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Cognition 73 (1999) B17–B26

COGNITION

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Affordance, proper function, and the physical basis of perceived heaviness

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Received 29 January 1999; received in revised form 9 April 1999; accepted 27 July 1999

Abstract

The physical basis of perceived heaviness requires consideration of the haptic perceptual system's role in controlling actions (the system's proper function) and the relation of an object's inertial properties to properties of the human movement system (the object's affordance). We show that the mass of a wielded object and particular scalar variables calculated from the object's inertia tensor combine linearly in determining perceived heaviness. The tensor-derived scalars reflect the symmetry and volume of the corresponding inertia ellipsoid. These measures bear directly on the object's wieldability, that is, on the patterning and level of muscular forces required to move the object in a controlled fashion. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Affordance; Perceived heaviness; Physical basis

Among the many challenges that must be faced in the scientific investigation of biological perceptual systems, none is more vexing, perhaps, than that of *referent*. To what properties of the environment do our perceptions refer specifically? Its close ally is the question of what is a perceptual system's or subsystem's *proper function* (Millikan, 1984, 1993); what has it done successfully in the history of the species to warrant reproduction?

In important respects, scientific psychology began with these questions, albeit implicitly. In 1834, Ernst Weber opened inquiry into the perception of weight (Weber, 1934/1978). He asked how a person's impression of heaviness related to the weight of a held and/or hefted object. As is well known to all psychologists, he documented the imperfect fit between perceptual and actual variations in weight and

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PII: S0010-0277(99)00050-5

initiated its quantification. Though imperfect, the fit was, nonetheless, lawful. Weber observed that discrimination among objects that differed in weight could be reasonably accounted for by a simple constant ratio: the minimal difference needed to distinguish a comparison object from a standard object divided by the weight of the standard object.

The slippage between actual and perceived weight was, however, more pronounced than the original forays into the psychophysical function made apparent. A person presented with objects of exactly the same weight but different volumes perceives the objects to decline in weight as volume increases (Charpentier, 1891). Historically, the so-called size-weight illusion made it very clear that one's perception of the heaviness of an object does not refer to the object's weight (Jones, 1986). A traditional substitute for the failed hypothesis that weight is perceived is the hypothesis that there could well be a mental state corresponding to the object's weight but it is unconsciously modified by the mental state corresponding to the object's size. The two mental states or percepts are coupled and 'heaviness' refers, therefore, not to a physical property of the object as such but to the mental state formed by the coupling.

The percept-percept coupling hypothesis of perceived heaviness is unsatisfactory for two major conceptual reasons and one major experimental finding. First, there is no rationale for why weight and size should be linked. The lack of clear purpose suggests that the proposed mechanism is not a proper function. Second, no principled reason is advanced for the particular directional influence of the size perception on the weight perception (why, precisely, should largeness imply lightness?). The experimental finding is that the application of the methods and analyses developed by Ashby and Townsend (1986) for addressing the relations between perceptions have revealed that haptically perceived heaviness is independent of haptically perceived size (Amazeen, 1999).

In the present article we consider a third hypothesis, namely, that one's haptic perception of an object's heaviness refers to neither an ordinary physical property of the object nor to a derived mental state. This hypothesis is motivated by Gibson's (1979) insistence that basic perceptions typically refer to *affordances*. An affordance of an object is objective, real and physical but the (objective, real and physical) properties constituting an affordance are not those of the object in isolation but of the object taken in reference to the properties and behavior of the animal being considered. By this third hypothesis, whereas weight is a fact of an object, the affordance that constrains the human perception of an object's heaviness is equally a fact of the object and a fact of human behavior.

