Chapter 5

Material categorization and hardness scaling in real and synthetic impact sounds

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5.1 Introduction

Several studies demonstrated the ability to scale or discriminate properly different features of sound sources on the basis of auditory information alone. Stunning abilities have been found in the judgments of geometrical properties of the sound source [145, 49, 142] or in judgments of geometry-independent features [82]. It was found that listeners are able to categorize correctly even more complex features, such as the type of interaction between objects [251], or the gender of walkers from the sound of their footsteps [153].

The ecological approach explains these abilities by assuming a direct link between the physical features of the sound source (distal stimulus) and the perceptual level. Direct and non mediated perception of the sound source features would be possible in virtue of the fact that the acoustical signal (proximal stimulus) specifies richly and uniquely the sound source [50]. The detection of a specific property of the physical event is hypothesized to be based on so-called invariants, structural properties of the acoustical signal that specify a given property of an event despite variations in other features of the sound source [50]. Invariant properties of the proximal stimulus are, for example, those that allow to recognize a piano despite the drastic acoustical signal variations associated, for example, with changes in the environment, in pitch and dynamics.

Theories based on the notion of invariants imply a one-to-one mapping between the physical features of the sound source and higher level acoustical properties (i.e., *specificity*). Furthermore, they imply the ability of listeners to scale or categorize a given feature *veridically*, and *independently* from variations in extraneous features of the sound source. The empirical test of these assumptions requires the use of *perturbation variables* 1. If perturbation variables have significant effects on recognition, then the assumptions of veridicality, and independence must be discarded for the investigated sound source feature.

These assumptions were directly tested in a first group of experiments, which investigated material type categorization with real impact sounds. An indirect test to these assumptions was provided by another set of experiments, that investigated hardness scaling with synthetic sounds. All stimuli were generated by the impact of a highly damped object, whose vibrations decay rapidly after impact (*hammer* or *non-sounding object*), on a resonating object, whose vibrations are the main source of fluctuation in the pressure of the air medium (*sounding object*). In the first set of experiments, hammer properties were treated as perturbation variables. In the second set of experiments, hammer properties were treated both as perturbation variables and as object of direct investigation. In both studies, geometrical properties of the sounding objects were used as perturbation variables.

Finally, both series of experiments addressed a more methodological problem, related to the nature of the investigated stimuli. Two options are actually available: real sounds, generated by manipulating real physical objects, or synthetic sounds, generated by manipulating simulations of the mechanical behavior of the physical objects. By definition, a model is a simplification of the modelled object. As such it carries, potentially, some simplifications. In particular, if physical models for sound source recognition research are concerned, there is the possibility that sound models cut out relevant acoustical information for the detection of a particular feature of the source. This suspicion was raised by Carello et al. [50] in reviewing Lutfi et al. [163] results on material discrimination in synthetic sounds. Performance was found far from perfect. On the contrary, a different study [142], conducted with real sounds, demonstrated almost perfect levels of recognition. Thus the legitimate objection was that the difference in results could be attributed to the fact that part of the acoustical information relevant to material categorization or discrimination, was present in the real stimuli investigated by Kunkler-Peck at al. [142], but not in those investigated by Lutfi et al. [163]. Results of previous researches will be compared with results reviewed in this chapter. This will allow us to finally develop a simple criterion for assessing the perceptual validity of a synthesis model.

5.2 Material

5.2.1 Previous researches

Several researches examined the potential acoustic information available for material recovery from impact sounds. Wildes and Richards [253] developed an analysis of the mechanical behavior of solids, in order to find an acoustical measure that uniquely identified material, despite variations in geometrical features. From the physical point of view materials can be characterized using the coefficient of internal friction $\tan\phi$, which measures their degree of anelasticity. This physical measure is measurable using the decay time of vibration or, alternatively, its bandwidth. This relation is expressed by Eq. (5.1).

$$\tan\phi = \frac{1}{\pi f t_e} = Q^{-1} \quad , \tag{5.1}$$

where f is the frequency of the signal, t_e is the time required for amplitude to decrease to $1/e$ of its initial value, and Q^{-1} is the bandwidth of the spectral components. In ascending order of $\tan\phi$, we have rubber, wood, glass, and metals. From rubber to metals spectral components have progressively longer decay times, and progressively decreasing bandwidths. As the invariant for material type is based on the acoustical measurement of the coefficient of internal friction, one should expect this physical measure to remain constant across variations of the shape of the objects. On the contrary, Wert [252] showed that the shape independence of the $\tan\phi$ coefficient is only an approximation. Furthermore Wildes and Richards model, assumes a simple relation of inverse proportionality between frequency and decay time. This was found to be a simplification, as measurements conducted on struck bars and plates sounds found the relationship between the frequency and decay times of the spectral components to be quadratic [92] or more complex than quadratic [52, 53].

If we focus on simple acoustical properties, the ambiguity of the acoustical signal features in respect to mechanical material properties emerges. Lutfi et al. [163], in solving the equation for the motion of the struck-clamped bar, outlined that both geometrical and non geometrical features of the struck bars influence the amplitude, frequency and decay times of the spectral components.

