Psychophysical Validation of a Proprioceptive Device by Cross-Modal Matching of Loudness

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Summary
A large number of studies performed by S. S. Stevens, J. C. Stevens and their collaborators have estimated the intensity of one sensory modality by way of another one related to the proprioceptive sensation of muscular force and limb position. As such, using a cross-modal matching procedure, it should be possible to associate a proprioceptive sensation with an auditory sensation (e.g. loudness, brightness, roughness) having an equivalent strength. A new proprioceptive estimation device for the continuous unidimensional judgment of nonstationary sounds has been developed, and in this paper we establish an individual calibration method and the loudness scale of stationary, 1-kHz pure tones by a cross-modal matching paradigm using the same device. The loudness and the proprioceptive sensation refer to muscular force.
possible to determine the psychophysical functions of other sensory modalities by cross-modal matching. For example, the psychophysical functions of different auditory attributes (loudness, roughness, sharpness) can be obtained by way of the proprioceptive function corresponding to the assessment 2. Technical description of the proprioceptive device

2.1. Weight-related resistance: device schema

In order to evaluate auditory sensation by a sensation of muscle tension, a proprioceptive device was developed for the evaluation being made by force feedback and the position of arm and hand with a direct method using the proprioceptive device. It is configured such that the output voltage is a linear function between the muscular force in Newtons and the sound pressure level in the direction corresponding to the auditory sensation. For example, the scale will be different if one squeezes on a water balloon or if one manipulates the handle of a pickaxe. The object is associated an appropriate scale of muscular effort. This system acts on the sensitivity of muscles, bones, ligaments, and joints, and provides information concerning the equilibrium and position of limbs of the body in space. The representation of the effort to be made is category corresponds the required muscular effort as a function of the lever angle. The electrical voltage is transformed into MIDI data and read by the computer program running the experiment. For example, the scale will be different if one squeezes on a water balloon or if one manipulates the handle of a pickaxe. The object is associated an appropriate scale of muscular effort. This system acts on the sensitivity of muscles, bones, ligaments, and joints, and provides information concerning the equilibrium and position of limbs of the body in space. The representation of the effort to be made is category corresponds the required muscular effort as a function of the lever angle. The electrical voltage is transformed into MIDI data and read by the computer program running the experiment.
function of the angle is given by

Note that $R$ is a force tangent to the movement applied by the subject in the direction of displacement of the lever and $P$ is the force applied by the mass ($P = mg$).

3. Loudness scaling experiments

3.1. Subjets

A group of 10 subjects (8 men and 2 women) with ages between 25 and 30 years participated in all of the tests. Ten additional subjects (5 men and 5 women, aged from 25 to 39 years) only participated in the magnitude estimation of the proprioceptive sensation and the
justed to two times that loudness was assigned a value of 2. The sound at the beginning of each series of adjustments was associated with the reference level. For none of the references levels does it contain the slope proposed by Stevens\cite{4}. However, a mean level was computed from the adjustments made by the subjects. The results indicate that loudness production for different reference levels: (a) 50 dB SPL, (b) 60 dB SPL, (c) 70 dB SPL. Asterisks indicate means across subjects and vertical bars represent ±1 standard deviation. A modulus of 10 was associated with the reference level.

Figure 3. Average loudness function obtained by magnitude production for different reference levels: (a) 50 dB SPL, (b) 60 dB SPL, (c) 70 dB SPL. Asterisks indicate means across subjects and vertical bars represent ±1 standard deviation. A modulus of 10 was associated with the reference level.
3.5. Experiment 3: Magnitude estimation

3.5.1. Procedure

Once again sounds were presented in pairs. The first was the reference sound to which a numerical value of 10 was attributed. The second was presented at a different level. The levels included 30, 35, 45, 55, 65, 70, 80, 85, and 90 dB SPL. The order of presentation was randomly chosen for each subject. The subject entered on the keyboard a numerical value corresponding to the loudness of the second sound, such that the ratio of the numbers corresponded to the ratio of the loudnesses, i.e. if the second sound seemed twice as loud, a value of 20 should be entered. Once the value was entered, the next pair was presented, the reference level always being the same. For each estimate, the level and corresponding numerical value of the comparison sound were recorded.

In order to evaluate the influence of the level of the reference sound on subjects' responses, different reference levels were used: 50, 60, and 70 dB SPL. For each reference level, the experimental procedure was repeated.

3.5.2. Results

The results obtained with this method show once again that loudness is a power function of acoustic pressure. The psychophysical functions thus obtained are the means of the magnitude estimations over the ten subjects as a function of acoustic pressure expressed in dB (Figure 4). The functions vary again with the reference level, giving slopes of 0.35, 0.40 and 0.40 for 50, 60, and 70 dB SPL, respectively. The mean slope is 0.38 with a standard deviation of 0.03.

Figure 4. Loudness function obtained by magnitude estimation for different reference values: (a) 50 dB SPL, (b) 60 dB SPL, (c) 70 dB SPL. Asterisks indicate means across subjects and vertical bars represent ±1 standard deviation. A modulus of 10 was associated with the reference level.
4. Force scaling

4.1. Experiment 4: Ratio production

4.1.1. Procedure

Nevertheless, a stable loudness function has been obtained from different methods: Robinson [5] and S. S. Stevens [6] with estimation, Scharf and J. C. Stevens [22] with ratio production and estimation, Feldtkeller, Zwicker and Port [23] for ratio production, Hellman and Zwischlocki [7] with estimation and magnitude production. The mean of these data gives a power function with exponent 0.54 for levels above 30 dB SPL. This result is in agreement with what we have found for ratio and magnitude production. As such we will retain this slope value for comparison with the rest of this study.

