Perceiving the lengths of rods wielded in different media

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In two experiments, we investigated the ability of participants to report the lengths of rods wielded in air or water. Homogeneous aluminum rods were employed in Experiment 1. The inertia of the rods was manipulated in Experiment 2 through the use of attached masses. Although the torques required in order to wield rods in water are substantially greater than those required to wield rods in air, the perceived lengths of rods wielded in the two media were very similar. Perceived length was found to be a function primarily of inertia in both media. The experiments also revealed a small influence of resistance due to the denser medium of water. The results demonstrate the ability of perceivers to extract a physical invariant from a complex array of forces. The discussion is focused on the role of invariants in dynamic touch.

The present article is directed at the spatial abilities of dynamic touch. This is the kind of touching that takes place when an object such as a hockey stick, a hammer, a cup, or a pencil is grasped and carried, turned, swung, positioned, and so forth. It is the kind of touch that is dominant in everyday manipulatory activity: The hand and fingers are in contact with only a part of the manipulated object, and the object, both in stasis and in motion, affects the tensile states of the muscles, tendons, and ligaments of the hand and arm. The latter tissue deformations (induced by the forces and torques engendered by holding and manipulating) characterize dynamic touch, more so than deformations of the skin and changes in joint angles (Gibson, 1966). Traditionally, cutaneous touch (e.g., an object resting on the skin) and haptic touch (e.g., the hands enveloping an object and sweeping thoroughly and freely over its surfaces) have been the types of touch, or kinds of haptic subsystems (Gibson, 1966), that have received the most attention. In the service of manipulatory activity, and in the service of locomotion

guided by a hand-held implement (e.g., Burton, 1992), however, the touch of greatest practical significance is dynamic touch. Haptic perceptions of holding must play a significant role in the control of actions involving hand-held objects. In the present article, we address the basis of the haptic ability to perceive the magnitude of hand-held objects wielded in air or water.

Dynamic touch is related primarily to the tensile states of muscles and tendons as these tissues undergo deformation during exploratory and performatory activity (Gibson, 1966; Turvey, 1996). Useful distinctions among the different kinds of touch have been provided by Loomis and Lederman (1986; see also Révész, 1950). Within their framework, *tactile perception* refers to perception based on information arising solely from cutaneous stimulation. *Kinesthetic perception* refers to the awareness of body posture, wielded objects, and probed surfaces, on the basis of afferent information originating in the muscles, joints, and skin. This includes cases in which "cutaneous stimulation serves only to indicate contact with the stimulus, while variations in kinesthetic stimulation convey all of the spatial information essential to the performance of the task" (Loomis & Lederman, 1986, p. 31-3). Finally, *haptic perception* refers to cases in which both the cutaneous and the kinesthetic senses convey information about distal objects and events. The kind of touch classified by Loomis and Lederman (1986) as kinesthetic is an apt description of that which is presently investigated under the term *dynamic touch* (see Pagano, Carello, & Turvey, 1996). Since the traditional usage (and most common present day usage) of the term *kinesthesia* occurs only with respect to the perception of the body and limbs, the term *dynamic touch* is often more useful. The term *dynamic touch* is more general, referring to use of the muscle sense in the detection of spatial properties of objects and adjacent surfaces. Thus, dynamic touch is implied not only in the perception of the body and limbs, but whenever an object

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is grasped and wielded, whenever a solid surface is palpated or vibrated, and whenever a hand-held implement is brought into contact with other objects (see, e.g., Turvey & Carello, 1995).

Movements of hand-held objects and body segments relative to each other are always rotational—occurring about one or more joints—and thus the tissue deformations in question are the physical consequences of rotational dynamics. Rotational motions about a fixed point of the kind characteristic of wielding an object about a joint follow from $N_i = I_i \dot{\omega}_i$. When one wields a given object, the torque N_i and angular acceleration $\dot{\omega}_i$ are coupled by inertia I_i . Thus the amount of torque required to produce a given angular acceleration is a function of the object's inertia. We will quantify inertia by I_1 , the maximum moment of inertia (the inertia about the major principal axis).¹

Whereas mass is an object's resistance to linear displacement, inertia is an object's resistance to angular displacement. That is, inertia is an object's resistance to being rotated. Inertia is based on mass and length; it has the dimension of (mass) $\times$ (length)². Because of its dependency on squared length, rotational inertia is often referred to as the *second moment* of an object's mass distribution. This dependency of inertia on length reveals the way in which inertia is based on an object's mass distribution relative to the point of rotation.

