Research Report

PERCEPTION OF OBJECT LENGTH BY SOUND

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Abstract—*Although hearing is classically considered a temporal sense, everyday listening suggests that subtle spatial properties constitute an important part of what people know about the world through sound. Typically neglected in psychoacoustics research, the ability to perceive the precise sizes of objects on the basis of sound was investigated during the routine event of dropping wooden dowels of different lengths onto a hard surface. In two experiments, the ordinal and metrical success of naive listeners was related to length but not to the simple acoustic variables (duration, amplitude, frequency) likely to be related to it. Additional analysis suggests the potential relevance of an object's inertia tensor in constraining perception of that object's length, analogous to the case that has been made for perceiving length by effortful touch.*

The identification of sound-source events such as leaves rustling or water dripping is reasonably commonplace. Laboratory verifications of this ability indicate that listeners provide source identifications rather than sound descriptions (Gaver, 1988; Jenkins, 1985; Van Derveer, 1979a, 1979b). Despite this propensity, the bulk of psychoacoustic research has been weighted in the opposite direction, exploring the perception of properties of a sound (e.g., pitch, loudness, timbre) rather than the perception of properties of the sound source (e.g., size, shape, material).[1] Nonetheless, it is sources that animals and humans perceive, and source properties that have consequences for behavior (Fowler, 1990, 1991; Gaver, 1993a, 1993b). Our research concerns accuracy in the perception of a sound source, not in terms of identifying the event—a wooden dowel dropping onto a hard surface—but in terms of assessing a metrical property of the object itself—its size.

Metrical accuracy is not a property typically associated with perception by sound. Classically, hearing is considered a temporal rather than a spatial sense, and size is a spatial property. But size differences are at least crudely perceptible on the basis of sound; a pool cue clattering to the floor surely sounds bigger than a chopstick dropped onto the table. Can listeners perceive how much bigger, or, even better, how big each object is? Such questions are concerned with identifying what Gibson (1963) referred to as the "useful dimensions of sensitivity" and have consequences for what is manipulated and measured in the study of auditory perception and what one assumes the auditory nervous system has to work with. The goal of the present research, therefore, was twofold: to provide an empirical evaluation of the basic capability of size perception by sound (in particular, perception of the lengths of dropped wooden dowels) and to identify the physical properties of the objects that constrain that perception.

The first goal was addressed by experiments in which participants listened to the sounds made by wooden dowels that were dropped (out of view) repeatedly from a fixed height. Listeners positioned a visible report board to indicate the length of each dowel. They were given no information about the possible lengths or the number of rods. The sizes of the rods differed between the experiments, with relatively large rods (1.27 cm in diameter, 30–120 cm long) in Experiment 1 and relatively small rods (0.32 cm in diameter, 10–40 cm long) in Experiment 2. The second goal was addressed with two types of physical analyses, one of acoustic structure and one of rotational inertia, a quantity that has proven fruitful in understanding perception of size by dynamic touch (cf. Turvey, 1996).

EXPERIMENT 1

Method

Participants

Eight undergraduates at the University of Connecticut participated in partial fulfillment of a course requirement. All reported normal hearing.

Apparatus

Seven rods ranging in length from 30 to 120 cm in 15-cm increments were cut from pine dowels 1.27 cm in diameter. A given rod was held in place by a support lever that could be turned by the experimenter to release it from a height of 71.8 cm above the linoleum floor (Fig. 1). The rods were occluded from view by a cloth-covered Styrofoam screen. The listeners sat at a student desk facing a motorized vertical surface whose position could be adjusted from the proximal edge of the desk (0 cm) to 200 cm away.

Procedure

On a given trial, a rod was dropped five times. Participants were told to listen to the rods and move the adjustable surface out from the proximal edge of the desk to a position that could just be reached with the rod—in other words, so its length would fit between the desk and the surface. They were free to begin moving the surface after the first drop and to continue adjusting until they were satisfied with their response. The experimenter recorded the location of the surface (in centimeters) from a tape measure on her side of the screen (see Fig. 1). The seven rod lengths were presented three times each in random order.