Figure 5. Schema of the experimental procedure for the evaluation of apparent muscular force. Position A, signaled by a sound signal, corresponds to the reference force. Position B corresponds to a muscular force judged to be the double of that at position A. A sound signal indicates to the subject that the lever is within an angle of 1.6° centered on position A.
Figure 6. Proprioceptive psychophysical functions obtained for production of ratios of two -- and one-half - . . . for different initial positions. All initial positions arc assigned an apparent force value of 1. Data are shown for four representative subjects: (a) subject 4 (pushing force, mean $a \equiv 1.59$; retaining force, mean $a \equiv 1.68$), (b) subject 5 (pushing force, mean $a \equiv 3.23$; retaining force, mean $a \equiv 1.11$), (c) subject 8 (pushing force, mean $a \equiv 2.25$; retaining force, mean $a \equiv 1.19$), (d) subject 10 (pushing force, mean $a \equiv 3.34$; retaining force, mean $a \equiv 2.69$).

For each subject, the predetermined positions were presented in a random order. The ten other subjects performed the two parts in reverse order.

4.2.2. Results

Figure 7 shows the mean ratings obtained for the set of 20 subjects. Here again, the slope for the retaining function (1.67) is lower than that for the pushing function (1.80). However, the difference between the two is smaller than that obtained by the ratio production method. Or the other hand, one should note that there is a slight departure.
5. Experiment 6: Cross-modal matching

5.1. Individual calibration of the device

There are important differences between individuals that require a personalized calibration of the device: physiological differences related to muscular strength and sensitivity and differences in response strategy and auditory representation of the stimuli. A simple calibration procedure consists in presenting stationary sounds at various values (eight) along the acoustic continuum to be studied, which cover the range of stimuli used in the experiment. The principle is to adjust the upper limit of variation of the device (maximum angle) to the maximal stimulus magnitude. In other words, the device is individually calibrated to avoid saturation of the judgments for stimuli with high values. This procedure is repeated two or three times for each subject for the same range of values (40–85 dB SPL). It takes no longer than five minutes. This calibration also ensures full resolution of the response continuum for each individual. For our device, the individual calibration is made possible by a modification of the inertia of the device, i.e. by adjusting the mass \( m \) and its distance from the axis of rotation \( l \).

To calibrate the device individually, a series of matching experiments was conducted, varying the position of the mass on the lower shaft and its weight. The resistance created by the device increases with both mass and distance from the axis of rotation. Three individual calibrations were performed, each with a different mass-distance pair that was chosen individually for each subject. Three ranges of levels were tested, each being realized with 11 levels. The ranges included 65–85, 55–85, and 45–85 dB SPL. Stimuli within each range were presented in random order. Each subject performed three blocks of cross-modal matchings corresponding to all combinations of three mass-distance pairs and three ranges of sound levels. The solid, dotted, and dash-dotted lines correspond to three different individual calibrations with progressively decreasing inertia.

As an illustration, the data for three male subjects 2, 8, and 10 are presented in Figure 8 for each of the ranges of levels (40–85 dB SPL). It takes no longer than five minutes. This procedure is repeated two or three times for each subject for the same range of values (40–85 dB SPL). It takes no longer than five minutes. This calibration also ensures full resolution of the response continuum for each individual. For our device, the individual calibration is made possible by a modification of the inertia of the device, i.e. by adjusting the mass \( m \) and its distance from the axis of rotation \( l \).

Examination of the curve in Figure 8 leads to the elimination of the 2 kg/14 cm pair and the selection of the 2 kg/20 cm pair, which corresponds to a maximal variation with respect to the range of levels tested. Even if this subject's responses were not all consistent, he has apparently performed a force matching; that is, he associated a given sound with two identical responses. As such, we obtained for two other representative subjects. As such, we obtained for two other representative subjects. As such, we obtained.

Figure 7. Magnitude estimations of the proprioceptive sensation as a function of the force intensity, obtained in pushing (circles) and retaining (squares) modes. Vertical bars represent ±1 standard deviation. The variables \( a \) and \( k \) are from equation (1) and \( r \) is the coefficient of regression of the data onto the straight line function.
rather than muscular force to the perceived loudness. The judgments obtained for another subject were saturated for the highest levels when the global resistance of the system, corresponding to one of the three mass-distance pairs, was the weakest. Finally, for each subject, we recorded the most appropriate mass-distance pair and used it in the main matching task below.

5.2. Stimuli
Eight 1-kHz pure tones were used with levels of 40, 45, 55, 60, 65, 70, 80 and 85 dB SPL. The duration of the sounds was 1 s.

5.3. Procedure
The subject started the experiment by pressing a button. A
determined independently by ratio scaling methods based on numerical estimation.

The results obtained in the present study confirm firstly that loudness and the proprioceptive sensation being measured can be described by power functions. They also confirm that the slope (0.29) of the matching function obtained directly by CMM using the new proprioceptive device is very close to that of the loudness function determined independently by ratio scaling methods based on numerical estimation. It is important to note that the results obtained with the cross-modal matching technique are less dependent on experimental conditions than those provided by direct estimation techniques. For example, the loudness functions determined by magnitude estimation and production are clearly dependent on the level of the reference sound. Note that a cross-modal matching experiment performed by Bond and S. S. Stevens [18], loudness was adjusted with respect to the perceived intensity of ten other experiments conducted by S. S. Stevens [27].
[16] S. S. Stevens: