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RESEARCH ARTICLE

Location of a grasped object's effector influences perception of the length of that object via dynamic touch

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Abstract
Perception of properties of a grasped object via dynamic touch (wielding) contributes to dexterity in tool use (e.g., using a hammer, screwdriver) and sports (e.g., hockey, tennis). These activities differ from simple object manipulation in that they involve making contact with an intended target. In the present study, we examined whether and how making (percussive) contact with a target influences perception of the length of a grasped object via dynamic touch. Making contact with a target by the tip resulted in a more accurate perception of the length than simple wielding. However, making contact with the target at a point along the length did not influence the accuracy of perception. These findings suggest that the location of a grasped object's effector influences perception of properties of that object via dynamic touch. We discuss these findings in terms of time-varying properties of vibrations generated by the percussive contact of the grasped object and target.

Keywords Dynamic touch · Effortful touch · Invariant · Perception · Tool use

Introduction

Humans can perceive various properties of an object or a surface either directly through the skin-surface contact or indirectly using a grasped object, employing one or more of three different haptic subsystems: cutaneous, haptic, and dynamic or effortful touch. Cutaneous touch concerns perception of touch, pressure, vibration, temperature, or pain through passive skin contact (Jones and Lederman 2006). Haptic touch concerns perception of the properties of an object or a surface through active exploration by a body part, such as fingers (Jones and Lederman 2006). Dynamic or effortful touch concerns perception of properties (e.g., length, width, shape, and orientation) of the body or objects attached to the body by movement via muscular effort (Carello and Turvey 2000; Turvey and Carello 2011). Upon grasping an object, the effectors of the three haptic subsystems shift from the hand to that object's tip (van Leeuwen et al. 1994; Baber 2003; Mangalam and Fragaszy 2016; Fragaszy and Mangalam 2018). Here, effector refers to the point on the body or the grasped object that makes contact with the intended target. This shift presumably alters the interdependence among the three haptic subsystems. For example, perception of the contour of an intended target using a grasped object via cutaneous touch is preceded by perception of one or more properties of that object via dynamic touch. Conversely, making contact with the intended target using a grasped object via dynamic touch contributes to perception of properties of that object (e.g., shape and hardness of the tip) via haptic touch. Given the interdependent functioning of the three haptic subsystems in human dexterity, a comprehensive understanding of this phenomenon is indispensable to advancing the field of haptic perception.

The localized activity of mechanoreceptors, thermoreceptors, and nociceptors in the skin underlie cutaneous and haptic touch (Jones and Lederman 2006), whereas global patterns of tissue deformation underlie dynamic touch. It is hypothesized that the anatomical basis of dynamic touch is a multifractal tensegrity (MFT) system (Turvey and Fonseca 2014). Localized load-bearing brings a global realignment of compression and tensional forces across the system comprising the skin, connective tissue, muscles, tendons, bones, joints, nerve fibers, et cetera. Consequently, local forces (e.g., at a particular anatomical site) that cast globally

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(i.e., across the whole system) provide the informational support for perception via dynamic touch. Individuals can perceive specific properties of a grasped object by wielding it with minimal effort (Burton and Turvey 1990; Carello et al. 1992a), by grasping and wielding it at different positions along its length (Solomon et al. 1989; Pagano et al. 1994; Cooper et al. 2000), by wielding it about their wrist, elbow, or shoulder (Pagano et al. 1993), and by wielding it with their limbs, torso, or head (Hajnal et al. 2007a, b; Palatinus et al. 2011; Wagman and Hajnal 2014a; Wagman et al. 2017).

An invariant mechanical property, rotational inertia, I, that specifies the resistance of an object to angular acceleration in different directions provides the informational support for dynamic touch (Carello and Turvey 2000; Turvey and Carello 2011). I is represented as ML^2, where M denotes mass and L denotes mass distribution with respect to the axis of rotation. I can be represented in a 3×3 matrix—the "inertia tensor" of the hand-object system (Fig. 1). The eigenvectors e_1, e_2, and e_3 of I describe the symmetry axes of the mass distribution of the hand-object system; these specify the orientation of the hand-object system (Pagano and Turvey 1992; Turvey et al. 1992). The eigenvalues I_1, I_2, and I_3 of I describe the resistance of the hand-object system to angular acceleration about the symmetry axes; these specify the extent of the attached/grasped object along each of those axes (Fitzpatrick et al. 1994; Turvey et al. 1998). The largest and the smallest eigenvalues, I_1 and I_3, specify the length and width, respectively, of the attached/grasped object. Finally, the ratio of I_1 and I_3 specifies the shape of the attached/grasped object (Burton et al. 1990).

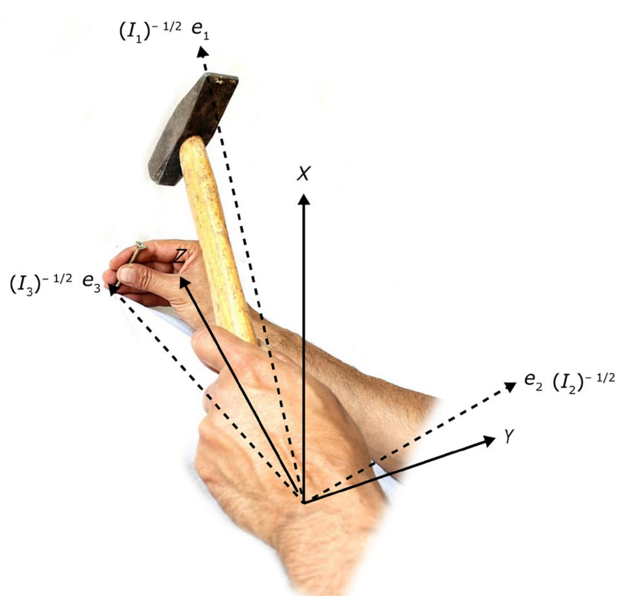

Fig. 1 Eigenvalues (I_1, I_2, and I_3) and eigenvectors (e_1, e_2, and e_3) of the inertia tensor of the hand-object system (the origin of the coordinate system is at a point in the wrist). Adapted from Mangalam et al. (2018). Copyright 2017 by the Springer US

Perception of properties of a grasped object via dynamic touch (wielding) contributes to dexterity in tool use (e.g., using a hammer, screwdriver) and sports (e.g., hockey, tennis). These activities differ from simple object manipulation in that they involve making contact with an intended target (henceforth, object–target contact), providing informational support auxiliary to that available during simple wielding (Carello et al. 1992b). Any mechanic or sportsman can testify to the importance of these instances of contact in acting upon an intended target (e.g., nail, screwdriver, or hockey/tennis ball) using a grasped object (hammer, hockey stick, or tennis racket). What is the form of this auxiliary informational support? To what degree, and in which contexts, does object–target contact influence the accuracy of perception via dynamic touch? Do certain properties of object–target contact result in faster or more accurate perception than other properties? Addressing such questions is imperative to understanding how object–target contact contributes to perception via dynamic touch.

Upon grasping an object, the effector (i.e., the point of object–target contact) shifts from the hand to the tip or to a point along the length of that object (Valk et al. 2016; Mangalam and Fragaszy 2016; Fragaszy and Mangalam 2018). The location and discreteness of a grasped object's effector can vary significantly. For example, a hammer's or screwdriver's effector is discretely located at the distal end, but a saw or file's effector is distributed throughout the extent of an edge. Given these nuances, it makes sense that certain properties of a grasped object's effector might influence (enhance or diminish) the informational support for perception via dynamic touch available during object–target contact. Making repetitive contact with an intended target using a grasped object defines a source of tissue deformation other than the one defined by simple wielding. For example, in one study (Carello et al. 1992b), the participants either wielded or struck obliquely against a cardboard box (target) grasped objects of different lengths, masses, and mass distributions, and reported perceived lengths of those objects. Making object–target contact altered the relationship between rotational inertias and perceived lengths of those objects. The straight-line distance from the point of rotation (lying in the wrist) to the point of object–target contact, mediated this relationship. Carello et al. (1992b) hypothesized that the patterns of tissue deformation brought about by wielding and by making object–target contact together support perception via dynamic touch.

Kelty-Stephen and Eddy (2015) revisited and repeated Carello's (1992b) study on perception via dynamic touch by striking, but allowed the participants to (1) strike and correct their length judgments in each trial, and (2) train themselves using striking with one stimulus scale over the first two blocks, and without warning them explicitly, changed the stimulus scale for the third block. They hypothesized that if striking increased the accuracy of length perception, then repeated striking should stabilize perception at zero-discrepancy, and the zero-discrepancy of perception should then be transferred to another stimulus subset. However, their results were more consistent with an alternate possibility that striking exaggerates perception of lengths of objects with greater rotational inertias.