Results and Discussion

Mean perceived length (and its standard deviation) is shown in Table 1 as a function of actual length. A repeated measures analysis of variance (ANOVA) showed a significant effect of length, $F(6, 42) = 40.25$,

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[1] The experimental investigations of sound-source properties using direct sound (as opposed to echo) are few. The properties examined in these experiments have included mallet hardness (Freed, 1990), propeller cavitation (Howard, 1983), geometric form (Lakatos, McAdams, & Caussé, 1997), sex of walkers (Li, Logan, & Pastore, 1991), hand configuration in clapping (Repp, 1987), and breaking and bouncing events (Warren & Verbrugge, 1984).

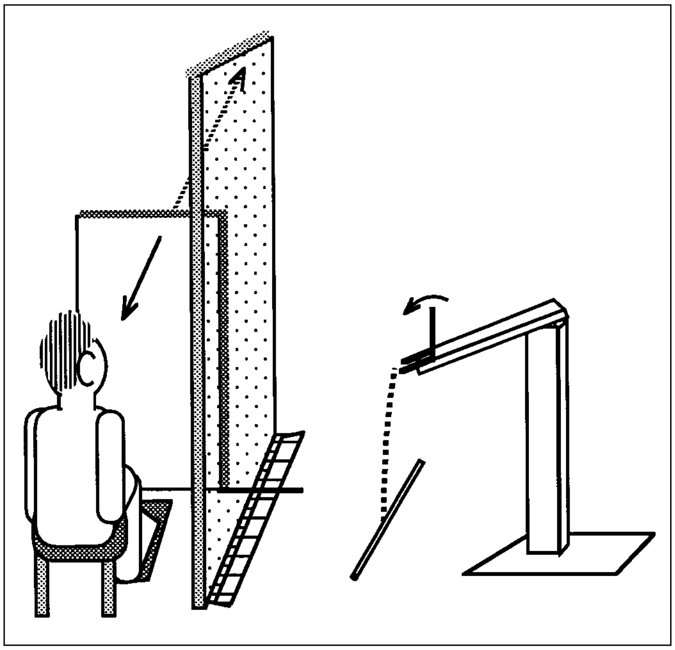

Fig. 1. The experimental apparatus. Listeners adjusted the distance of a visible surface in front of them to match the length of a rod that they could hear being dropped on the other side of an occlusion screen. A pointer attached to the bottom of the surface extended under the occlusion screen so that the reported length could be read off a tape measure visible to the experimenter.

$MSE = 133.37$, $p < .0001$. The regression of perceived length onto actual length was significant in the mean ($r^2 = .95$ with a slope of .78) as well as for each individual participant (with r^2 between .64 and .98). These regressions are comparable to those obtained in experiments on the perception of length by wielding nonvisible homogeneous rods (e.g., Solomon & Turvey, 1988).

This may well be the first demonstration of such a fine-grained attunement to acoustic structure and, as such, is remarkable enough. But the real test of listeners' abilities is to be found not simply in rank-ordering length but in a meaningful scaling of disparate lengths. Experiment 2 addressed whether listeners would reduce the range of produced magnitudes for a set of relatively smaller rods.

EXPERIMENT 2

Method

Six undergraduates at the University of Connecticut participated in partial fulfillment of a course requirement. All reported normal hearing.

Seven rods ranging in length from 10 to 40 cm in 5-cm increments were cut from pine dowels 0.32 cm in diameter. All other features of the apparatus and procedure were the same as in Experiment 1, with the exception that the rods were dropped onto an elevated surface (2-cm-thick plywood) to reduce the back and knee strain on the experimenter.