Inertia is greatest when an object's mass is concentrated far from the point of rotation. A baseball bat, for example, is typically grasped at its thin end and swung with its thicker end far from the hand. With the mass of the bat concentrated far from the hand, the inertia is much greater than it would be if the bat were turned around to be grasped and swung from the thicker end (see Turvey, 1996, Figure 3). Such a reversal would alter neither the bat's length nor its overall weight, but it would alter the bat's inertia. In terms of the equation $N_i = I_i \dot{\omega}_i$, this means that in initiating a swing, greater muscular torque N_i is required in order to produce a given acceleration $\dot{\omega}_i$ for a bat held at its thin end, owing to the greater inertia I_i associated with that configuration. Although a batter is undoubtedly sensitive to the torque produced while swinging a bat, a recent series of experiments has demonstrated that the perception of persistent object properties—such as a bat's length—is a function of sensitivity to inertia.

With a given point of rotation, inertia does not change; it is a constant property of the rigid object. It can, therefore, be used to quantify the information for perceiving the object's unchanging dimensions (see, e.g., Solomon, 1988; Solomon & Turvey, 1988; Turvey, 1994). Even when an object's motions occur about several joints—such as the wrist, elbow, and shoulder taken singly or in combination—an invariant rendering of inertia can be found that maps onto perceived object properties (Pagano, Fitzpatrick, & Turvey, 1993). The implication is that dynamic touch is tuned to the invariant parameters of the object's dynamics, rather than to the varying states (displacements, velocities) and torques (see Amazeen & Turvey, 1996).

Recent research on dynamic touch has revealed that inertia maps onto perceived object magnitudes such as object length (e.g., Fitzpatrick, Carello, & Turvey, 1994; Pagano et al., 1993; Pagano & Turvey, 1993; Solomon & Turvey, 1988; Solomon, Turvey, & Burton, 1989a), width (Turvey, Burton, Amazeen, Butwill, & Carello, 1998), shape (Burton, Turvey, & Solomon, 1990), and weight (Amazeen & Turvey, 1996). Importantly, in this work researchers have investigated other mechanical parameters as being possibly relevant to wielding, such as torque and kinetic energy (and thus angular velocity and acceleration), muscular torsion, mass, center of mass, and center of oscillation; each of these, however, has been ruled out in favor of inertia (see Amazeen & Turvey, 1996; Burton & Turvey, 1990; Solomon & Turvey, 1988; Solomon, Turvey, & Burton, 1989a, 1989b).²

In the present set of experiments, we sought to explore the role of inertia in the perception of length further, by changing the medium in which the rods were wielded. When the medium varies, torques produced to counter the medium affect the participant's ability to wield a rod. The total torque required in order to rotate an object in a given medium is a function of resistances tied to inertia plus resistances offered by the medium. The resistances due to the medium, or drag (D), are related to the projected surface area (A_p) of the object and the density of the medium. For cylindrical rods oriented perpendicular to the direction of motion, A_p is equal to the length of the rod immersed in the medium (e.g., water) times its diameter. For a rod with a given A_p , a quantification of D can be obtained by scaling A_p by the density of the medium. Thus for a rod in air, $D = 1.2A_p$, and for a rod in water, $D = 998.2A_p$, the densities of air and water being 1.2 and 998.2 kg/m³, respectively (assuming an ambient temperature of 20°). Whereas for thin rods the resistance due to air is typically negligible, that offered by water is substantial, being nearly a thousand times as great as that offered by air. Thus the total torque required in order to rotate an object through water is many times greater than that required in order to rotate it in air, the denser medium offering more resistance to motion. As a result, there are greater deformations and distortions in the tissues of the body when one is wielding an object in water. An important test of the inertia tensor hypothesis would be to determine whether perceivers could extract the physical invariant of inertia from the complex arrays of forces created by the denser medium of water.

As indicated above, the pick-up of inertia has been robust over experimental manipulations of the forces (torques, pressure patterns) acting on the haptic tissues. Various experiments have manipulated wielding rate (Amazeen & Turvey, 1996; Solomon & Turvey, 1988), orientation to gravity (Solomon et al., 1989a; Turvey, Burton, Pagano, Solomon, & Runeson, 1992), the configuration of the limb as it performs the wielding explorations (Solomon & Turvey, 1988; Solomon et al., 1989a), number and location of joints employed (Pagano et al., 1993), locations on the body surface in contact with the

object (Carello, Fitzpatrick, Domaniewicz, Chan, & Turvey, 1992; Pagano, Kinsella-Shaw, Cassidy, & Turvey, 1994), and the presence of an intervening probe (Peck, Jeffers, Carello, & Turvey, 1996), without appreciably altering the mapping from inertia to perceived object properties.³