In the present study, we further examined whether and how making contact with a target influences perception of the length of a grasped object via dynamic touch. We employed a paradigm similar to the one employed by Carello et al. (1992b), though we did two things differently. First, we incorporated two different locations of the effector: the tip of each stimulus object and a specific point along the length. Our reasoning to incorporate these two specific locations of the effector was that the coupling between the time-varying states (e.g., displacements, velocities) of the grasped object and the time-varying torques would differ. Second, in one of the two experiments we conducted, we bypassed the geometric relationship between object length and angle of object–target contact—i.e., the straight-line distance from the point of rotation to the point of object–target contact—which was fundamental to the Carello et al.'s (1992b) apparatus and interpretations of their findings. To achieve this end, we asked the participants to strike the grasped object against a perpendicular rod, thereby ensuring a 90° angle of object–target contact howsoever they struck that object.

In two related experiments, the participants either wielded or struck (against a target) grasped objects of different lengths, masses, and/or mass distributions and reported their perceived lengths, in the absence of vision. In Experiment 1, the participants either wielded or made object–target contact with the tip of the grasped objects (i.e., each object's effector located at the tip). In Experiment 2, the participants either wielded or made object–target contact at a point along the length of grasped objects (i.e., each object's effector located at a point along the length).

Striking a rigid-grasped object against an intended target generates elastic, vibratory waves, originating at the point of object–target contact and propagating along the extent of that object (Achenbach 1975). We hypothesized that the time-varying magnitude of these waves—as perceived by the wielder—must depend on the extent of the grasped object between the point of origin of the waves and the location of grasp (Fig. 2a). For an object of a given composition, perception of the vibratory waves originating at the tip should depend on the

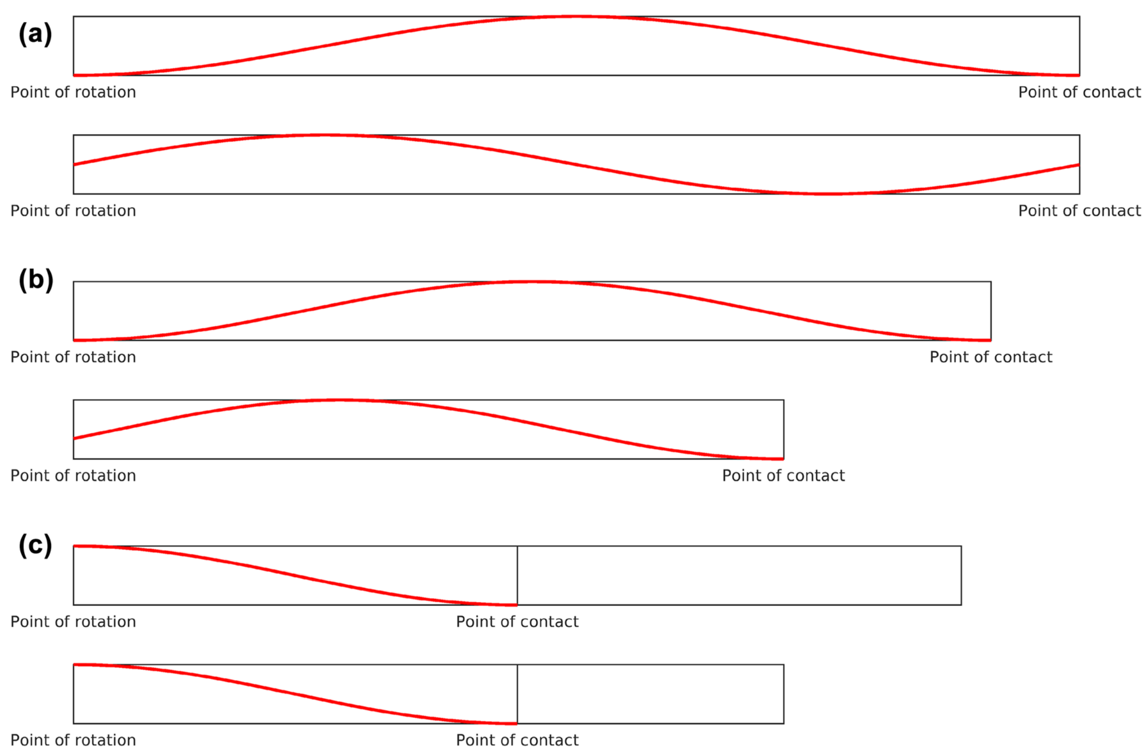

Fig. 2 Schematic illustration of the nature of the propagation of vibratory waves through elongated grasped objects struck against a target. **a** Elongated grasped objects making contact with the target by the tips. **b** Along grasped objects of different lengths making contact with the target by the tips. **c** Along grasped objects of different lengths making contact with the target at a point along their lengths

length of that object (Fig. 2b). Perception of the vibratory waves originating at a point along the length of an object should depend on the segment's length up to that point (Fig. 2c). Thus, the time-varying amplitude of vibratory waves originating at the tip is informative of the length, but those of waves originating at a point along the length are not. Given how the effector's location might alter the properties or the prorogation of vibratory waves along an elongated grasped object, we expected that in experiment 1, making the object–target contact by the tip would enhance perception of the lengths of the grasped objects, but in experiment 2, making the object–target contact at a point along the length of an object would not. Moreover, we expected that if vibratory waves do contribute to perception via dynamic touch by striking, then perceived lengths of the segments up to the point of object–target contact (i.e., partial lengths) of the grasped objects would not vary with their rotational inertias, although perceived (whole) lengths would vary.

Experiment 1

We examined whether and how making object–surface contact influences perception of the length of a grasped object via dynamic touch. The participants both wielded and struck against a hard surface (by the tips) and reported perceived lengths of objects of two different types: (1) unweighted objects (rods) of different lengths but the same composition; rotational inertias of these objects varied directly with their lengths. (2) Weighted objects of identical lengths but different compositions and mass distributions; rotational inertias of these objects varied independently of their lengths. Given that an invariant mechanical property—rotational inertia, *I*—provides the informational support for perception via dynamic touch (Fitzpatrick et al. 1994; Carello and Turvey 2000; Turvey and Carello 2011), we expected that perceived lengths of the unweighted objects would vary directly with their actual lengths (due to a one-to-one correspondence between the lengths and rotational inertias for dowels of the same composition), and that perceived lengths of the weighted objects would vary directly with their rotational inertias (due to a much weaker correspondence between the lengths and rotational inertias for dowels of different compositions and weights attached at different locations along their lengths). We hypothesized that making object–target contact would yield a more accurate perception of the lengths of those objects compared with wielding [i.e., more closely reflect actual lengths (unweighted objects) or rotational inertias (weighted objects)].

Methods

Participants

Seven adult males and four adult females participated in the present study (mean ± SD age = 19.4 ± 1.5 years; range 18–22 years; 10 right-handed and 1 left-handed). Each participant signed a consent form with information regarding the purposes of the study, the procedures, and the potential risks and benefits of participation. The Institutional Review Board (IRB) at the University of Georgia (Athens, GA, USA) approved the present study.

Experimental objects

All participants manipulated 19 objects, seven unweighted and 12 weighted. The unweighted objects were maple wood dowels (lengths = 30.0, 35.0, 40.0, 45.0, 50.0, 55.0, and 60.0 cm; diameter = 1.2 cm). The lengths of these objects varied directly with their rotational inertias. The weighted objects were dowels of distinct compositions (length = 50.0 cm; diameter = 1.2 cm; mass = pine wood: 27 g; maple wood: 45 g; hollow aluminum: 75 g; solid aluminum: 171 g) with a number of stacked steel rings (inner diameter = 1.4 cm, outer diameter = 3.4 cm; height = 0.2 cm each; mass = 14 g each) attached at three distinct locations along their lengths (Table 1). We attached two rings to the pine wood dowels, three rings to the maple wood dowels, four rings to the hollow aluminum dowels, and five rings to the solid aluminum dowels at 25.0, 35.0, or 45.0 cm from their proximal end. We attached different numbers of rings on dowels of different compositions to maintain the relative

Table 1 LogI_1 of the weighted objects ($n = 12$) used in Experiment 1

Composition, mass of the dowel (g)	Mass of the attached rings (g)	Location of the attached rings (cm)	I_1 (g·cm^2)
Pine wood, 27	28	25.0	30,673
Pine wood, 27	28	35.0	44,745
Pine wood, 27	28	45.0	64,322
Maple wood, 44	42	25.0	47,988
Maple wood, 44	42	35.0	69,101
Maple wood, 44	42	45.0	98,466
Hollow aluminum, 75	56	25.0	71,214
Hollow aluminum, 75	56	35.0	104,070
Hollow aluminum, 75	56	45.0	148,070
Solid aluminum, 171	70	25.0	141,420
Solid aluminum, 171	70	35.0	176,640
Solid aluminum, 171	70	45.0	225,530

differences in the mass of different dowels so that their rotational inertias lie uniformly across the whole range of values. The lengths of these objects were identical but their rotational inertias varied independent of their lengths. To prevent perception of the material composition of an object via cutaneous or haptic touch, we put a weightless rubber grip (length = 15.0 cm) of negligible thickness and mass on each object.