In ordinary everyday interactions with objects, the forces and torques required to bring about motions in particular directions at particular speeds must be tailored to the resistances of any given object to translation and rotation. These resistances are defined, respectively, by an object's mass (measured in kilograms, kg) and inertia tensor (measured in kilograms times meters squared, kg m^2). A reasonable guess is that a proper function of the haptic perceptual system is, roughly stated, the registering of these resistances in a form and a manner that satisfy the requirements for generating the muscle tensile states that move an object in the desired way. The

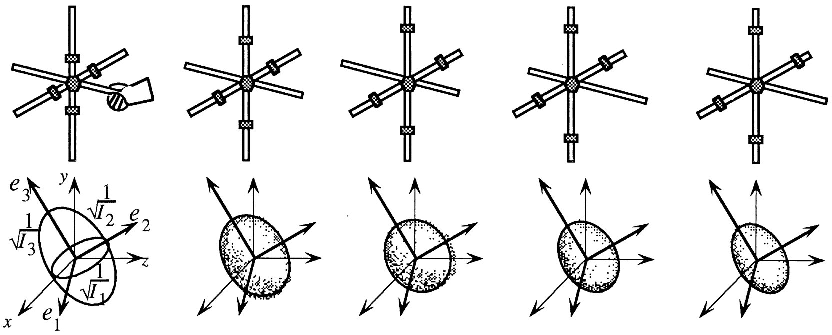

Fig. 1. (Top) Tensor objects include a stem that is grasped in the right hand, with a cross attachment whose distance from the hand can be adjusted along with the positions of masses on the cross branches. (bottom) These adjustments have consequences for the inertia ellipsoids whose axes and radii are given by the eigenvectors $\boldsymbol{e}_k$ and the inverse square roots of the eigenvalues I_k, respectively, of the objects' inertia tensors (where $k = 1, 2, 3$). As can be seen, the ellipsoids vary in shape and volume.

hypothesized affordance to which perceived heaviness refers can be developed in the context of this proper function. The key to this development is the inertia tensor.

The inertia tensor, defined for a given point of rotation O, is a 3×3 matrix with moments of inertia on the diagonal and products of inertia off the diagonal. There are three axes through O about which the object's mass is evenly distributed. The inertia tensor computed about these axes, referred to as the principal axes or eigenvectors, has only diagonal components, I_1, I_2, and I_3, referred to as the principal moments or eigenvalues. Rigid bodies or objects fall into three dynamically distinct classes depending on the relative values of the principal moments. A rigid object is *centro-symmetric* when none are distinct (all three moments are equal), *axially symmetric* when only two are distinct, and *asymmetric* when all three are distinct (Hestenes, 1986). How an object rotating about O responds to applied torques, that is, its rotational dynamics, depends on the object's rotational inertia symmetry relative to O. Let the object be a handheld object and let O be a point in the wrist. Then, for an object that is centrosymmetric about O, the dynamics about any given axis of rotation through O is equal to the dynamics about any other axis of rotation through O. Simply put, the object is as easy (or as hard) to turn in any one direction as it is in any other. In contrast, the dynamics of an object that is asymmetric relative to O depend dramatically on the chosen axis. It is much harder to turn about the principal axis corresponding to the maximal moment I_1, and much easier to turn about the principal axis corresponding to the minimal moment I_3, than it is about any other axis. From the perspective of muscular synergies and coordination, controlling the motions of an asymmetric object is more challenging than controlling the motions of a centrosymmetric object. (Intuitively, the cascade juggle is more difficult with rectangular blocks than with balls.)

The importance of the preceding distinctions is brought home by Amazeen and Turvey's (Amazeen & Turvey, 1996) observation that the perceived heaviness of a freely wielded but nonvisible object of a given mass decreased as its principal

Table 1
Object mass, symmetry (S), eigenvalues (I_1, I_2, I_3) and mean perceived weight in Experiment 1

Object[a]	Mass (g)	S	I_1 (kg m^2)	I_2 (kg m^2)	I_3 (kg m^2)	Mean (SD)[b]
1	458	0.20	4.98	4.80	0.98	93.5 (2.62)
2		0.43	4.16	3.78	1.71	87.0 (8.28)
3		0.73	3.56	3.06	2.43	78.6 (12.92)
4	518	0.20	4.88	4.80	0.97	103.1 (6.24)
5		0.44	4.15	3.75	1.73	93.1 (7.66)
6		0.73	3.56	3.03	2.41	84.1 (9.82)
7	578	0.20	4.99	4.84	0.97	109.9 (6.38)
8		0.44	4.16	3.73	1.73	100.4 (6.19)
9		0.74	3.55	2.98	2.41	92.4 (6.28)