Table 1. *Actual rod lengths and average perceived lengths (with standard deviations) in Experiment 1 (radius = 0.64 cm) and Experiment 2 (radius = 0.16 cm)*

Experiment 1		Experiment 2	
Rod length (cm)	Mean perceived length (cm)	Rod length (cm)	Mean perceived length (cm)
30	23.5 (6.7)	10	13.6 (8.5)
45	34.8 (10.3)	15	17.4 (7.8)
60	53.1 (22.9)	20	19.4 (7.1)
75	71.7 (18.9)	25	21.9 (7.3)
90	64.1 (19.2)	30	25.0 (8.0)
105	84.9 (22.9)	35	25.7 (8.4)
120	95.3 (21.5)	40	26.6 (7.7)

Results and Discussion

Mean perceived length (and its standard deviation) is shown in Table 1 as a function of actual length. A repeated measures ANOVA showed a significant effect of length, $F(6, 30) = 22.11$, $MSE = 6.34$, $p < .0001$. The regression of perceived length onto actual length was significant in the mean ($r^2 = .95$ with a slope of .44) as well as for each individual participant (with r^2 between .16 and .65). The rods were ordered appropriately (and without the reversal obtained in Experiment 1). However, length discrimination (as indexed by the slope of the regression) for the small rods seemed to be little better than half that for the larger rods. Nonetheless, perceived length remained tightly coupled to actual length for the combined data ($r^2 = .97$ with a slope of .77). In order to understand the seeming compression of perceived length at the small scale, we had to confront our second goal—identifying the relevant physical properties that constrain perceived length.

ANALYSIS OF ACOUSTIC STRUCTURE

The first and obvious strategy was to examine aspects of the acoustic structure that have a likely relationship to length. Three aspects of the acoustic structure—signal duration, amplitude, and frequency—were examined to account for perceptual performance. These acoustic quantities were calculated from digitized tape recordings of each rod dropped three times under the described experimental conditions. The quantities obtained for each rod were then averaged over the three drops. None of the simple regressions of perceived length onto these acoustic variables was as successful as actual length in accounting for performance in the two experiments individually or combined. The results for duration were as follows: overall, $r^2 = .09$, $p > .30$; Experiment 1, $r^2 = .65$, $p < .06$; Experiment 2, $r^2 = .12$, $p > .40$. Amplitude (in log-log coordinates) fared somewhat better: overall, $r^2 = .70$, $p < .0004$; Experiment 1, $r^2 = .21$, $p > .35$; Experiment 2, $r^2 = .96$, $p < .0001$. The results for frequency centroid (in log-log coordinates) were mixed: overall, $r^2 = .66$, $p < .001$; Experiment 1, $r^2 = .59$, $p < .08$; Experiment 2, $r^2 = .37$, $p < .15$. Even the limited success of amplitude and the centroid in the overall data is attributable to a coarse difference between size categories; these variables do not pick up the fine gradations within each set that perceivers do.

CONSTRAINTS ON VIBRATION

Although actual length is certainly a successful predictor of perceived length in these experiments, it cannot be the physical constraint of relevance. Length, a geometric property, cannot physically affect the acoustic structure. Sound waves are fashioned by vibrations set up by interacting materials. Those materials have consequences for sound waves through properties such as stiffness, elasticity, density, and inertia, all of which influence the restoring forces by which an object recovers from impact, and thereby influence the amplitude, frequency, and damping of its vibrations (Gaver, 1993b). The relevant physical property must be mechanical, so it can affect acoustic structure, and given the present data, it must both distinguish the rods from one another and anchor their perceived length in the appropriate metrical range. That is, it must relate systematically to actual length so as to account for perceivers' success in hearing length. Of the aforementioned properties of interacting materials, stiffness, elasticity, and density do not distinguish the rods used in the present experiments because the rods were all the same material. Rotational inertia, in contrast, varied with the length, radius, and mass of the rods. In principle, therefore, it could have provided both the basis for distinguishing rod lengths and the necessary constraint on metrical precision.