Experimental setup and procedure

We tested each participant individually in a 75–90-min session. The participant (irrespective of being right- or left-handed) could insert his/her right hand into a 30-cm slit in the curtain at his/her midriff height and grasp an occluded unweighted or weighted object (Fig. 3). S(he) could report perceived length of the object on a meter scale vaulted at his/her shoulder height in the front by changing the position of a pointer. The readings on the meter scale were facing the other side, and therefore, out of view of the participant.

In each trial, the participant grasped the object handed to him/her by the experimenter (J.D.C.) at about 5 cm from the proximal end. J.D.C. instructed the participant to "wield" or to "strike" the grasped object and report the length, $L_{perceived}$ of that object. When instructed to wield, the participant wielded the grasped object until s(he) could confidently report his/her length judgment. When instructed to strike, the participant struck the grasped object against a flannel-coated surface placed on a table at his/her waist height until s(he) could confidently report his/her length judgment. After attending to these instructions, the participant wielded or struck the grasped object, s(he) reported his/her length judgment on the meter scale. J.D.C. recorded the scale reading, the participant handed the object back to J.D.C., and a new trial began. After having completed all trials for one object type (i.e., unweighted or weighted), the participant took a 5-min break. After the break, the trials for the next object type began.

Each participant completed 114 trials (7 unweighted objects × 3 trials/unweighted object × 2 activities + 12 weighted objects × 3 trials/weighted objects × 2 activities). We blocked the trials for the weighted and unweighted objects. In addition, we randomized the order of presentation of each type of objects for each participant.

Statistical analysis

We performed statistical analyses using two-tailed tests in SPSS 21 (IBM, Inc.) and considered outcomes significant at the level of $\alpha = 0.05$.

Results and discussion

Unweighted objects

We conducted a 7 (object) × 2 (activity) repeated-measures analysis of variance (ANOVA) on $L_{perceived}$ with within-subject factors of object and activity. There was a significant main effect of object ($F_{6,60} = 14.053$, $P < 0.001$, $\eta^2 = 0.584$). Pairwise comparisons with Bonferroni corrections revealed that $L_{perceived}$ varied across the seven objects (Ps < 0.05). There was a significant main effect of activity ($F_{1,11}$ = 11.066, $P = 0.008$, $\eta^2 = 0.525$). $L_{perceived}$ corresponding to striking were longer than $L_{perceived}$ corresponding to wielding [M ± SEM difference = 1.968 ± 0.591, 95% CI (− 0.650, 3.285)]. Moreover, the interaction effect of object × activity was not significant ($F_{6,60} = 0.668$, $P = 0.675$, $\eta^2 = 0.063$).

In general, $L_{perceived}$ of the unweighted objects did not exceed their L_{actual}, but the participants showed inter-individual differences. To examine whether these differences reflected the same underlying perceptual process, we analyzed the values of the slopes, intercepts, and explained variances of the regression lines of $L_{perceived}$ against L_{actual}

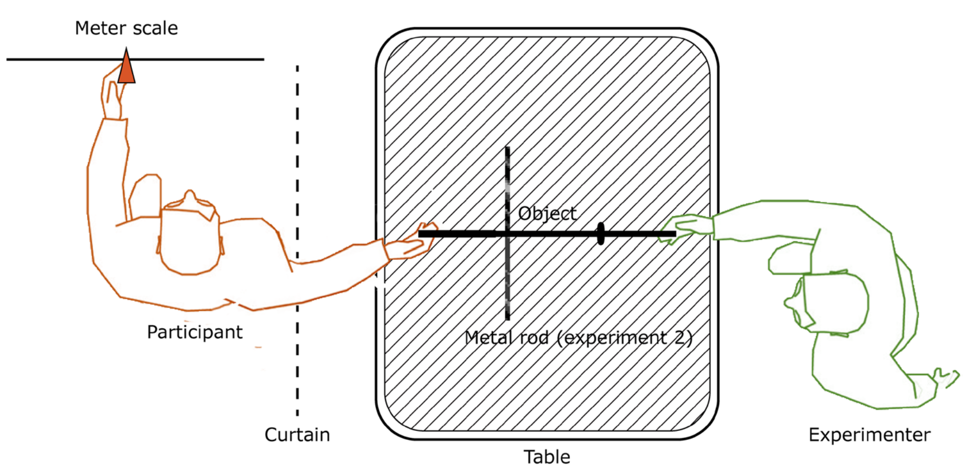

Fig. 3 Top view of the experimental setup [the flannel-coated surface was used in Experiment 1 (not shown here for clarity), whereas the metal rod was used in Experiment 2]

for each participant. The intercept indicates perceived length when the actual length [rotational inertia (weighted objects)] is zero, or in other words, it is a rough estimate of discrepancy in perception (e.g., Withagen and Michaels 2004). The slope indicates the scaling relationship between actual and perceived lengths [rotational inertia (weighted objects)]. $L_{\text{perceived}}$ corresponding to each activity varied directly with L_{actual} for each participant (range of values of r^2: wielding: 0.685–0.974; striking: 0.871–0.988; Table 2). A one-way ANOVA with a within-subject factor of activity on the values of Fischer's z' (obtained by transforming the values of r to meet the assumption of normality) revealed no differences between wielding and striking ($F_{1,10} = 0.616$, $P = 0.451$, $\eta^2 = 0.058$). A one-way ANOVA with a within-subject factor of activity on the values of slopes revealed no differences between wielding and striking ($F_{1,10} = 0.771$, $P = 0.401$, $\eta^2 = 0.072$). Finally, a one-way ANOVA with a within-subject factor of activity on the values of intercepts revealed no differences between wielding and striking ($F_{1,10} = 0.002$, $P = 0.966$, $\eta^2 = 0.000$).

At the level of mean data, simple linear regressions confirmed significant linear relationships between L_{actual} and $L_{\text{perceived}}$ corresponding to each activity: (1) wielding: $L_{\text{perceived}} = 0.594 \times L_{\text{actual}} + 10.418$ (in cm), $F_{1,5} = 278.654$, $P < 0.001$, $r^2 = 0.979$; (ii) striking: $L_{\text{perceived}} = 0.637 \times L_{\text{actual}} + 10.414$ (in cm), $F_{1,5} = 284.166$, $P < 0.001$, $r^2 = 0.984$ (Fig. 4a; Table 3).

A multiple regression revealed that L_{actual} and activity accounted for 98.2% of the variance in $L_{\text{perceived}}$ [$P < 0.001$, $L_{\text{perceived}} = (0.594 \times L_{\text{actual}}) + (0.043 \times \text{activity}) + 10.415$], wielding = 1, striking = 0; Table 3)]. L_{actual} accounted for a significant and large portion of the variance ($\beta = 0.945$, $P < 0.001$). Activity accounted for a significant but comparatively smaller portion of the variance ($\beta = 0.163$, $P = 0.001$).

We conducted a 7 (object) × 2 (activity) ANOVA on error in perceived length, $\Delta L_{\text{perceived}}$ (i.e., $L_{\text{perceived}} - L_{\text{actual}}$) with within-subject factors of activity and activity. The main effect of object was not significant ($F_{6,60} = 1.188$, $P = 0.325$, $\eta^2 = 0.106$). There was a significant main effect of activity ($F_{1,11} = 14.487$, $P = 0.003$, $\eta^2 = 0.592$). $\Delta L_{\text{perceived}}$ were smaller corresponding to striking than $\Delta L_{\text{perceived}}$ corresponding to wielding [M ± SEM difference = − 2.056 ± 0.540, 95% CI (− 3.259, − 0.852)]. The interaction effect of object × activity was not significant, $F_{6,60} = 0.271$, $P = 0.948$, $\eta^2 = 0.026$.

At the level of mean data, simple linear regressions confirmed significant linear relationships between L_{actual} and $\Delta L_{\text{perceived}}$ corresponding to each activity: (1) wielding: $\Delta L_{\text{perceived}} = 0.150 \times L_{\text{actual}} + 5.993$ (in cm), $F_{1,5} = 21.358$, $P = 0.006$, $r^2 = 0.772$; (2) striking: $\Delta L_{\text{perceived}} = 0.155 \times L_{\text{actual}} + 3.725$ (in cm), $F_{1,5} = 24.285$, $P < 0.001$, $r^2 = 0.785$ (Fig. 4b; Table 3).

A multiple regression revealed that L_{actual} and activity accounted for 82.6% of the variance in $\Delta L_{\text{perceived}}$ [$P < 0.001$, $\Delta L_{\text{perceived}} = (0.174 \times L_{\text{actual}}) - (0.043 \times \text{activity}) + 4.859$], wielding = 1, striking = 0 (Table 3). L_{actual} accounted for a significant and large portion of the variance ($\beta = 0.883$, $P < 0.001$). Activity accounted for a significant but comparatively smaller portion of the variance ($\beta = -0.515$, $P = 0.001$).