[a] Object 4 served as the standard, with an assigned value of 100, for magnitude estimations.
[b] Each mean is based on five observations. Standard deviations (SD) are calculated over participants.

moments became more nearly identical. As interpreted here, the observation was that haptically perceived heaviness varied inversely with an object's dynamical symmetry. In their experiments, Amazeen and Turvey used 'tensor objects' similar to those depicted in the top of Fig. 1. They manipulated the principal moments of these objects (of fixed linear dimensions) to conform to the measured changes in principal moments that accompany changes in size in a typical set of same-weight objects used to demonstrate the size-weight illusion (e.g. Charpentier, 1891; Stevens & Rubin, 1970). We hypothesize, therefore, that the haptic size-weight illusion reflects the specificity, when mass and other factors are constant, of perceived heaviness to dynamical symmetry.

An implication of this hypothesis is that 'perception of heaviness' is, more appropriately, 'perception of wieldability (or steerability).' That is, it is the perception of the opportunities a handheld object affords for varying the patterning and level of muscular forces required to move the object in a controlled fashion. A handheld object is unwieldy or unwieldable to the extent that there are relatively few ways in which forces can be applied to the object in order to bring about a desired trajectory. The objective, real and physical basis for this affordance of wieldability is the handheld object's mass distribution taken with reference to the force-producing neuromuscular system. In this complementation of object and neuromuscular system, the symmetry of the inertia tensor emerges as the relevant physical quantity.

In Amazeen and Turvey (1996), manipulations of dynamical symmetry were not accompanied by manipulations of mass. It is apparent, however, that in the most general case, the affordance to which perceived heaviness refers (namely, wieldability) is inclusive of an object's inertia tensor and its mass (Amazeen, 1997). We consider the hypothesis suggested by Kreidfeldt and Chuang (1979) in their original investigation of sensitivity to rotational inertia: consistent with the laws of rigid body motion, the individual perceptual effects of the inertia tensor and mass should be additive.

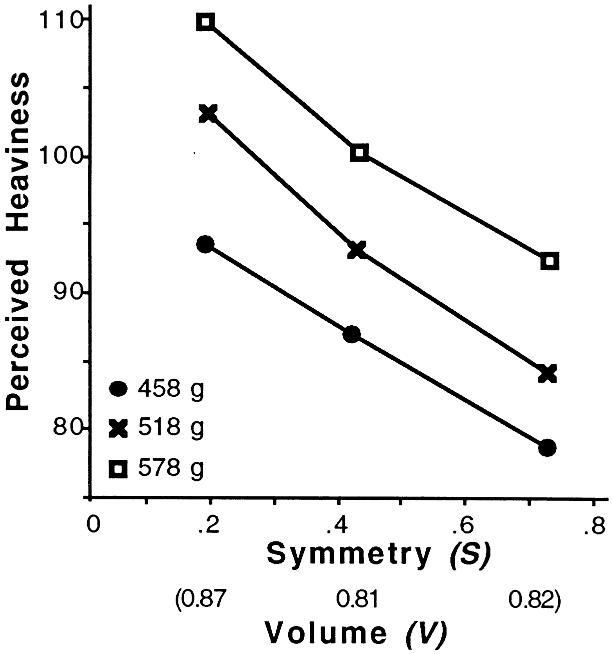

Fig. 2. Perceived heaviness as a function of mass and S in Experiment 1 (V is added for comparison with Experiment 2).