Of particular relevance to the present research are experiments in which the magnitudes of torque have been explicitly manipulated through variations in winding rate while the specific values of inertia have been held unchanged. Solomon and Turvey (1988, Experiment 4) constrained the winding motions to a repetitive, nearly planar motion about the wrist of fixed amplitude. Varying the frequency of winding by means of a metronome was found to have no effect on perceived length despite the resulting systematic variations in torque. Amazeen and Turvey (1996, Experiment 2) similarly manipulated torque in their experiments involving haptic weight perception and also found that perception was a function of inertia, remaining unchanged over variations in winding frequency. Importantly, Amazeen and Turvey recorded the angular positions, velocities, and accelerations of the object during winding and were thus able to measure the resulting angular acceleration and torque values and confirm that neither contributed anything additional to perceived heaviness once inertia was included in the model. These results indicate that perception by winding is uniquely constrained by inertia and is not a function of the maximum or time average values of torque (or of kinetic energy or work). Since winding in water likewise involves a uniform increase in torques, the pick-up of inertia may be robust under manipulations of medium.

The Present Study

Our first experiment was designed to extend Solomon and Turvey's (1988) Experiment 1 involving homogeneous aluminum rods (see also Pagano et al., 1993). They found that participants could accurately perceive the lengths of occluded uniformly dense rods by winding the rods in air. We asked participants to wind rods in air and water during different portions of the experiment, to determine whether the function from actual length to perceived length would be altered by the presence of the denser medium of water. Our second experiment extended Solomon and Turvey's Experiment 5, in which the welded aluminum rods had masses attached (see also Pagano et al., 1993; Solomon et al., 1989a). By using these attached masses to break the covariation between inertia and length, Solomon and Turvey demonstrated that although length perception by dynamic touch follows actual length for homogeneous rods, this perception is actually a function of the mechanical quantity of inertia, rather than the geometric quantity of length. Our main goal in the present experiments was to determine whether perceivers would be able to extract the physical invariant of inertia from the complex arrays of forces created by the denser medium of water. In addition, these experiments were designed to determine whether length perception by dy-

namic touch would differ as a function of the varying resistances offered by the two media. Previous research did not of course reveal the possible role of the medium, because only dynamic touch in air was investigated.

Previous research indicated a negligible effect of altered air resistance on perception by dynamic touch. Average air resistance increases with angular velocity, but as has been noted above, no such variation appeared in the perceived values (Amazeen & Turvey, 1996; Solomon & Turvey, 1988). The irrelevance of air resistance is further underscored by identical mappings between inertia and perceived length for objects with very different surface areas (e.g., thin rods and large cubes; Fitzpatrick, Carello, & Turvey, 1994), and by identical mappings between inertia and perceived weight for objects constructed of thin cylinders that were either left bare or covered by a paper webbing designed to create a large volume (Amazeen & Turvey, 1996, Experiment 6). These results suggest that no change in effect should be observed with the addition of water resistance. However, although the magnitudes of air resistance varied greatly in previous experiments (although that was not the specific intent in those experiments), the overall torques required in order to counter the air resistance remained small. The utilization of water in the present study created much larger variations in resistance owing to medium, and thus provided a more sensitive test of possible medium effects.

An alternative hypothesis is suggested by experiments involving haptic probing. Haptic probing involves the winding of an object (the probe) in such a manner as to bring it into contact with environmental surfaces. Such research has been directed at the perception of aspects of environmental surfaces, such as distance (Carello, Fitzpatrick, & Turvey, 1992; Chan & Turvey, 1991), gap width (Barac-Cikoja & Turvey, 1991, 1993, 1995; Garrett, Barac-Cikoja, Carello, & Turvey, 1996), and properties of relevance to walking and posture (Burton, 1992; Fitzpatrick, Carello, Schmidt, & Corey, 1994). This work has also been directed at uncovering the effect of probing on perceived properties of the probe itself. The latter research has indicated that the perception of probe length is affected by contact with environmental surfaces (Carello, Fitzpatrick, & Turvey, 1992; Chan & Turvey, 1991). Specifically, these experiments have demonstrated that when a cylindrical rod is brought into contact with an external surface, perceived rod length is a function of both inertia and the rod's center of percussion. When no contact is made, the perceived lengths for the same rods are solely a function of I_{ij} . The center of percussion is a mechanical variable associated with contact forces. In the present experiments, the added water effectively acted as an external object that must be contacted. Although the water acted as a substance that must be displaced, rather than as an unyielding surface to be struck, it was possible that the contact forces associated with moving the rod through the water would alter the effect of inertia on perceived length. The appropriate parameter associated with the contact forces in the present configuration was

Table 1
Rod Length, Rod Mass, I_1 , and A_p
for the Rods Used in Experiment 1

Rod Length (cm)	Rod Mass (g)	I_1 ($\text{kg} \cdot \text{m}^2 \times 1,000$)	A_p (cm^2)
20	71.2	0.751	10.16
30	104.6	2.428	22.86
40	137.7	5.858	48.26
50	172.6	11.831	60.96
60	207.0	20.950	83.88

D , a measure of the amount of a medium that must be displaced to move the rod, scaled by the medium's density.