Actual lengths of the grasped objects predicted their perceived lengths obtained by means of both wielding and striking. However, the scaling relationship between actual length and perceived length differed between the two activities; perceived lengths obtained by means of striking reflected actual lengths more closely compared to perceived lengths obtained by wielding. This finding is evident that striking a grasped object against an intended target (or more

Table 2 Slopes, intercepts, and explained variances of the regression lines of $L_{\text{perceived}}$ against L_{actual} (unweighted objects), and $\log L_{\text{perceived}}$ against $\log I_1$ (weighted objects), for each participant in Experiment 1

Participant	Unweighted objects ($n = 7$)						Weighted objects ($n = 12$)					
	Wielding			Striking			Wielding			Striking		
	Slope	Intercept	r^2	Slope	Intercept	r^2	Slope	Intercept	r^2	Slope	Intercept	r^2
1	0.662	5.818	0.938	0.660	10.557	0.896	0.251	0.392	0.808	0.122	1.068	0.332
2	0.486	11.011	0.778	0.609	9.311	0.909	0.193	0.733	0.673	0.205	0.698	0.552
3	0.963	− 11.243	0.958	1.064	− 12.618	0.978	0.218	0.549	0.865	0.139	0.943	0.734
4	0.760	− 1.043	0.971	0.584	6.650	0.915	0.072	1.258	0.306	− 0.005	1.643	− 0.094
5	0.536	4.532	0.702	0.519	5.532	0.871	0.126	0.828	0.650	0.162	0.664	0.224
6	− 0.815	98.304	0.883	− 0.874	99.354	0.928	− 0.310	3.246	0.844	− 0.342	3.356	0.738
7	0.894	− 6.314	0.955	1.032	− 9.561	0.988	0.175	0.723	0.516	− 0.007	1.668	− 0.097
8	0.716	1.936	0.967	0.663	7.114	0.964	0.204	0.629	0.790	0.167	0.834	0.884
9	0.365	9.632	0.685	0.689	− 1.618	0.983	0.087	1.039	0.056	0.309	0.050	0.759
10	0.898	− 3.032	0.920	0.741	6.125	0.913	− 0.094	2.044	0.334	− 0.044	1.841	− 0.005
11	1.076	4.579	0.974	1.313	− 5.693	0.950	0.242	0.595	0.617	0.126	1.162	0.061

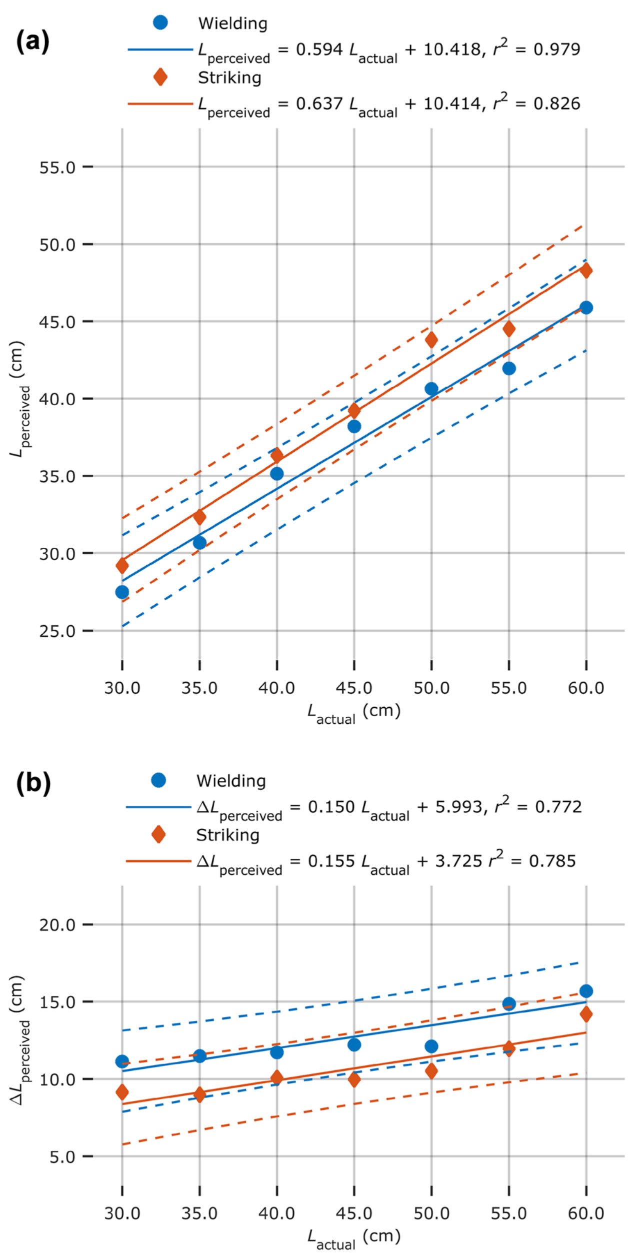

Fig. 4 Linear relationships between **a** L_{actual} and $L_{perceived}$, and **b** L_{actual} and $\Delta L_{perceived}$ of the unweighted objects ($n=7$) in Experiment 1. Dashed lines represent 95% CI around the estimate

generally, making contact with an intended target by means of a grasped object) yields a more accurate perception of the properties of that object.

Weighted objects

We conducted a 12 (object) × 2 (activity) repeated-measures (ANOVA) on $\log L_{perceived}$ with within-subject factors of object and activity. There was a significant main effect of $\log I_1$ ($F_{11,110} = 2.501$, $P = 0.008$, $\eta^2 = 0.200$). Pairwise comparisons with Bonferroni corrections revealed that $\log L_{perceived}$ varied across the 12 objects (Ps < 0.05). The main effect of activity was not significant ($F_{1,10} = 3.957$, $P = 0.075$, $\eta^2 = 0.283$). Moreover, the interaction effect of object × activity was not significant ($F_{11,110} = 0.561$, $P = 0.857$, $\eta^2 = 0.053$).

In general, perceived lengths of the weighted objects did not exceed their actual lengths (i.e., 50.0 cm), as in two previous studies with the same objects (Mangalam et al. 2017, 2018), but the participants showed unusually high inter-individual differences. We analyzed the values of the slopes, intercepts, and explained variances of the regression lines of $\log L_{perceived}$ against $\log I_1$ for each participant. $\log L_{perceived}$ corresponding to each activity varied linearly with $\log I_1$ for each participant (range of values of r^2: wielding: 0.056–0.865; striking: 0.000–0.884; Table 2). A one-way ANOVA with a within-subject factor of activity on the values of Fischer's z' (obtained by transforming the values of r) revealed no differences between wielding and striking ($F_{1,10} = 1.694$, $P = 0.222$, $\eta^2 = 0.145$). A one-way ANOVA with a within-subject factor of activity on the values of slopes revealed no differences between wielding and striking ($F_{1,10} = 0.828$, $P = 0.384$, $\eta^2 = 0.076$). Finally, a one-way ANOVA with a within-subject factor of activity on the values of intercepts revealed no differences between wielding and striking ($F_{1,10} = 1.181$, $P = 0.303$, $\eta^2 = 0.106$).

At the level of mean data, simple linear regressions confirmed significant linear relationships between $\log I_1$ and $\log L_{perceived}$ for each activity: (1) wielding: $\log L_{perceived} = 0.106 \times \log I_1 + 1.107$ (in cm), $F_{1,10} = 49.615$, $P < 0.001$, $r^2 = 0.815$; (2) striking: $\log L_{perceived} = 0.107 \times \log I_1 + 1.127$ (in cm), $F_{1,10} = 49.283$, $P < 0.001$, $r^2 = 0.814$ (Fig. 5a; Table 3).

A multiple regression revealed that $\log I_1$ and activity accounted for 84.9% of the variance in $\log L_{perceived}$ [$P < 0.001$, $\log L_{perceived} = (0.104 \times \log I_1) + (0.006 \times \text{activity}) + 1.117$], activity: wielding = 1, striking = 0 (Table 3). $\log I_1$ accounted for a significant and large portion of the variance ($\beta = 0.804$, $P < 0.001$). Activity accounted for a significant but comparatively smaller portion of the variance ($\beta = 0.425$, $P < 0.001$).

We conducted a 12 (object) × 2 (activity) ANOVA on $\log \Delta L_{perceived}$ with within-subject factors of object and activity. There was a significant main effect of $\log I_1$ ($F_{11,110} = 2.098$, $P = 0.026$, $\eta^2 = 0.173$). Pairwise comparisons with Bonferroni corrections revealed that $\log \Delta L_{perceived}$ varied across the 12 objects (Ps < 0.05). There was a significant main effect of activity ($F_{1,10} = 7.705$, $P = 0.020$, $\eta^2 = 0.435$). $\log \Delta L_{perceived}$ corresponding to striking was smaller than $\log \Delta L_{perceived}$ corresponding to wielding [M ± SEM difference = − 2.468 ± 0.889, 95% CI (− 4.449, − 0.487)]. The interaction effect of object × activity was not significant ($F_{11,110} = 1.219$, $P = 0.283$, $\eta^2 = 0.109$).

