09 and .03, respectively; in their Experiment 5, the I exponent was .36 and the P exponent was .17. Although the preceding scalings do not make an unequivocal point, they do highlight the possibility of conditions in which perceived surface distance and perceived probe length scale in the same way to the same parameters. This possibility defines the second reason for caution, and it may have implications for understanding the hypothesized information types. If perceiving surface distance and perceiving probe length are specific to invariant properties of the tissue deformation field, then it can be assumed that (1) both properties are linked to the mechanical parameter space composed of Θ , I , and P , and (2) as Θ approaches 0, the magnitudes of these deformation quantities approach equality.

With surfaces closer than probe lengths, our experiments show, as noted, a relatively constant scaling of perceived surface distance to Θ (precisely, $\cos \Theta$) and I . (Additional statistical analyses revealed that the power function from any one of Experiments 3–6 would account for approximately 90% of the variance of the data from all four experiments taken together.) In the present analyses, Θ has been advanced as a parameter coupling the forces on the probe (in wielding and striking) to the states of the probe. However, as with P , it is important to underscore that the manner in which Θ affects this coupling is unknown in the absence of a thoroughgoing account of the dynamics of probing.

Selective Perception of Probe Length and Surface Distance

On any given trial, subjects asked to perceive either the length of the probe or the distance of the surface probed were able to do so without confusion. The experiments have shown that these distinct perceptions of extent were based on different configurations of the parameters involved in the mechanical act of striking. The implication is that the subjects could detect selectively the tissue deformation consequences of one parameter configuration or the other and, in so doing, perceive the spatial extent in question.

How might the perception achieved by dynamic touch come under such restrictions? One potential answer is that subjects behave differently when instructed to perceive surface distance than when instructed to perceive probe length. Perhaps one manner of striking adjacent surfaces emphasizes the I , Θ configuration of parameters and another emphasizes the I , P configuration. There is ample evidence that a perceiver engages in activities that will reveal information specific to the perceiver's intent. Doc-

umentation of property-specific haptic explorations began with Lotze (1856/1885) and has been continued by Katz (1925/1989), Gibson (1962), and Lederman and Klatzky (1987). As a simple example, selective attention to the weight of an object and to the throwability of an object (Bingham, Schmidt, & Rosenblum, 1989) requires hefting, whereas selective attention to its hardness requires palpating. More germane for the present results, perceivers appear to engage in patterns of wielding to perceive shape different from patterns of wielding to perceive orientation (Turvey, Carello, & Kim, 1990). Whether or not exploratory activities distinguish the two kinds of perceiving studied in the present experiments will have to be resolved by future research. For now, it should be noted that casual inspection of subjects in the present experiments revealed no obvious behavioral differences under the two intentions.

There are different ways of construing the selectivity of perceiving. In broad terms, the construal intimated in the preceding is that of attention as "effect" rather than attention as "cause," a distinction drawn originally by William James (1890/1950) and reintroduced recently by Johnston and Dark (1986). In attention-as-cause theories, the limited processing capacity of the brain imposes a constraint on how much can be perceived—selective attention is a mechanism that causes input to be filtered, attenuated, or otherwise rejected. If the processing capacity were unlimited, it has been argued, then there would be no need for attentional mechanisms (Broadbent, 1971; Mesulam, 1985). In attention-as-effect theories, the information that is detected is constrained by the intentions of the perceiver—selective attention is the effect of what perceivers need to know and, particularly, need to do. Attention will be evident, therefore, whenever there are potentially competing information kinds for satisfying an intent and controlling an action (Allport, 1989; Gibson, 1966; Michaels & Carello, 1981).

Concluding Remark

Self-evidently, touch is not simply a proximal sense. By probing with cutaneous appendages (e.g., beaks in the case of birds, hand-held implements in the case of humans), one can ascertain, without vision and without sound, the properties of objects and surfaces at a distance from the body. Because probings engender torques and impulse forces, and because of the mechanoreceptor basis of the haptic perceptual system, an understanding of touch as a distance sense must begin with an appreciation of the dynamics of probing. Recognizing the natural division between the variable forces impressed upon the probe, the variable states of the probe, and the fixed parameters that couple them, research can be guided by the reasonable hypothesis that what is perceived under conditions of probing is constrained primarily by what is invariant. The same holds for the perceptions of the extents of hand-held objects that follow from wielding without contact. Consonant with the preceding hypothesis, the present experiments have highlighted the significance of the parameters inherent within the dynamics of wielding

objects and striking surfaces. Beyond this, the experimental results should be viewed circumspectly, given that the parameter configurations of the obtained scaling equations (power functions) are, at best, approximations to the parameters of relevance. Future experiments and developments in the dynamical analyses of wielding and probing will be needed to clarify the exact nature of the defining parameters and the chain of specificity (Gibson, 1960) that links these mechanical quantities to invariants of tissue deformation and awarenesses of spatial (geometric) dimensions.