EXPERIMENT 1

The resistance produced by a medium increases proportionately as rod length, and thus D , increases. As the objects become longer, more surface area is exposed to the medium. If the influence of torques associated with the increased surface area is large, we would expect an interaction between rod length and medium. Specifically, perceived length should increase with actual length in all media, owing to the covariation of length with inertia, but if participants rely heavily on torques due to D , this increase will occur at a greater rate in water than in air. Alternatively, if participants rely mainly on inertia, there should be little difference in perceived lengths of similar rods wielded in air and water, because inertia remains invariant over medium.

Method

Subjects. Ten undergraduate students (5 men and 5 women) at Clemson University participated in Experiment 1 in partial fulfillment of course requirements. Two of the male and 1 of the female participants were left handed.

Materials and Apparatus. The objects used were five aluminum rods 20, 30, 40, 50, and 60 cm in length. The lengths, masses, I_1 values, and A_p values for the rods are presented in Table 1. A 25-cm rod was used for instructional purposes. Each rod had a radius of 0.635 cm. The experiment was conducted in a small room that was partitioned in half by a curtain. The participant sat on a tall stool and placed his/her right arm through a narrow opening in the curtain. Two 100-gal. containers, one filled with water and the other empty, were positioned on the side of the curtain opposite to the participant. The containers had the shape of truncated cones 100 cm tall, 73 cm in diameter at the top, and 60 cm in diameter at the base. The participant's forearm rested on a flat surface positioned over the top of one of the containers, with the wrist at the edge of the surface. The participant was instructed to keep the forearm immobile against the horizontal surface. In the container with water, the surface of the water was 6 cm below the participant's wrist. The fact that a portion of each rod was not submerged was taken into account in the calculations of A_p and D . On the participant's side of the curtain was a visible 100-cm report rod, consisting of a pointer attached to a line and pulley system that ran along the length of a vertically oriented rod. The experimenter read the position of the pointer from a measuring tape that was not visible to the participant. The experimental arrangement is depicted in Figure 1.

At the beginning of each trial, one of the rods was placed in the participant's right hand in the downward position. The rod was held in an enclosed fist with the top end of the rod even with the thumb,

and the length of the rod extended downward into one of the containers. The participant's task was to wield the rod by using motions about the wrist and to use the left hand to position the marker on the report rod so that the distance from the top end of the report rod to the tip of the marker corresponded to the length of the wielded rod. Each participant was allowed to wield the object and to readjust the report surface for as long as he/she desired until satisfied with his/her judgment.

In half of the trials, the rod was wielded in the container with water; in the remaining trials, the rod was wielded in the empty container. Half of the participants received water first; the remaining participants received air first. After half of the experiment was completed with the one container, the chair and report device were repositioned along side the other container. The participants were instructed to avoid hitting the sides of the container during wielding. If the side of the container was hit, the data from that trial were not recorded and it was repeated at a later time. The participants had little difficulty complying with this instruction; no participant hit the side more than twice, and 6 never hit at all. With the exception of the restrictions to move only about the wrist and not to hit the side of the container, the participants were free to wield the rods using three-space motions about any and all desired axes. The participants were told that the containers were used to restrict the amplitude of movement; they were not informed that wielding might occur in water. Ear protectors were worn during the experiment to muffle any sound produced by the water. Each rod length was wielded four times in each of the media, for a total of 40 trials. The rod lengths were presented in a randomized order with no practice or feedback given. The experiment lasted approximately 40 min.

Results and Discussion

Figure 2 shows the results of Experiment 1 with perceived length (L_p) plotted as a function of actual length. Overall, mean L_p was 20.5, 31.3, 43.4, 59.4, and 73.1 cm for the 20-, 30-, 40-, 50-, and 60-cm rods, respectively. The mean perceived reachable distances with the rods wielded in air and water were 43.6 and 47.4 cm, respectively. A 2×5 analysis of variance (ANOVA) with within-

Figure 1. The apparatus used in the experiments.

Figure 2. Mean perceived rod length as a function of actual length and medium for Experiment 1. The error bars represent $\pm 1SE$ of measurement.

subjects factors of medium and rod length confirmed significant main effects for medium [$F(1,9) = 9.5, p = .01$] and rod length [$F(4,36) = 214.7, p < .0001$]. The medium $\times$ rod length interaction was nonsignificant [$F(4,36) = 1.0, p = .40$].