Table 3 Outcomes of simple linear regressions across all 11 participants in Experiment 1

Activity	$F_{1,5}$, $F_{1,10}$	P	r^2		Estimate ± SE	β	t	P
$L_{\text{perceived}}$—unweighted objects ($n=7$)								
Wielding	278.654	< **0.001**	0.979	Intercept	10.418 ± 1.639		6.356	**0.001**
				Coefficient of L_{actual}	0.594 ± 0.036	0.991	16.693	< **0.001**
Striking	284.166	< **0.001**	0.984	Intercept	10.414 ± 1.523		6.836	**0.001**
				Coefficient of L_{actual}	0.637 ± 0.033	0.993	19.279	< **0.001**
Overall	362.879	< **0.001**	0.982	Intercept	10.415 ± 1.067		9.763	< **0.001**
				Coefficient of L_{actual}	0.594 ± 0.024	0.945	25.067	< **0.001**
				Coefficient of activity (wielding = 0; striking = 1)	0.043 ± 0.010	0.163	4.332	**0.001**
$\Delta L_{\text{perceived}}$—unweighted objects ($n=7$)								
Wielding	21.358	**0.006**	0.772	Intercept	5.993 ± 1.496		4.005	**0.010**
				Coefficient of L_{actual}	0.150 ± 0.032	0.900	4.621	**0.006**
Striking	24.285	< **0.001**	0.785	Intercept	3.725 ± 1.450		2.569	**0.050**
				Coefficient of L_{actual}	0.155 ± 0.031	0.911	4.928	**0.004**
Overall	31.863	< **0.001**	0.826	Intercept	4.859 ± 1.050		4.626	**0.001**
				Coefficient of L_{actual}	0.174 ± 0.023	0.883	7.463	< **0.001**
				Coefficient of activity (wielding = 0; striking = 1)	− 0.043 ± 0.010	− 0.515	− 4.352	**0.001**
Log$L_{\text{perceived}}$—weighted objects ($n=12$)								
Wielding	49.615	< **0.001**	0.815	Intercept	1.107 ± 0.074		14.941	< **0.001**
				Coefficient of logI_1	0.106 ± 0.015	0.912	7.044	< **0.001**
Striking	49.283	< **0.001**	0.814	Intercept	1.127 ± 0.075		14.926	< **0.001**
				Coefficient of logI_1	0.107 ± 0.015	0.912	7.020	< **0.001**
Overall	65.449	< **0.001**	0.849	Intercept	1.117 ± 0.052		21.621	< **0.001**
				Coefficient of logI_1	0.104 ± 0.010	0.804	9.902	< **0.001**
				Coefficient of activity (wielding = 0; striking = 1)	0.006 ± 0.001	0.425	5.229	< **0.001**
Log$\Delta L_{\text{perceived}}$—weighted objects ($n=12$)								
Wielding	10.259	< **0.001**	0.457	Intercept	2.403 ± 0.421		5.705	< **0.001**
				Coefficient of logI_1	− 0.273 ± 0.085	− 0.712	− 3.203	**0.009**
Striking	1.382	< **0.001**	0.034	Intercept	1.394 ± 0.370		3.769	**0.004**
				Coefficient of logI_1	− 0.088 ± 0.075	− 0.348	− 1.176	0.267
Overall	9.414	**0.001**	0.423	Intercept	1.899 ± 0.295		6.439	< **0.001**
				Coefficient of logI_1	− 0.171 ± 0.060	− 0.454	− 2.863	**0.009**
				Coefficient of activity (wielding = 0; striking = 1)	− 0.019 ± 0.006	− 0.494	− 3.110	**0.005**

Boldfaced values indicate statistical significance

At the level of mean data, simple linear regressions confirmed significant linear relationships between logI_1 and log$\Delta L_{\text{perceived}}$ for (1) wielding: log$\Delta L_{\text{perceived}}$ = − 0.273 × logI_1 + 12.403 (in cm), $F_{1,10}$ = 10.259, $P<0.001$, $r^2=0.457$, but not for (2) striking: log$\Delta L_{\text{perceived}}$ = − 0.088 × logI_1 + 1.394 (in cm), $F_{1,10}$ = 1.382, $P=0.267$, $r^2=0.034$ (Fig. 5b; Table 3).

A multiple regression revealed that logI_1 and activity accounted for 42.3% of the variance in log$\Delta L_{\text{perceived}}$ [$P=0.001$, log$\Delta L_{\text{perceived}}$ = (− 0.171 × logI_1) + (− 0.019 × activity) + 1.899], activity: wielding = 1, striking = 0 (Table 3). LogI_1 accounted for a significant but small portion of the variance (β = − 0.454, $P=0.009$). Activity also accounted for a significant but small portion of the variance (β = − 0.494, $P=0.005$).

Striking by the tips yielded greater values of perceived lengths compared to simply wielding. However, the influence of striking on perceived lengths was less apparent than the magnitude of error in perceived length in the case of weighted objects due to high inter-individual variation in the scaling of perception (range of values of r^2: wielding: 0.056–0.865; striking: 0.000–0.884). LogI_1 predicted perceived lengths of the grasped objects obtained by wielding and striking. The scaling relationship between logI_1 and perceived length differed between the two activities; perceived lengths obtained by striking reflected logI_1 more closely compared to perceived lengths obtained by wielding. Together, these findings strongly support the hypothesis that making object–target contact yields a more accurate perception of the length of a grasped object compared

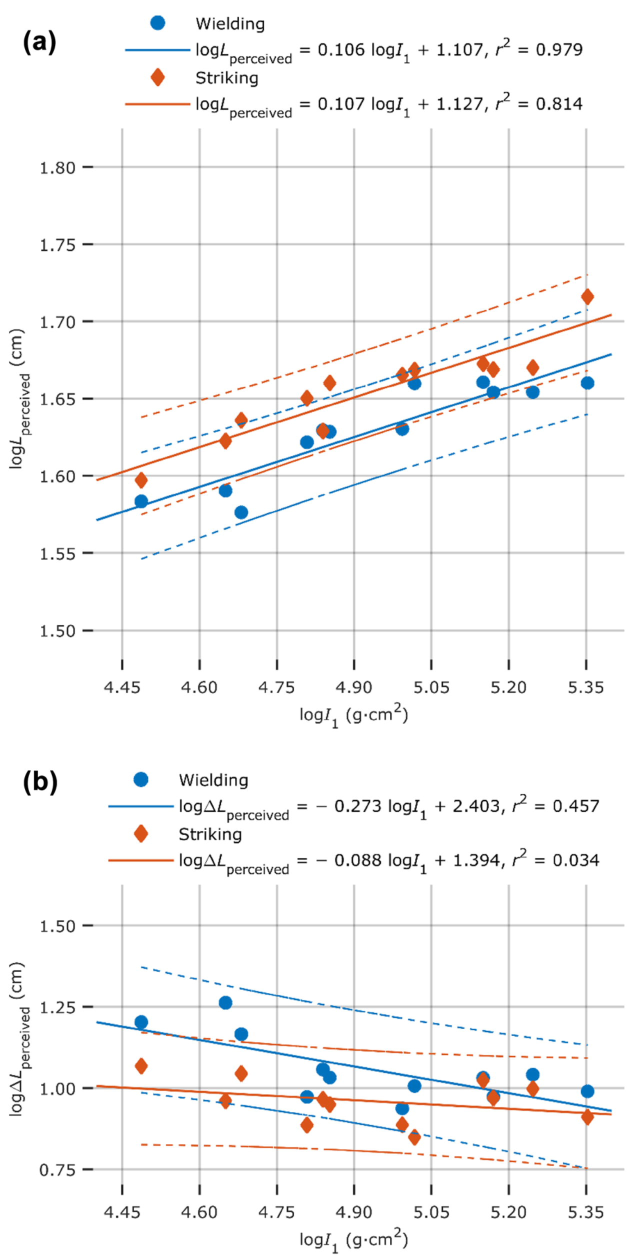

Fig. 5 Linear relationships between **a** $\log I_1$ and $\log L_{perceived}$, and **b** $\log I_1$ and $\log \Delta L_{perceived}$, of the weighted objects ($n = 12$) in Experiment 1. Dashed lines represent 95% CI around the estimate

with wielding. The fact that in the case of weighted objects the errors in perceived length did not vary with rotational inertias is particularly revealing. It suggests that striking yielded some information other than rotational inertia and that this contributed to more accurate perception of lengths. In addition, these findings are highly consistent with those of Carello et al. (1992b). Perceived lengths of (weighted) objects with identical lengths varied with their rotational inertias, suggesting that their rotational inertias provided the primary informational support for perception. The angle of object–target contact did not vary when the participants struck (weighted) objects of identical lengths but differed when they struck (unweighted) objects of different lengths. However, striking invariably yielded a more accurate relationship between actual lengths and perceived lengths (unweighted objects), or between rotational inertias and perceived lengths (weighted objects). Thus, object–target contact contributed partially to perception of the length of the grasped objects, depending on the angle of object–target contact, likely through the mechanism proposed by Carello et al., (1992b).