The potential relevance of the inertia tensor can be appreciated by considering how it has been used to address the perception of spatial properties of objects by dynamic touch (Turvey, 1996). In tasks very similar to the ones reported here, naive participants easily perceived the lengths of rods that were wielded out of view. As is true for acoustics, length per se cannot affect the relevant medium: The rods were gripped at one end, not drawn across the hand or pressed at their ends between the hands. When a rod is supported by a hand in contact with only a portion of the rod, the tissue medium is deformed by mass-based variables. We say "mass-based" because a variety of experiments have ruled out mass itself, along with center of mass, equivalent pendulum length, center of percussion, and torque, as accounting for subjects' perception of length (see Turvey & Carello, 1995, for a review). Instead, the major constraint on perceived length by wielding is the inertia tensor, a quantification of the resistance of an object to being rotated in different directions (Figs. 2a and 2b). It is affected by how an object's length and radius distribute its mass relative to the rotation point. A variety of experiments have shown that haptically perceived length scales positively to the maximum principal moment of inertia, I_1, and negatively to the minimal principal moment of inertia, I_3 (Fitzpatrick, Carello, & Turvey, 1994; Turvey, Burton, Amazeen, Butwill, & Carello, 1998). The particular scalings derive from the dimensional relationship of actual length to the tensor (see Fitzpatrick et al., 1994) and serve to constrain perceived length to the approximate range of actual lengths even while driving perceived length from absolute fidelity to actual length.

In the present experiments, actual length scales to the tensor (Figs. 2c and 2d), r^2 = 1.00, with a positive exponent on I_1 and a negative exponent on I_3. Therefore, as in perceived length by dynamic touch, a positive scaling of acoustically perceived length to I_1 and a negative scaling of acoustically perceived length to I_3 is expected, and it is, indeed, obtained (Fig. 3). In particular, the size and sign of the exponents on I_1 and I_3 are characteristic of dynamic touch experiments in which the radius of wielded rods varies (e.g., Fitzpatrick et al., 1994). Although this relationship is not statistically superior to simple length in constraining perceived length, we reiterate that, as a mechanical variable, its logical status is more secure. Additionally, it provides a rationale for why the acoustically perceived lengths of the small-radius rods were compressed relative to actual length. It is not that those rods are less discriminable or push the limits of resolving power. Rather, the compressed perception of small rods is a result of their compressed magnitudes with respect to a major physical variable constraining a rod's reactions on striking a surface and, therefore, the sounds it produces.

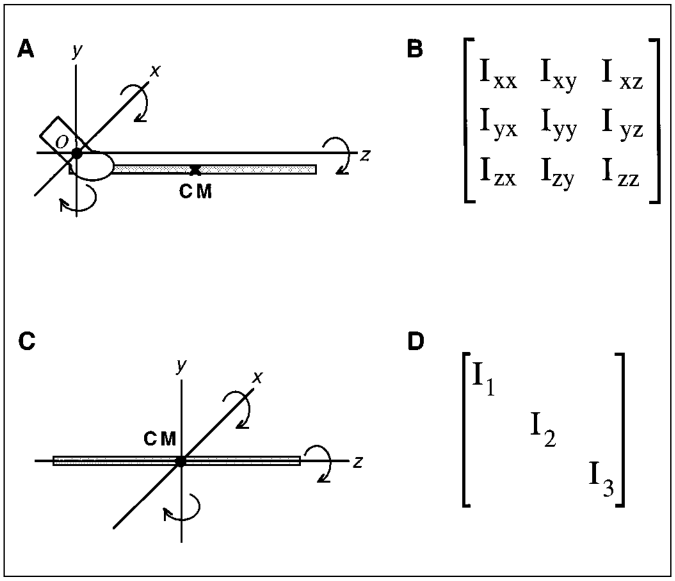

Fig. 2. Rotational dynamics. For a rod grasped firmly in the hand (a), the point of rotation, *O*, is through the wrist rather than the center of mass (CM). The rod's resistance to being rotated about *O* is quantified in a 3 × 3 symmetric matrix (b). For rods in free fall as in the present experiment (c), *O* is at CM, and the off-diagonal components go to zero so that the matrix reduces to principal moments of inertia, the so-called eigenvalues I_1, I_2, and I_3 (d).