To test the relative contributions of I_1 and D , a multiple regression was performed predicting $\log L_p$ from $\log I_1$ and $\log D$.⁴ This multiple regression resulted in an $r^2(400) = .78$, with both $\log I_1$ and $\log D$ significant. The partial F s were 1,340.2 ($p < .0001$) and 10.8 ($p < .01$), for $\log I_1$ and $\log D$, respectively. The significant main effects indicate that both inertia and drag contributed to the participants' judgments of length. The resulting regression equation was $\log L_p = \log 280 + .38 \log I_1 + .01 \log D$, yielding the power function $L_p = 280(I_1^{.38} \times D^{.01})$. The scaling of I_1 by .38 is nearly identical to that which has been observed previously in experiments involving wielding only in air (e.g., Fitzpatrick, Carello, & Turvey, 1994; Pagano & Turvey, 1993). This power function is depicted in Figure 3 for the mean data. Similar multiple regressions predicting mean L_p values resulted in r^2 s(10) = .98, .94, .97, .99, .98, .99, .95, .96, .97, and .94, for Participants 1–10, respectively, and .996 for the overall means.

The much smaller partial F for D compared with I_1 —10.8 versus 1,340.2—indicated that although D was statistically significant, it contributed much less than did I_1 . This was confirmed by a simple regression predicting $\log L_p$ from $\log I_1$, resulting in an $r^2(400) = .77$, and second simple regression predicting mean L_p from $280(I_1^{.38})$ resulting in an $r^2(10) = .97$. That is, these simple regressions produced r^2 values—.77 and .97—very close to those which were observed when D was included in the model—.78 and .996, respectively.

In summary, the results of Experiment 1 indicate a small main effect for media but no media $\times$ rod length interaction. Perception of rod length was a function of inertia in both air and water, with a small effect of the additional torques associated with the denser medium of water. In short, participants were able to extract the physical invariant of inertia from a complex array of forces, with the additional forces associated with overcoming water resistance increasing perceived length by a small factor.

EXPERIMENT 2

In Experiment 2, we sought to further explore the role of inertia and drag in the perception of rods wielded in different media. The rods used in Experiment 1 were such that length, and thus A_p and D , were highly correlated with I_1 (see also Pagano et al., 1993; Solomon & Turvey, 1988). This relation might have obscured the separate contributions made by inertia and D . In Experiment 2, I_1 was manipulated independently of length and D by the attachment of masses at different positions along the rods. By manipulating the location at which masses are attached along rods of similar mass and length, we were able to manipulate inertia while holding the overall mass, geometric length, and D constant. The inertia values are larger when a mass is placed farther from the point of rotation than when it is placed near that point. Any effect of mass placement on perceived length is due to inertia, and not due to mass, length, or D per se.

Method

Subjects. Twelve undergraduate students (3 men and 9 women) at Clemson University participated in Experiment 2 in partial fulfillment of course requirements. One of the male participants was left handed, and the remaining participants were right handed. None of the subjects had participated in Experiment 1.

Figure 3. Mean perceived rod length predicted from the power function obtained from the multiple regression of inertia (I_1) and drag (D) for Experiment 1.

Table 2
Rod Length, Rod Mass, Added Mass, I_1 , and A_p as a Function of Mass Placement Condition for Rods Used in Experiment 2

Rod Length (cm)	Rod Mass (g)	Added Mass (g)	I_1 ($\text{kg} \cdot \text{m}^2 \times 1,000$)	A_p (cm^2)
Added Mass Placed Near to Hand				
30	106.5	58.4	3.314	27.36
37	131.6	60.0	5.602	36.25
44	157.5	55.4	9.006	45.14
50	172.7	58.4	12.674	52.76
Added Mass Placed Far From Hand				
30	106.5	58.8	6.013	27.36
37	128.0	58.5	10.368	36.25
44	156.2	58.2	16.660	45.14
50	177.1	59.2	23.696	52.76

Materials and Apparatus. The aluminum rods used in Experiment 2 were 30, 37, 44, and 50 cm in length. Two rods of each length were used, for a total of eight rods. Each rod had a mass of approximately 60 g added to it. In one set of rods, masses were added at the distal (bottom) end of the rod, far from the hand. In the other set of rods, masses were placed 14.5 cm from the proximal (top) end of the rod, near to the hand. Table 2 presents length, mass, added mass, I_1 , and A_p for the rods used in Experiment 2. Each rod configuration was wielded three times in each of the media, for a total of 48 trials. The experiment lasted approximately 45 min. All other procedures were identical to those used in Experiment 1.