1. Experiment 1

A metric for dynamical symmetry (S) can be defined in several ways. A convenient definition (given $I_1 \geq I_2 \geq I_3$) is the ratio

$$S = 2I_3/(I_1 + I_2)$$

This ratio increases as the principal moments become more nearly identical attaining unity (the highest value) when the object is centrosymmetric. Experiment 1 used tensor objects that allowed three levels of S to be crossed with three levels of mass (Table 1). The expectation was that perceived heaviness would increase with mass and decrease with S, with the rate of decrease the same for each mass value. That is, no mass $\times$ S interaction in the analysis of variance and perceived heaviness should equal a(mass) $-$ $b(S)$ $+$ c in the corresponding multiple regression (where a, b, and c are constants).

Eight undergraduates at the University of Connecticut participated in partial fulfillment of a course requirement. The tensor objects were never seen throughout the experiment (participants were blindfolded) and no information was given about the objects' design or variety. The objects were firmly grasped in the right hand in the manner shown in Fig. 1 with the proximal end of the stem flush with the bottom of the fist and with the stem always parallel to the fist. Wielding was about the wrist with the forearm supported. Perceived heaviness was reported by magnitude estima-

Table 2
Object mass, symmetry (S), volume (V), eigenvalues (I_1, I_2, I_3) and mean perceived weight in Experiment 2

Object[a]	Mass (g)	S	V	I_1 (kg m^2)	I_2 (kg m^2)	I_3 (kg m^2)	Mean (SD)[b]
1	449	0.39	1.62	2.71	2.48	1.00	119.9 (14.53)
2		0.60	1.35	2.71	2.35	1.51	102.1 (7.42)
3		0.81	1.21	2.70	2.23	1.99	89.6 (5.85)
4		0.59	0.88	3.60	3.17	2.00	112.5 (12.15)
5		0.47	0.69	4.50	4.08	2.00	134.0 (21.57)
6	509	0.39	1.62	2.70	2.48	1.00	126.4 (16.41)
7		0.60	1.35	2.70	2.33	1.50	111.7 (12.09)
8		0.80	1.21	2.71	2.21	1.98	103.5 (5.99)
9		0.59	0.88	3.60	3.15	1.99	123.0 (15.36)
10		0.47	0.69	4.50	4.06	2.01	146.4 (23.79)
11	569	0.39	1.62	2.70	2.48	1.00	144.2 (25.97)
12		0.60	1.35	2.70	2.31	1.49	133.6 (19.08)
13		0.81	1.21	2.71	2.17	1.98	116.2 (8.23)
14		0.59	0.88	3.62	3.13	1.99	136.4 (17.66)
15		0.47	0.69	4.51	4.04	2.00	153.7 (28.85)

[a] Object 8 served as the standard, with an assigned value of 100, for magnitude estimations.
[b] Each mean is based on four observations. Standard deviations (SD) are calculated over participants.

tion relative to a standard (Object 4, see Table 1) presented on every trial. There were five trials per condition.

1.1. Results

The mean judgments of heaviness as a function of mass and S are reported in Fig. 2. An analysis of variance (ANOVA) found main effects of mass (heaviness increased with mass), $F(2,28) = 51.63$, $P < 0.001$, and S (heaviness decreased with S), $F(2,28) = 30.86$, $P < 0.001$. The mass $\times$ S interaction was not significant, $F < 1$. In sum, the results confirmed the expected 'size-weight illusion' at each mass level and were consistent with the hypothesis that perceived heaviness depends on a linear combination of an object's mass and S. Also consistent with the linear combination hypothesis was the outcome of a multiple regression of mean perceived heaviness on mass and S. The r^2 values were 0.92, 0.92, 0.97, 0.83, 0.95, 0.96, 0.73, and 0.92 for the individual participants. In each individual regression, both mass and S were significant, $P = 0.0001$.