Experiment 2

In this experiment, we examined whether and how the location of a grasped object's effector (i.e., shifting the effector from the tip—as in Experiment 1—to some point along the length of the grasped object) influences perception of the length of a grasped object via dynamic touch. The participants wielded and struck against a perpendicular rod unweighted and weighted objects of different lengths and rotational inertias at some point along the lengths. They reported perceived lengths of the objects and the extents of the grasped objects from the point of rotation (in the hand) to the point of object–target contact. Given that an invariant mechanical property—rotational inertia, I—provides the informational support for perception via dynamic touch (Fitzpatrick et al. 1994; Carello and Turvey 2000; Turvey and Carello 2011), we expected that perceived whole lengths of the grasped objects would vary directly with their rotational inertias. We hypothesized that the nature of the time-varying amplitude of vibratory waves generated at an effector along the length of a grasped object and vibratory waves generated at the tip differ fundamentally (Fig. 2). We expected that unlike in Experiment 1, making object–target contact would not influence perception of the lengths of those objects compared with wielding. Moreover, we hypothesized that vibratory waves generated at some point along the length of a grasped object convey information about the extents of the grasped objects from the point of rotation (in the hand) to the point of object–target contact. We expected that the participants would accurately perceive these extents.

Methods

Participants

Eight adult males and three adult females participated in the present study (mean ± SD age = 23.5 ± 4.8 years; range 18–32 years; right-handed). Each participant signed a consent form with information regarding the purposes of the study, the procedures, and the potential risks and benefits of participation. The Institutional Review Board (IRB) at the University of Georgia (Athens, GA, USA) approved the present study.

Experimental objects

The participants manipulated nine objects, three unweighted and six weighted. The unweighted objects were oak wood dowels of three different lengths (lengths = 50.0, 55.0, and 60.0 cm; diameter = 1.2 cm; mass = 44, 41, and 49 g; Table 4). The weighted objects consisted of the same oak wood dowels with three stacked steel rings (inner diameter = 1.4 cm, outer diameter = 3.4 cm; height = 0.2 cm each, mass = 12 g each) attached along their lengths either at 25.0 cm from the proximal end or at 5.0 cm from the distal end (Table 4). Including both types of objects allowed us to independently vary the lengths and rotational inertias of the experimental objects.

Experimental setup and procedure

We tested each participant individually in a 60–75-min session. The experimental setup was similar to that in Experiment 1 except that a metal rod oriented perpendicularly to the participant's frontal plane was placed on the table at 30 cm from his/her hand at his/her midriff height.

In each trial, the participant grasped the object handed to him/her by the experimenter, J.D.C., at about 5 cm from the proximal end. J.D.C. instructed the participant to "wield" or to "strike" the grasped object and report the (whole) length, $L_{perceived}$ or partial length, $\partial L_{perceived}$, of that object. We defined the partial length as the extents of the grasped objects from the point of rotation (in the hand) to the point of object–target contact. When instructed to wield, the participant wielded the grasped object until s(he) could confidently report his/her length judgment. When instructed to strike, the participant struck the grasped object against the metal rod until s(he) could confidently report his/her length judgment. After attending to these instructions, the participant wielded or struck the grasped object, s(he) reported his/her length judgment on the meter scale. J.D.C. recorded the scale reading, the participant handed the object back to J.D.C., and a new trial began.

Each participant completed 81 trials [9 objects × 3 trials/object × 3 activities (wielding: $L_{perceived}$, striking: $L_{perceived}$ and $\partial L_{perceived}$)]. We randomized the order of presentation of the nine objects and the three activities for each participant.

Table 4 LogI_1 of the experimental objects ($n = 9$) used in Experiment 2

Length of the dowel (cm)	Mass of the dowel (g)	Location of the attached rings, 42 g	I_1 (g·cm^2)	$L_{predicted}$ (cm)
50.0	44	No rings attached	28,355	37.9
50.0	44	25.0 cm	47,521	40.1
50.0	44	45 cm	98,007	43.3
55.0	41	No rings attached	32,571	38.5
55.0	41	25 cm	51,742	40.4
55.0	41	50 cm	120,130	44.2
60.0	49	No rings attached	47,093	40.0
60.0	49	25 cm	66,124	41.5
60.0	49	55 cm	154,510	45.4

Statistical analysis

We performed statistical analyses using two-tailed tests in SPSS 21 (IBM, Inc.) and considered outcomes significant at the level of $\alpha = 0.05$.

Results and discussion

We conducted a 9 (object) × 3 (activity) repeated-measures ANOVA on log$L_{perceived}$ (wielding and striking) or log$\Delta\partial L_{perceived}$ (striking) with within-subject factors of logI_1 and activity. There was a significant main effect of object ($F_{8,80} = 24.062$, $P < 0.001$, $\eta^2 = 0.706$). Pairwise comparisons with Bonferroni corrections revealed that log$L_{perceived}$ (wielding and striking) or log$\Delta\partial L_{perceived}$ (striking) varied across the nine objects (Ps < 0.05). There was a significant main effect of activity ($F_{2,20} = 72.640$, $P < 0.001$, $\eta^2 = 0.879$). Pairwise comparisons with Bonferroni corrections revealed that log$L_{perceived}$ did not differ between wielding and striking [M ± SEM difference = 0.000 ± 0.007, $P = 1.000$, 95% CI (− 0.020, 0.020)], but log$\partial L_{perceived}$ was smaller than log$L_{perceived}$ corresponding to both wielding [M ± SEM difference = − 0.258 ± 0.029, $P < 0.001$, 95% CI (− 0.342, − 0.175)] and striking [M ± SEM difference = − 0.258 ± 0.031, $P < 0.001$, 95% CI (− 0.326, − 0.170)]. Finally, there was a significant interaction effect of object × activity ($F_{16,160} = 13.583$, $P < 0.001$, $\eta^2 = 0.576$). Pairwise comparisons with Bonferroni corrections revealed that log$L_{perceived}$ (wielding, striking) varied across the 12 objects (Ps < 0.05), but log$\Delta\partial L_{perceived}$ did not (Ps > 0.05).

Log$L_{perceived}$ varied directly with logI_1 for each participant in both activities (range of values of r^2: wielding: 0.217–0.978; striking: 0.247–0.941), but log$\partial L_{perceived}$ did not (range of values of r^2: 0.000–0.422; Table 5). As in experiment 1, we analyzed the values of the slopes, intercepts, and explained variances of the regression lines of log$L_{perceived}$ (wielding and striking) and log$\partial L_{perceived}$ (striking) against logI_1. A one-way ANOVA with a within-subject

Table 5 Slopes, intercepts, and explained variances of the regression lines of $\log L_{perceived}$ against $\log I_1$ for the unweighted and weighted objects for each participant in Experiment 2

Participant	Unweighted and weighted objects ($n=9$)								
	Wielding			Striking: full length			Striking: partial length		
	Slope	Intercept	r^2	Slope	Intercept	r^2	Slope	Intercept	r^2
1	0.332	0.110	0.958	0.383	− 0.151	0.827	0.061	1.865	0.000
2	0.287	0.040	0.491	0.143	0.749	0.333	− 0.091	1.692	0.022
3	0.098	0.344	0.871	0.426	− 0.291	0.941	0.046	1.279	0.000
4	0.324	0.075	0.818	0.307	0.143	0.670	− 0.108	1.749	0.000
5	0.135	1.008	0.557	0.201	0.657	0.790	0.131	0.826	0.228
6	0.303	0.204	0.834	0.280	0.390	0.844	− 0.040	1.445	0.000
7	0.240	0.360	0.477	0.179	0.671	0.565	− 0.186	2.107	0.422
8	0.323	0.118	0.978	0.317	0.111	0.908	0.097	0.464	0.000
9	0.293	0.253	0.871	0.175	0.815	0.754	0.063	1.178	0.113
10	0.063	1.345	0.217	0.055	1.377	0.247	− 0.075	1.770	0.000
11	0.523	− 0.848	0.923	0.433	0.379	0.889	0.149	0.768	0.089