Results and Discussion

Overall, mean L_p of the 30-, 37-, 44-, and 50-cm rods were 28.7, 35.9, 44.7, and 52.7 cm, respectively. Mean L_p with the added mass placed near and mass added far were 36.9 and 44.1 cm, respectively. The mean perceived lengths of the rods wielded in air and water were 39.1 and 41.9 cm, respectively. A $2 \times 2 \times 4$ ANOVA with within-subjects factors of mass placement, media condition, and rod length confirmed significant main effects of mass placement [$F(1,11) = 64.1, p < .0001$] and rod length [$F(3,33) = 58.0, p < .0001$], but not media condition [$F(1,11) = 1.8, p > .10$]. There was a significant mass placement $\times$ length interaction [$F(3,33) = 6.1, p < .01$], but all other interactions were nonsignificant ($p > .05$).

To test the relative contributions of I_1 and D , a multiple regression was performed predicting $\log L_p$ from $\log I_1$ and $\log D$. This multiple regression resulted in an $r^2(576) = .42$, with both $\log I_1$ and $\log D$ significant. The partial F s were 401.1 ($p < .0001$) and 6.9 ($p < .01$) for $\log I_1$ and $\log D$, respectively. The significant main effects indicate that both inertia and drag contributed to the participants' judgments of length. The resulting regression equation was $\log L_p = \log 230 + .40 \log I_1 + .01 \log D$, yielding the power function $L_p = 230(I_1^{.40} \times D^{.01})$. This power function is depicted in Figure 4 for the mean data. Similar multiple regressions predicting mean L_p values resulted in r^2 s(16) = .92, .93, .83, .91, .94, .87, .84, .89, .95, .88, .91, and .88, for Participants 1–12, respectively, and .96 for the overall means.

The much smaller partial F for D compared with I_1 —6.9 versus 401.1—indicated that although D was statis-

tically significant, it contributed much less than did I_1 . This was confirmed by a simple regression predicting $\log L_p$ from $\log I_1$, resulting in an $r^2(576) = .41$, and second simple regression predicting mean L_p from $230(I_1^{.40})$, resulting in an $r^2(16) = .93$ (see Figure 5). That is, these simple regressions produced r^2 values—.41 and .93—very close to those observed when D was included in the model—.42 and .96, respectively.

In summary, the results of Experiment 2 were similar to those of Experiment 1, except that no main effect of media was obtained in the ANOVA. There was no media $\times$ rod length interaction. Perception of rod length was a function of inertia in both air and water, with a small effect of the additional torques associated with the denser medium of water. As in Experiment 1, participants were able to extract the physical invariant of inertia from a complex array of forces, with the additional forces associated with overcoming water resistance increasing perceived length by a small factor.

GENERAL DISCUSSION

The main finding in the research reported here is that perceivers reliably extracted the physical invariant of moment of inertia from the complex array of forces associated with the media wielded. That is, perceived length was found to be constrained by inertia under both media. An additional finding was that while the perceived lengths of wielded rods are very similar for wielding in air or water, there was a small contribution of drag when wielding occurred in water. Each of these findings will be discussed in turn.

A major finding of the present work is that inertia constrained the perceived length of rods wielded in water as well as in air (see Figure 5). This result further demonstrates the ability of participants to pick up on physical

Figure 4. Mean perceived rod length predicted from the power function obtained from the multiple regression of inertia (I_1) and drag (D) for Experiment 2.

Figure 5. Mean perceived rod length predicted from inertia (I_T) for Experiment 2.

invariants, such as inertia, when these invariants are embedded within complex arrays of forces. As was discussed in the introduction, previous research has established the ability of dynamic touch to extract the invariants of rotational dynamics in different force conditions. In these previous experiments, the force conditions have varied according to the nature of the wielded object, the anatomical components involved in the wielding, and/or the pattern of movements allowed during exploration (e.g., Amazeen & Turvey, 1996; Carello, Fitzpatrick, Domaniewicz, et al., 1992; Pagano et al., 1993; Solomon & Turvey, 1988; Solomon et al., 1989a). In the present experiments, each of these aspects was held constant and the density of the medium was varied. The dependency of perception on inertia in both media adds to the growing understanding of invariants as a basis for perception within the context of active exploration (see, e.g., Gibson, 1966, 1979).

In both experiments, the perceived lengths of wielded rods tended to be very similar when the wielding occurred in air or water. Despite the very different forces involved in the two media, perceived lengths in the two media were of similar scale and were of a scale appropriate to the actual values. In Experiment 2, the mean L_p of the 30-, 37-, 44-, and 50-cm rods was 28.7, 35.9, 44.7, and 52.7 cm, respectively, and thus perceived length tracked actual length quite well despite variations in mass placement and media. However, the slopes for perceived length tended to be greater than 1, and in Experiment 1 the perceived lengths were consistently larger than the actual lengths (see Figure 2). This indicates that the participants may not have been producing *absolute* judgments of rod length.