2. Experiment 2

Geometrically, the inertia tensor corresponds to an ellipsoid. The principal axes of this ellipsoid are the principal axes of the inertia tensor and the lengths of the semi-axes are the inverses of the square roots of the tensor's principal moments (e.g. Borisenko & Tarapov, 1979). The bottom of Fig. 1 shows how the ellipsoid of inertia

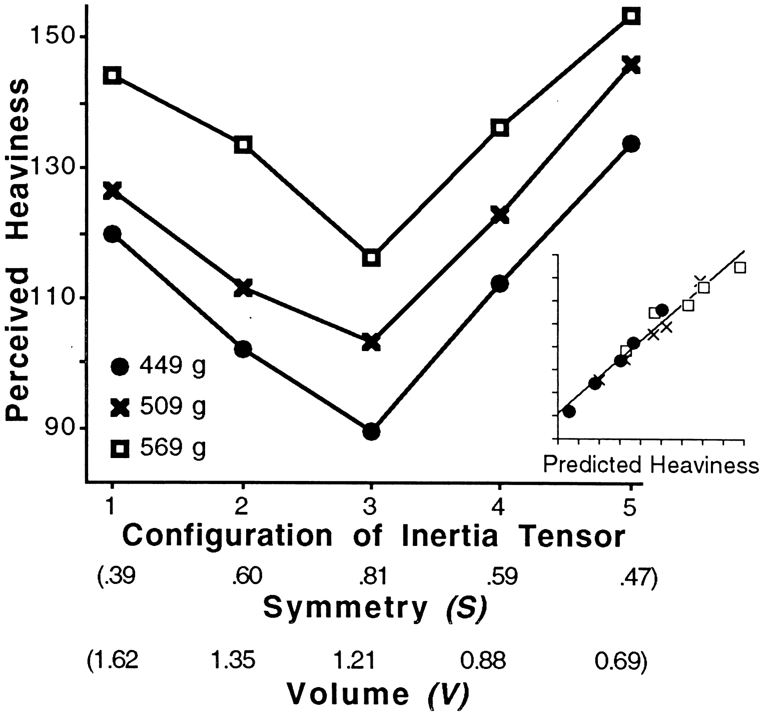

Fig. 3. In Experiment 2 there were five distinct configurations (1–5) of the inertia tensor, yielding five values each of S and V, for each of three levels of mass. The main figure illustrates how perceived heaviness varied with the configurations 1–5 of the inertia tensor, more specifically, S and V, and with mass. The inset shows perceived heaviness averaged across participants as a function of the equation generated by the multiple regression on mass, S, and V.

transforms as a function of the relative values of the principal moments, that is, as a function of its dynamical symmetry, S.

In addition to its symmetry, an ellipsoid is characterized by its volume

$$V = 4\pi/3\left(\mathrm{Det}\, I_{ij}\right)^{-1/2}$$

where Det I_{ij} is the determinant of the tensor given by the product of its principal moments. When wielding an object, its overall resistance to being wielded, expressed by the reciprocal of V, should be a factor. Returning to the notions of affordance and proper function, the wieldability of an object must reflect V (what mean level of torque is needed?) as well as S (how should the torque be directed?) and the somatosensory capability deserving of reproduction must be, presumably, the dual registration of V and S in order that muscular forces appropriate to the control requirements of wielding an object can be generated.

In Experiment 1, V was relatively constant (see Fig. 2). In Experiment 2, V differed among the tensor objects and was uncorrelated with S ($r^2 = 0.03$). Using

15 tensor objects of the kind depicted in Fig. 1, five different tensors of inertia, yielding five values each of S and V, were repeated for each of three levels of mass. The details of the 15 tensor objects are shown in Table 2. The following outcomes were expected. First, the perceptual effects of the manipulations of mass and tensor of inertia should be additive in affirmation of the linear-combination hypothesis. Second, it should prove to be the case that mass and S are not fully predictive of perceived heaviness; V is also required. Seven graduate students at the University of Connecticut participated on a volunteer basis. The procedure was identical to that of Experiment 1 with the exception of the standard (Object 8, see Table 2) and the use of only four trials per condition.