CONCLUSION

The foregoing examination of listeners' ability to identify the size of objects on the basis of the sound they make during impact events reveals success that is, perhaps, surprising. Recently, Lakatos, McAdams, and Caussé (1997) have shown that listeners are able to discriminate two struck bars of different width-to-height ratios. In that study, listeners selected the appropriate ordering of the two bars that they heard from two visible depictions that showed the actual cross sections of those bars (simply ordered AB or BA). The present results are more remarkable. They show an ability to scale objects appropriately without any standard of comparison. That is, in the absence of any foreknowledge of the size range or number of objects, listeners elected to use that portion of the report apparatus that fit the objects.

This emphasis on sound sources, rather than sound per se, has been referred to as everyday listening (Gaver, 1993a, 1993b). As a

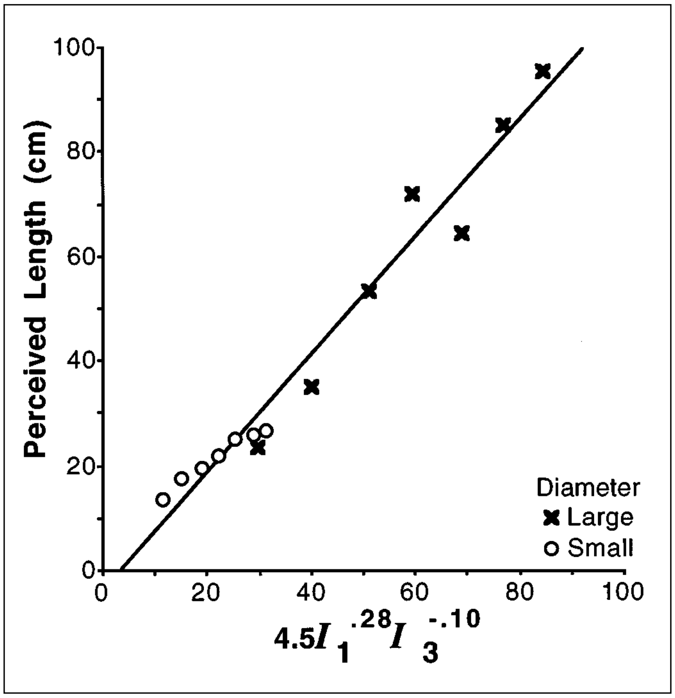

Fig. 3. Combined data of the two experiments. Perceived length is a function of the power equation obtained from a multiple regression of log perceived length onto log I_1 and log I_3 ($r^2 = .97$).

framework for understanding auditory perception, studies of everyday listening begin by asking about the properties of events that can be perceived. Additionally, and following a general ecological approach to perception, we have tried to characterize the objects in a sound-producing event in terms of physical properties that could structure an energy medium reliably. The strong test of the tensorial account of acoustic perception of length will come, as it has for dynamic touch, with an examination of a wider range of object variations. For dynamic touch, for example, the same scaling that characterizes variations of radius was shown to suit variations of material density (Carello, Fitzpatrick, Flascher, & Turvey, 1998; Fitzpatrick et al., 1994). Moreover, it did so with conditions, anchored in the tensor, in which perceived length did not track actual length with such metrical precision. Such a strong test of acoustic perception of length is required before we can assert that the auditory nervous system extracts physical invariants from its interactions with the physical world (Fitzpatrick et al., 1994; Gibson, 1966). Nonetheless, the commonality between perception of length by sound and by touch remains an intriguing possibility.

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