To say that perception of rod length is appropriately scaled is to say that perceived length is in the scale of actual length (in the ballpark of the actual metrical values of rod length) despite the fact that perceived length de-

rives from nongeometric variables such as inertia and drag (Bingham, 1988; Carello, Fitzpatrick, Domaniewicz, et al., 1992; Solomon, 1988; Solomon & Turvey, 1988). Such scaling is thought to be a hallmark of smart perceptual systems, measuring instruments that are assembled out of a subset of possible anatomical components to register quantities specific to general dynamical principles (Bingham, 1988; Kugler & Turvey, 1987; Runeson, 1977). To be more exact, the type of scaling observed in the present results appears to be a *definite* scaling rather than an *absolute* scaling (Bingham, 1993, p. 1155). That is, although the participants did not exactly reproduce the absolute lengths of the rods in both media, they were able to provide estimates that were consistently within a marginal tolerance of actual values and were not merely reproducing a *relative* ordering of rod lengths (see Carello, Fitzpatrick, Flascher, & Turvey, 1998). The perceptions were a function of information more definite than that which would only support relative scaling. An absolute scaling would have appeared in the results as length perceptions that corresponded to the actual values despite variations in inertia (e.g., via mass placement) and drag (e.g., via changing media). Definite scaling, in contrast, was observed in the present data as length perceptions that were scaled to the physical quantities of inertia and drag. It seems that definite scaling characterizes perception by dynamic touch under a variety of circumstances (see also Carello et al., 1998; Peck et al., 1996; Turvey, 1996).

An additional finding revealed by the present research is that drag contributed to perceived rod length when wielding occurred in water. That is, while the perceived lengths were very similar in air and water, and while perception was a function of inertia in both media, drag was found to make a small but statistically significant contribution when wielding occurred in water. This finding suggests that when wielding occurs in water, participants may not be limited to the extraction of object properties rendered in the inertia ellipsoid. Recent research has identified the inertia ellipsoid as a useful geometric representation of inertia for dynamic touch (e.g., Fitzpatrick, Carello, & Turvey, 1994; Pagano & Turvey, 1993; Turvey, Burton, et al., 1998). Put simply, the inertia ellipsoid captures an object's mass "in the mean" about the point of rotation O (Starzhinskii, 1982). The inertia ellipsoid defines the magnitudes, shape, and orientation as perceived by dynamic touch.⁵

With respect to the directions of the inertia ellipsoid, it has been found that when participants wield an object, they can apprehend only the overall orientation of the object if it has two branches, not the orientation of the two branches taken separately (Pagano & Turvey, 1992). This is because the separate branches contribute to the orientation of a single ellipsoid, and such an object is indistinguishable from one with a single (larger) branch. In water, however, the presence or two branches will result in a very different pattern of drag from that of a single branch, and thus it may be possible for some aspects of separate branch orientations to be apprehended through

wielding the object in water. In short, the drag produced by a dense medium may allow for the pick-up of geometric properties not available when an object is wielded in air. The possible effect of drag on the perceived orientation of hand-held objects should be an important topic for further investigation.

The role of drag in the perception of rod length in water suggests that the present task was similar to those involving "haptic probing," the use of a hand-held tool or probe to act on or explore the environment (see, e.g., Barac-Cikoja & Turvey, 1991; Carello, Fitzpatrick, & Turvey, 1992). As outlined in the introduction, in some experiments the perception of rod length has been investigated in the context of haptic probing tasks. Such research has indicated that the perception of probe length is affected by contact with environmental surfaces. Specifically, these experiments have demonstrated that perceived rod length is a function of both I_{ij} and aspects of the contact dynamics (i.e., the rod's center of percussion) when the rod is brought into contact with an external surface and a function of I_{ij} alone when no contact is made (Carello, Fitzpatrick, & Turvey, 1992; Chan & Turvey, 1991). The present work has revealed that when there is contact between the rod and water, perceived rod length is similarly affected by both the rod's rotational inertia and aspects of the contact dynamics (i.e., drag as quantified by D). With respect to the registration of objects or surfaces in the environment, only about 1 in 3 participants in the present study indicated that they could tell when wielding had occurred in water.⁶ Even though participants were not instructed to pick up on aspects of the media and were not told that differences in media should be expected, this result was surprising. The question as to what aspects of a medium can be picked up via an intervening probe would be an interesting topic for future inquiry. It is possible that D would play a more prominent role if participants were asked to detect properties of the media rather than properties of the probe.

Collectively, the results of work involving the wielding of objects in a variety of contexts suggest that the perception of extent is a function of inertia when an object is wielded freely in air, of inertia and center of percussion when an object is brought in contact with a rigid surface, and of inertia and drag when an object is wielded in a dense medium. That is, at first glance haptic perception appears to be a function of different parameters in different circumstances. However, it is important to recognize that the measurable mechanical parameters associated with haptic manipulations refer directly to the mechanics of moving objects, and refer only indirectly to aspects of the deformable body motions of arm and hand tissues.