2.1. Results

Mean perceived heaviness is plotted in Fig. 3 as a function of tensor of inertia, with the five distinct configurations labeled 1–5, and with mass as the curve parameter. The different ranges of perceived heaviness in Figs. 2 and 3 may be attributed to differences in V and standard objects between experiments. Inspection of Fig. 3 suggests that perceived heaviness was affected additively by mass and the inertia tensor. An ANOVA found main effects of mass, $F(2,48) = 29.38$, $P < 0.001$ and tensor of inertia, $F(4,48) = 17.95$, $P < 0.001$ and no interaction, $F \approx 1$. Inspection also suggests that perceived heaviness was not linear with S ($S = 0.39$ yielded consistently lower perceptions than $S = 0.47$) indicating that the uncorrelated variation in V may have contributed. A multiple regression conducted on mean perceived heaviness with independent variables of mass and S accounted for 78, 77, 80, 51, 78, 50 and 80% of the variance in the performance of the individual participants. When V was added to mass and S in the multiple regression, the variance accounted for was 93, 88, 89, 87, 95, 89, and 86%. For each participant, the coefficients on mass, S and V were positive, negative, and negative, respectively; that is, perceived heaviness increased with mass and decreased with the symmetry and volume of the inertia ellipsoid. Perceived heaviness as a function of the equation derived by aggregating participants is shown in the inset of Fig. 3.

2.2. General discussion

To understand any phenomenon, a major first step is identifying the ‘right degrees of freedom’ (Krieger, 1992, p. 30). These lead to simple observation and orderly knowledge. In respect to the perceived heaviness that accompanies the hefting and wielding of objects, the present research identifies mass, S and V as the right degrees of freedom. The deeper significance of S and V is that they are physical characterizations of an object’s resistance to rotational acceleration (its inertia tensor) taken in reference to the human movement system. The inertia tensor per se is not a right degree of freedom but particular configurations of its principal moments or eigenvalues are right degrees of freedom – they promise a simpler and biologically plausible understanding of the body of data on haptically perceived heaviness.

It is important to underscore the distinction being drawn between the inertia tensor per se and the S and V characterizations of the inertia tensor. Patently, the definition of the inertia tensor is strictly in terms of an object's mass distribution relative to a point of rotation. No reference to the particular origin or source of the forces that act upon the object is necessary. In contrast, the definition of a *preferred configuration* of the inertia tensor (e.g. centrosymmetry) must make reference to the system from which the forces originate. Biological systems are distinguished from nonbiological systems by the capability to control the magnitudes and directions of applied forces in functionally specific ways. This capability is selective with respect to the configurations of the inertia tensor's eigenvalues. Other things being equal, the more symmetric is an object's inertia tensor, the simpler is the specification of forces required to control the object's motions. As noted above, for a wielded centrosymmetric object, the stability of its rotational dynamics is the same for any arbitrarily chosen axis of rotation.

The overall conclusions of the present article may be seen as elaborations of earlier arguments that the size-weight effect: (a) is not an illusion but an indication that 'heaviness' properly refers to a specific relation between size and weight (Stevens & Rubin, 1970; Cross & Rotkin, 1975); and (b) can only be understood in the light of well-defined functional contexts that focus upon the affordances of objects (e.g. their throwability and manipulability; Bingham, Schmidt & Rosenblum, 1989). More generally, whereas centrosymmetry may be preferred for functional contexts that favor ease of movement, axial symmetry may be preferred for other functional contexts (e.g. those that favor striking with power, as in the design of a baseball bat or tennis racket; Carello, Thuot, Anderson & Turvey, 1999).