factor of activity on the values of Fischer's z' (obtained by transforming the values of r) revealed significant differences ($F_{2,20}$ = 29.034, $P<0.001$, $\eta^2=0.744$). Pairwise comparisons with Bonferroni corrections revealed that the values of Fischer's z' corresponding to $\log L_{perceived}$ did not differ between the two activities [M ± SEM difference = − 0.002 ± 0.038, $P=1.000$, 95% CI (− 0.112, 0.108)], but the values corresponding to $\log\partial L_{perceived}$ were smaller than those corresponding to $\log L_{perceived}$ [wielding: M ± SEM difference = − 0.261 ± 0.044, $P<0.001$, 95% CI (− 0.389, − 0.134); striking: M ± SEM difference = − 0.259 ± 0.035, $P<0.001$, 95% CI (− 0.360, − 0.159)]. A one-way ANOVA with a within-subject factor of activity on the values of slopes revealed significant differences ($F_{2,20}$ = 29.610, $P<0.001$, $\eta^2=0.748$). Again, pairwise comparisons with Bonferroni corrections revealed that the values of slopes corresponding to $\log L_{perceived}$ did not differ between the two activities [M ± SEM difference = − 0.138 ± 0.121, $P=0.843$, 95% CI (− 0.486, 0.210)], but the values corresponding to $\log\partial L_{perceived}$ were smaller than those corresponding to $\log L_{perceived}$ [wielding: M ± SEM difference = − 1.302 ± 0.237, $P=0.001$, 95% CI (− 1.983, − 0.620); striking: M ± SEM difference = − 1.164 ± 0.180, $P<0.001$, 95% CI (− 1.682, − 0.646)]. Finally, a one-way ANOVA with a within-subject factor of activity on the values of intercepts revealed significant differences ($F_{2,20}$ = 20.509, $P<0.001$, $\eta^2=0.672$). Pairwise comparisons with Bonferroni corrections revealed that the values of intercepts corresponding to $\log L_{perceived}$ did not differ between the two activities [M ± SEM difference = 0.167 ± 0.158, $P=0.944$, 95% CI (− 0.286, 0.621)], but the values corresponding to $\log\partial L_{perceived}$ were greater than those corresponding to $\log L_{perceived}$ [wielding: M ± SEM difference = 1.103 ± 0.202, $P=0.001$, 95% CI (0.523, 1.683); striking: M ± SEM difference = 0.936 ± 0.194, $P=0.002$, 95% CI (0.379, 1.492)].

At the level of mean data, simple linear regressions confirmed significant linear relationships between $\log I_1$ and $\log L_{perceived}$ corresponding to each activity: (1) wielding: $\log L_{perceived} = 0.303 \times \log I_1 + 0.195$ (in cm), $F_{1,7}$ = 384.729, $P<0.001$, $r^2=0.980$; (2) striking: $\log L_{perceived}$ = $0.276 \times \log I_1 + 0.323$ (in cm), $F_{1,7}$ = 109.479, $P<0.001$, $r^2=0.931$ (Fig. 6a; Table 6). However, $\log\partial L_{perceived}$ did not vary with $\log I_1$: $\log\partial L_{perceived} = 0.020 \times \log I_1 + 1.295$ (in cm), $F_{1,7} = 0.021$, $P=0.726$, $r^2=0.000$.

A multiple regression revealed that $\log I_1$ and activity accounted for 95.5% of the variance in $\log L_{perceived}$ [$P<0.001$, $\log L_{perceived} = (0.290 \times \log I_1) + (-0.001 \times \text{activity}) - 0.259$], activity: wielding = 1, striking = 0 (Table 6). $\log I_1$ accounted for a significant and large portion of the variance ($\beta=0.981$, $P<0.001$). Activity did not account for any variance ($\beta=-0.018$, $P=0.730$).

Given that in Experiment 2 the participants struck the grasped objects along their lengths, and not by the tips, we did not use L_{actual} to determine $\log\Delta L_{perceived}$. Instead, we calculated their predicted perceived lengths, $L_{predicted}$, using the relationship between $\log I_1$ and $\log L_{perceived}$ in Experiment 1: $\log L_{perceived} = 0.106 \times \log I_1 + 1.107$ (in cm; Table 4). We determined $\log\Delta L_{perceived}$ of each object for each participant using the equation: $\log\Delta L_{perceived} = \log(L_{perceived} \sim L_{predicted})$.

We conducted a 9 (object) × 3 (activity) repeated-measures ANOVA on $\log\Delta L_{perceived}$ with within-subject factors of object and activity. There was a significant main effect of $\log I_1$ ($F_{8,80}=4.397$, $P<0.001$, $\eta^2=0.305$). Pairwise comparisons with Bonferroni corrections revealed that $\log\Delta L_{perceived}$ varied across the nine objects (Ps < 0.05). The main effect of activity was not significant ($F_{1,10}$ = 3.252, $P=0.102$, $\eta^2=0.245$). The interaction effect of object × activity was not significant ($F_{8,80}$ = 1.837, $P=0.082$, $\eta^2=0.155$).

At the level of mean data, simple linear regressions confirmed significant linear relationships between $\log I_1$ and

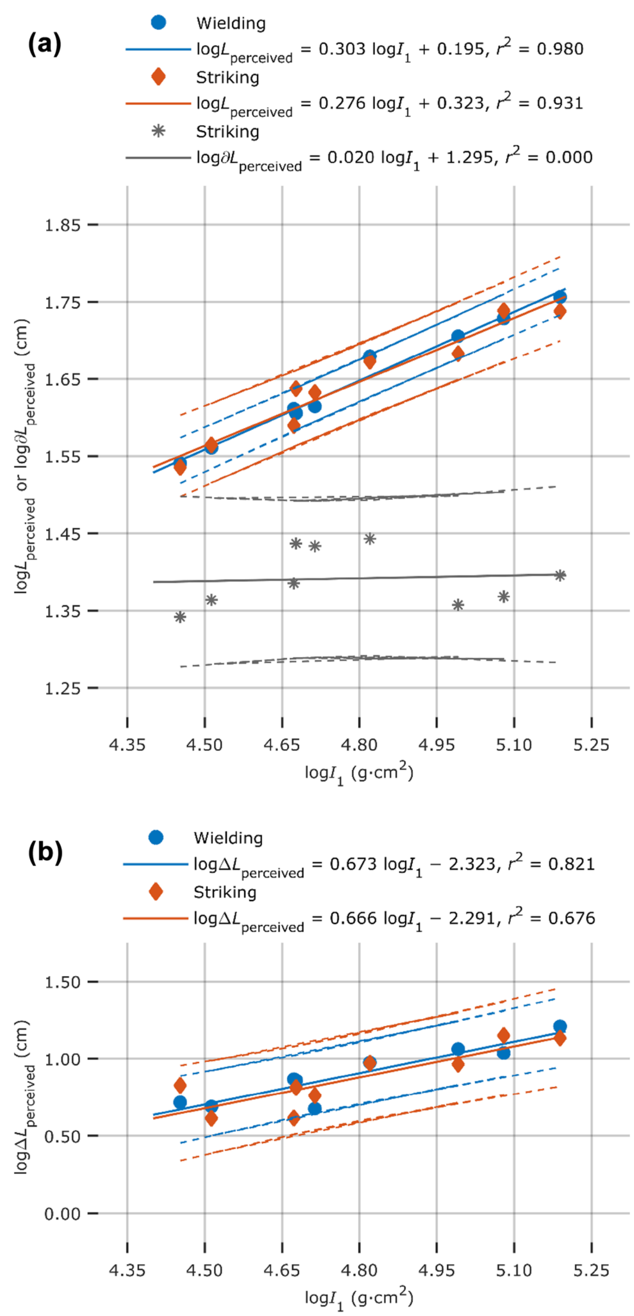

Fig. 6 Linear relationships between **a** $\log I_1$ and $\log L_{perceived}$ or $\log \partial L_{perceived}$, and **b** $\log I_1$ and $\log \Delta L_{perceived}$, of the unweighted and weighted objects ($n = 9$) in Experiment 2. Dashed lines represent 95% CI around the estimate

$\log \Delta L_{perceived}$ corresponding to each activity: (1) wielding: $\log \Delta L_{perceived} = 0.673 \times \log I_1 - 2.323$ (in cm), $F_{1,7} = 37.687$, $P < 0.001$, $r^2 = 0.821$; (2) striking: $\log \Delta L_{perceived} = 0.660 \times \log I_1 - 2.291$ (in cm), $F_{1,7} = 17.695$, $P = 0.004$, $r^2 = 0.676$ (Fig. 6b; Table 6).

A multiple regression revealed that $\log I_1$ and activity accounted for 77.8% of the variance in $\log \Delta L_{perceived}$ [$P < 0.001$, $\log \Delta L_{perceived} = (0.694 \times \log I_1) - (0.014 \times \text{activity}) - 2.409$], activity: wielding = 1, striking = 0 (Table 6). LogI_1 accounted for a significant and large portion of the variance ($\beta = 0.914$, $P < 0.001$). Activity did not account for any variance ($\beta = -0.186$, $P = 0.131$).