It has been hypothesized that the information for the haptic perceptual system is defined over properties of the tissue deformation patterns brought about by the play of forces incident to haptic manipulations, with such tissue deformation patterns likely expressed through strain and rate of strain tensors (e.g., Barac-Cikoja & Turvey, 1991, 1993; Burton & Turvey, 1990; Carello, Fitzpatrick,

Domaniewicz, et al., 1992; Fitzpatrick, Carello, & Turvey, 1994; Solomon & Turvey, 1988). Haptic perception is a direct function of these tissue deformations, with the relevant mechanical parameters acting as useful quantifications of invariant aspects of the forces acting on the tissues, and thus also of aspects of the tissue deformations themselves (Fitzpatrick, Carello, & Turvey, 1994; Pagano et al., 1993). As Barac-Cikoja and Turvey (1993, pp. 367–368) have pointed out, it is commonplace to reserve the term *information* for properties of ambient energy distributions satisfying invariant relations, and that for haptics the medium for mechanical energy distributions is composed of body tissues, just as air and water are the media for light, sound, and chemical energy distributions.

In summary, the main finding of this study is that perceived length is primarily a function of inertia when objects are wielded in air or water. This result underscores the ability of perceivers to extract a physical invariant from a complex array of forces, and makes a unique contribution to the growing body of evidence giving credence to Gibson's (1966) hypothesis that "the stimulus information from wielding can only be an invariant of the changing flux of stimulation in the muscles and tendons, an exterospecific invariant in this play of forces" (p. 127).

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NOTES

1. The complete equation to describe rotational motions about a fixed point is $\dot{N}_i = (I_{ij} \cdot \dot{\omega}_j) + \omega_j \times (I_{ij} \cdot \omega_j)$, where $\cdot$ is the matrix product, $\times$ is the vector cross product, N_i is the torque vector, ω_j is the angular velocity vector, $\dot{\omega}_j$ is the angular acceleration vector, and I_{ij} is the inertia tensor comprising of three eigenvalues defined about three eigenvectors (Goldstein, 1980). We use the term *inertia* to refer to the maximum moment of inertia I_1 , which is also referred to as the largest principal moment of inertia or eigenvalue. Units are torque $N_i = \text{N} \cdot \text{m}$, inertia $I_i = \text{kg} \cdot \text{m}^2$, and angular acceleration $\dot{\omega}_i = \text{rad} \cdot \text{sec}^{-2}$.

2. Recent work by Pagano, Aten, and Alley (1998) has underscored the falsifiability of the inertia hypothesis. They found that most participants did not use inertia when wielding with vision, despite the fact that inertia was available and had been used in a previous condition involving occluded wielding.

3. This should be qualified by noting that length perceived via static holding is a function of the first moment of inertia (Carello, Fitzpatrick, Domaniewicz, et al., 1992; see also Burton & Turvey, 1990) and that length perceived via an intervening probe is a function of a higher order inertia term incorporating both the inertia of the object and the inertia of the probe (Peck et al., 1996).

4. Preliminary analyses indicated no significant contribution of I_3 , the minimum moment of inertia.

5. A general explanation of dynamic touch's ability to perceive different extents of a hand-held object in different directions involves the attitude spinor in conjunction with the ellipsoid of inertia (Turvey, Carello, Fitzpatrick, Pagano, & Kadar, 1996; Turvey, Park, Dumais, & Carello, 1998).

6. During debriefing, only a few of the 22 participants of Experiments 1 and 2 indicated that they could tell that wielding had occurred in water during a portion of the experiment. Four participants discovered that they were wielding in water during the experiment when their hand inadvertently hit the water surface. Of the remaining 18 participants, 4 felt the rod was in water during the appropriate half of the experiment, 1 replied that he/she was wielding in oil or some other liquid that was thicker than water, 4 replied that they felt magnets were placed at the bottom of the barrel, 1 replied magnets or "some liquid," 4 replied that cloth or "something" was attached to the ends of the rods, and 4 noticed no difference between the two conditions and gave no indication as to why the chair and report device were moved to a second barrel after half of the experiment was completed. In a pilot experiment, we used standard-sized 30-gal. garbage cans. This proved problematic because in addition to more restricted wielding, motions of the rod would set the smaller quantity of water in motion in such a way that the rod became buffeted about by the water and was difficult to control. Of 10 participants in this pilot study, 3 replied water or a denser liquid, 4 replied magnets, rubber bands, or "something" causing resistance, and 3 indicated no difference.