Finally, the present research suggests that translational and rotational inertia combine linearly in determining perceived heaviness, as predicted by Kreidfeldt and Chuang (1979). Such additivity implicates the engagement of two independent subsystems of the haptic perceptual system (e.g. Holway, Goldring & Zigler, 1938) and the involvement of the complex law of motion for a rigid body (Hestenes, 1986, p. 426). The generalizability of the present evidence for additivity must be considered in light of the facts that: (a) the required factorial combination of mass and the inertia tensor imposes severe physical restrictions on the mass variation achievable in any given experiment; and (b) the tensor objects were in the higher range of mass values for objects that an adult person typically transports unimanually (e.g. ceramic cups, books). In future research, it will be important to consider the generalization of additivity to the perception of heaviness in nonterrestrial environments (e.g. Ross & Reschke, 1982). We conclude by noting that the present study adds to the growing body of data showing the sensitivity of haptic perception to the invariants of rotational dynamics (Turvey & Carello, 1995; Turvey, 1996).

Acknowledgements

This research was supported by NSF Grant SBR 97-09678. Correspondence should be addressed to M.T. Turvey, CESPA U-20, 406 Babbidge Road, University of Connecticut, Storrs, CT 06269-1020.

References

Amazeen, E. (1997). The effects of volume on perceived heaviness by dynamic touch: With and without vision. *Ecological Psychology*, *9*, 245–264.

Amazeen, E. (1999). Perceptual independence of size and weight by dynamic touch. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 102–119.

Amazeen, E., & Turvey, M. T. (1996). Weight perception and the haptic size-weight illusion are functions of the inertia tensor. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 213–232.

Ashby, G., & Townsend, J. T. (1986). Varieties of perceptual independence. *Psychological Review*, *93*, 154–179.

Bingham, G., Schmidt, R. C., & Rosenblum, L. (1989). Hefting for a maximum distance throw: A smart perceptual mechanism. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 507–528.

Borisenko, A. I., & Tarapov, I. E. (1979). *Vector and Tensor Analysis*, New York: Dover.

Carello, C., Thuot, S., Anderson, K. L., & Turvey, M. T. (1999). Perceiving the sweet spot. *Perception*, *28*, 307–320.

Charpentier, A. (1891). Analyse experimentale de quelques elements de la sensation de poids [Experimental study of some aspects of weight perception]. *Archives de Physiologie Normales et Pathologiques 3*, 122–135.

Cross, D. V., & Rotkin, L. (1975). The relation between size and apparent heaviness. *Perception and Psychophysics*, *18*, 79–87.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*, Boston: Houghton Mifflin.

Hestenes, D. (1986). *New Foundations for Classical Mechanics*, Dordrecht, The Netherlands: Kluwer Academic.

Holway, A. H., Goldring, L. E., & Zigler, M. J. (1938). On the discriminability of minimal differences in weight: IV. *Kinesthetic adaptation for exposure intensity as variant. Journal of Experimental Psychology*, *23*, 536–544.

Jones, L. A. (1986). Perception of force and weight: Theory and research. *Psychological Bulletin*, *100*, 29–42.

Kreidfeldt, J. G., & Chuang, M. -C. (1979). Moment of inertia: Psychophysical study of an overlooked sensation. *Science*, *206*, 588–590.

Krieger, M. (1992). *Doing Physics*, Bloomington, IN: Indiana University Press.

Millikan, R. (1984). *Language, Thought and Other Biological Categories*, Cambridge, MA: MIT Press.

Millikan, R. (1993). *White Queen Psychology and Other Essays for Alice*, Cambridge, MA: MIT Press.

Ross, H. E., & Reschke, M. F. (1982). Mass estimation and discrimination during brief periods of zero gravity. *Perception and Psychophysics*, *31*, 429–436.

Stevens, J. C., & Rubin, L. L. (1970). Psychophysical scales of apparent heaviness and the size-weight illusion. *Perception and Psychophysics*, *8*, 225–230.

Turvey, M. T. (1996). Dynamic touch. *American Psychologist*, *51*, 1134–1152.

Turvey, M. T., & Carello, C. (1995). Dynamic touch. In W. Epstein, & S. Rogers, *Handbook of Perception and Cognition: V. Perception of Space and Motion*, (pp. 401–490). San Diego, CA: Academic Press.

Weber, E. H. (1978). In H. E. Ross, *The Sense of Touch*, London: Academic Press. Original work published 1834.