The participants accurately perceived the extents of the grasped objects from the point of rotation (in the hand) to the point of object–target contact. Perception of these extents did not vary with $\log I_1$. In contrast, $\log I_1$ predicted perceived lengths of the grasped objects obtained by both wielding and striking against a perpendicular rod at some point along their lengths. As predicted, neither the lengths of the grasped objects not the scaling relationship between $\log I_1$ and perceived length, or between $\log I_1$ and error in perceived length differ between the two activities. The finding that error in perceived length varied directly with rotational inertia is consistent the relationship between rotational inertia and perceived length of weighted objects in experiment 1. However, unlike between wielding and striking with the tips, this relationship did not differ between wielding and striking at some point along the lengths of the grasped objects. Note that in Experiment 1, the scaling relationship between $\log I_1$ and perceived length differed between the two activities; making contact with the target with the tip of the grasped object improves the accuracy of perception. Together, these findings strongly support the hypothesis that the location of a grasped object's effector influences perception of the length of that object via dynamic touch. Our findings are consistent with how elastic, vibratory waves originating at the point of object–target contact propagate along the extent of an object (Achenbach 1975), potentially influencing perception of the length of that object via dynamic touch.

Discussion

In the present study, we examined whether and how making (percussive) contact with a target influences perception of the length of a grasped object via dynamic touch. In two related experiments, the participants either wielded or struck (against a target) grasped objects of different lengths, masses, and/or mass distributions and reported their perceived lengths in the absence of vision. Striking a rigid-grasped object against an intended target generates elastic, vibratory waves, originating at the point of object–target contact and propagating along the extent of that object (Achenbach 1975). We hypothesized that the time-varying magnitude of these waves—as perceived by the wielder—must depend on the extent of the grasped object between the point of origin of the waves and the location of grasp. We reasoned that for an object of a given composition, perception of the vibratory waves originating at the tip should depend on the length of that object. Perception of the vibratory waves originating at a point along the length

Table 6 Outcomes of simple linear regressions across all 11 participants in Experiment 2

Activity	$F_{1,7}$	P	r^2		Estimate ± SE	β	t	P
Log$L_{perceived}$								
Wielding	384.729	**< 0.001**	0.980	Intercept	0.195 ± 0.074		2.633	**0.034**
				Coefficient of logI_1	0.303 ± 0.015	0.919	19.615	**< 0.001**
Striking	109.479	**< 0.001**	0.931	Intercept	0.323 ± 0.126		2.556	**0.038**
				Coefficient of logI_1	0.276 ± 0.026	0.969	10.463	**< 0.000**
Striking ($\partial L_{perceived}$)	0.133	0.726	0.000	Intercept	1.295 ± 0.267		4.842	**0.002**
				Coefficient of logI_1	0.020 ± 0.056	0.137	0.365	0.726
Overall	182.380	**< 0.001**	0.955	Intercept	0.259 ± 0.073		3.565	**0.003**
				Coefficient of logI_1	0.290 ± 0.015	0.981	19.089	**< 0.000**
				Coefficient of activity (wielding: 0; striking: 1)	− 0.001 ± 0.002	− 0.018	− 0.352	0.730
Log$\Delta L_{perceived}$								
Wielding	37.687	**< 0.001**	0.821	Intercept	− 2.323 ± 0.525		− 4.418	**0.003**
				Coefficient of logI_1	0.673 ± 0.110	0.918	6.139	**< 0.001**
Striking	17.695	**0.004**	0.676	Intercept	− 2.291 ± 0.753		0.000	**0.019**
				Coefficient of logI_1	0.660 ± 0.157	0.846	− 3.044	**0.004**
Overall	30.771	**< 0.001**	0.778	Intercept	− 2.409 ± 0.421		− 5.721	**< 0.001**
				Coefficient of logI_1	0.694 ± 0.089	0.914	7.845	**< 0.001**
				Coefficient of activity (wielding: 0; striking: 1)	− 0.014 ± 0.009	− 0.186	− 1.599	0.131

Boldfaced values indicate statistical significance

of an object should depend on the segment's length up to that point. Thus, the time-varying amplitude of vibratory waves originating at the tip is informative of the length, but those of waves originating at a point along the length are not. Consistent with our predictions, making contact with a target by the tip resulted in a more accurate perception of the length than simple wielding. However, making contact with the target at a point along the length did not influence the accuracy of perception. These findings suggest that the location of a grasped object's effector influences perception of properties of that object via dynamic touch by striking. We discuss these findings in terms of time-varying properties of vibrations generated by the percussive contact of the grasped object and target.

The propagation of vibratory waves generated by object–target contact is highly dependent on object dimensions, as illustrated in Fig. 2. Therefore, we used dowels of different composition in experiment 1 to vary their rotational inertias while keeping their lengths the same; we used dowels of the same composition in experiment 2. The propagation of vibratory waves in objects in experiment 2 should depend on the length and not on the composition of these objects. In light of these arguments, the present findings indicate that vibratory waves can contribute significantly to perception via dynamic touch by object–target contact.

In the literature concerning perception via dynamic touch, the term "partial length" has been consistently used to describe the extent of a grasped object on either end of the location of grasp, given that each object was grasped somewhere along the middle (e.g., Carello et al. 1996; Cooper et al. 2000). However, "partial length," as we have used it, refers to the extent of the grasped object between the location of grasp at the proximal-most end and the location of object–target contact. As such, in experiment 2, partial length becomes perceptually relevant only in the event of an object–target contact. Given that the rotational inertias of the objects varied, they could have in no way contributed to perception of partial lengths. The finding that partial lengths of all objects remained constant (about 30 cm) for all objects, suggests that some information other than rotational inertia contributed to perception of partial lengths. The same information could have resulted in an enhanced accuracy of perception of (whole) lengths by striking compared to wielding. We propose that vibratory waves provided this information. We did not explicitly examine whether striking exaggerated perception of lengths of objects with greater rotational inertias, as proposed by Kelty-Stephen and Eddy (2015). However, we intend to investigate the confluence of such exaggeration of perception and the proposed role of vibratory waves in future research.

We place the present findings within the perspective that perception is organized functionally rather than anatomically. According to Gibson's ecological approach (Gibson 1966, 1979), perception of a particular feature of the environment is based on detection of invariant patterns of stimulation. A premise of this approach is that an object or an event lawfully structures the patterns of energy distributions (e.g., optic or acoustic array) such that this structure is specific to the source. Such invariance putatively underlies the perceiver's capability to perceive a given feature of the environment with different configurations of either the same perceptual modality or by entirely different perceptual modalities (Carello et al. 1998; Palatinus et al. 2011; Wagman and Abney 2012; Wagman and Hajnal 2014a, b; Wagman et al. 2017). That is, to a large extent, perception of a given property is independent of both anatomy and modality; instead, perception is organized functionally.

Previous research has shown that auditory and dynamic perceptions of length of an object are each constrained by the object's mechanical properties (Carello et al. 1998; Wagman and Abney 2012). People can perceive the length of an object by the sound produced by it falling on a hard surface (Carello et al. 1998). They can recalibrate perception using information obtained by other modalities (sound vs. haptic or vice versa) (Wagman and Abney 2012). Together, these findings imply that the two modalities (sound vs. haptic) share a length-specifying variable in the expressions of that information. The present findings indicate that the expression of this length-specifying variable occurs through time-varying properties of the elastic, vibratory waves propagating along the length of a grasped object perceived via dynamic touch by striking, just as it occurs through time-varying properties of the sound waves produced by an occluded, fallen object perceived auditorily.

Using a grasped object to interact with a target utilizes all three haptic subsystems: cutaneous, haptic and dynamic touch. Their confluence provides information about both the grasped object and the target to varying degrees, as per the invoked exploratory process(es). Identifying the confluence of factors relevant to the cutaneous, haptic and dynamic touch occurring within specific exploratory processes has implications for applied ergonomics, such as the incorporation of perceptual variance implied by the location and discreteness of the effector(s) into the design and functionality of certain hand-held tools (e.g., file, knife, saw). The patterns of haptic stimulation relevant for perception via dynamic touch occur at the level of tissue deformation across the entire multifractal tensegrity (MFT) system; they are anatomically independent (Pagano et al. 1993; Hajnal et al. 2007a, b; Palatinus et al. 2011; Wagman and Hajnal 2014a; Wagman et al. 2017). Given that a grasped object is not an MFT system, unlike the human body (Turvey and Fonseca 2014), such anatomical independence of perception does not extend to the body-plus-object system. This fact alters our understanding of perceptuomotor limitations of prosthetic devices. A prosthesis resembles a grasped object in that neither are MFT systems. To design into hand prostheses the confluence of haptic perceptual capacities of the human hand and arm, we need first to understand the functioning of the MFT system of the body in dynamic touch (Turvey and Fonseca 2014).

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Compliance with ethical standards

Conflict of interest The authors declare that no competing interests exist.

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