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NOTES

1. There is some disagreement as to whether haptically perceived length is equivalent to visually perceived length (e.g., compare Jastrow, 1886; Kelvin & Mulik, 1958; and Teghtsoonian & Teghtsoonian, 1970; with Chan et al., 1990; Jones, 1983; Kelvin, 1954; and Teghtsoonian & Teghtsoonian, 1965). For present purposes, this sort of visual match has two advantages: (1) It can be adjusted while the subject is holding the rod, thus avoiding an explicit memory demand (Durlach et al., 1989), and (2) the continuously adjustable surface yields metrical data, thereby allowing a more precise assessment of the influence of mechanical variables than the simple ordering that would be permitted by haptic-haptic comparisons.

2. Because the sounds of a wooden rod striking a wooden surface are quite sharp and not easily masked, several steps were necessary to eliminate auditory information. White noise was played over "personal stereo" earphones, which were themselves worn under industrial headphones. The surface to be struck was 2.5 cm thick to dampen vibration. Finally, in order to keep the required noise level reasonably comfortable, the sounds of striking were further dulled by covering the surface with a rubberized mat. The resulting sounds were easily audible without earphones. Separate pilot experiments were run for perceived surface distance and perceived probe length. In each, information condition (haptics alone or haptics + acoustics) was blocked and counter-balanced over subjects. Both surface distances ($p < .0006$) and probe lengths ($p < .0002$) were discriminated, but neither the main effect of information condition nor the interaction with extent was significant in either experiment.

APPENDIX

Figure A1 shows how a variety of mechanical properties are affected by our experimental manipulations. Calculation methods are based largely on Den Hartog (1948).

Moment of Inertia

The rod is treated as a linear bar. I about the x -axis through the bar's center of mass (CM) is given by

$$I_{CM} = ml^2/12, \quad (1)$$

where m is the mass of the rod and l is its length. Because the rod is wielded from one end, the parallel axis theorem is required to obtain I about this new axis:

$$I_{end} = ml^2/12 + m(l/2)^2 = ml^2/3. \quad (2)$$

The added term reflects the distance between the two axes. If a mass is attached to the rod, then its moment of inertia is simply added to that of the rod. For a rectangular block (as was used in Experiment 1),

$$I_{end} = m(a^2 + b^2)/12 + mr^2, \quad (3)$$

where m is the mass of the block, a and b are the sides perpendicular to the shaft of the rod, and r is the distance between the position of the block (through its CM) and the center of rotation (the mr^2 term is the parallel axis theorem component). If the added mass is a circular disk (as was used in Experiments 2-6), then the appropriate formula is that for a hollow cylinder:

$$I_{end} = m/12(3R_1^2 + 3R_2^2 + H^2) + mr^2, \quad (4)$$

where R_1 is the inner radius (i.e., the radius of the hole), R_2 is the outer radius, and H is the height of the cylinder. As before, mr^2 is the parallel axis theorem component.

Distance to Center of Percussion

$$P = L - CP, \quad (5)$$

Figure A1. A rod is swung about a point of rotation in the wrist and struck against a vertical surface. When a mass is attached to the uniform rod, several mechanical properties change as a function of the location of the mass. In each panel, an "X" indicates the metrical center of the plain wooden rod; all rods are of length L . (a) For a homogeneous wooden rod, the center of mass, CM, is at the center of the rod; the center of percussion, CP, is $1/2L$ from the distal end of the rod. (b) Attaching a mass on the proximal side of X moves CM and CP toward the hand. (c) Attaching a smaller mass at the same location moves CM and CP in the same direction, but less so. (d) Attaching the smaller mass on the distal side of X moves CM and CP to the distal side of the original CM. The rod depicted in (a) will have the smallest moment of inertia I , (c) will be less than either (b) or (d). The ordering of (b) and (d) will depend on the precise size and location of the mass. None of these is affected by the angle of strike. CP is undefined when the rod does not contact a surface.

where CP is the center of percussion or oscillation, which is given by

$$CP = I/SM. \quad (6)$$

I is the moment of inertia, and SM is the static moment of the rod-plus-added mass. I is calculated as above, and static moment is given by

$$SM = m \cdot CM. \quad (7)$$

The center of mass of the the rod-plus-added mass is

$$CM_{total} = (m_{rod} \cdot cm_{rod} + m_{added \ mass} \cdot cm_{added \ mass}) / m_{rod} \cdot m_{added \ mass}. \quad (8)$$