The ambiguity of the acoustical features in respect to material type is in contrast with previous researches on material recognition in real impact sounds. Gaver [92] tested material recognition in sounds generated by percussing wood and iron bars of different lengths, with percent correct performances between 96% and 99%. Kunkler-Peck et al. [142] investigated shape and material recognition in struck plates sounds. Material recognition was almost perfect.

Results gathered on synthetic stimuli provide insight on the acoustical determinants of material recognition and discrimination. Lutfi et al. [163] studied material discrimination in synthetic struck clamped bar sounds. Synthesis parameters were chosen to model glass, crystal, quartz, and different metals. Performance was analyzed in respect to three acoustical features: amplitude, decay rate and frequency. This analysis revealed that material discrimination was mainly based on frequency. Amplitude and decay rate had only a secondary role. Klatzky et al. [137] investigated material discrimination in stimuli with variable frequency and decay modulus τ_d[1]. In a first experiment subjects were asked to estimate the perceived difference in material. Results indicated that judgments were significantly influenced by both τ_d and frequency, even though the contribution of the first to judgments was higher than the latter. The same experiment, conducted on amplitude equalized signals, did not give different results, thus pointing toward an absence of this acoustical variable on material recognition. An effect of both the τ_d coefficient and the fundamental frequency was found in a subsequent experiment, where subjects were asked to categorize material into four categories: steel, rubber, glass and plexiglass. Steel and glass were chosen for higher τ_d values than rubber and wood, and, thus, for longer decay times. Glass and wood were chosen for higher frequencies than steel and rubber. Similar results were obtained by [10]. Stimuli varied in the quality factor Q of the spectral components[2] and in frequency. Participants had to categorize material type using four response categories: steel, glass,

[1] $\tau_d = 1/\pi \tan\phi$ and $t_e = \tau_d/f$.
[2] $Q = \pi f t_e$.

wood, and rubber. A dependence of material categorization on both controlled acoustical parameters was found. As t_e, and thus decay times, increased, material categorization changed from rubber to wood to glass, and finally, to steel. Coherently with what found in [137], steel was chosen for lower frequencies than glass while, contrary to their result, a slight tendency to choose rubber for higher frequencies than wood was observed.

As frequency content is also determined by the geometrical features of the objects, the effects of frequency on material recognition point toward a limited ability of subjects to recognize correctly material from impact sounds. The following experiments tested these effects with real impact sounds.

5.2.2 Experiments

Three experiments tested material recognition upon the effect of different perturbation variables. Stimuli were generated by striking rectangular plates made of four different materials: steel, glass, wood, and plastic. In all the experiments the area of the plates ranged from 75 to 1200 cm^2. In the first and second experiment plates were struck using a steel pendulum. Plates varied also in height/width ratio, this latter ranging from 1 (square plate) to 5. In the first experiment plates could vibrate freely after being struck by the pendulum. In the second experiment plates were artificially damped with an equal shape and area low density plastic plate. In the last experiment square plates were struck with penduli made of four different materials: steel, glass, wood, and plastic. The starting angle of the penduli was kept fixed for all the experiments.

Stimuli were characterized using two acoustical parameters. First, a measure of the frequency of the lowest spectral component F. Second, a measure of the amplitude decay velocity T_e, defined as the time required for the spectral level to decay to $1/e$ of the attack value.

In all the experiments stimuli were presented via headphones. Subjects were asked to categorize the material of the struck objects. They were not informed about the variation in perturbation variables.

5.2.3 Freely vibrating plates - material, area, and height-/width ratio variation

Categorization performance can be summarized using the concept of material macro–categories, which describes pattern of confusions among physical materials. The first macro–category includes steel and glass materials, the second includes plastic and wood. Confusion between the two material macro–categories was absent, glass and steel being almost never chosen in wood and plastic plates sounds, and vice versa. Confusion between materials inside the same macro–category was high: glass was confused frequently with steel, and vice versa; plastic was confused frequently with wood, and vice versa. Inside the macro–categories, responses revealed a strong effect of the area, where small glass and steel plates were identified as being made of glass, while large glass and steel plates were identified as being made of steel. The same effect was found in the plastic/wood macro–category, where plastic was chosen for large area plates, and wood was chosen for small area plates. A small group of subjects revealed an opposite response profile, wood being chosen for larger area plates, plastic being chosen for small area plates. Data were analyzed using three separate logistic regression models. The first studied the probability of choosing the steel/glass macro–category over the probability of choosing the wood/plastic one. The second studied the probability of choosing steel over the probability of choosing glass. The third studied the probability of choosing wood over the probability of choosing plastic. In general identification correctness was above chance level. Recognition of the material macro–categories was almost perfect. In contrast recognition inside the macro–categories was almost at chance level. In none of the cases the height/width ratio significantly influenced the response proportions. Macro–categorical categorization was determined only by the physical material. In particular the macro–categorical response proportions did not differ between glass and steel on one side, and between wood and plastic on the other side. The steel/glass categorization was, instead, significantly influenced by both area and material. The plastic/wood categorization was determined by area variations alone.

Both F and T_e were found to have significant effects in all the regression models. The effect of the decay time T_e, on macro–categorical responses, was greater than that of F. Steel and glass were chosen for higher frequencies and longer decay times than plastic and wood. Categorization inside the macro–categories was, instead, influenced more by frequency than decay times. In particular glass was chosen for higher frequencies and shorter decay times than steel, and plastic was chosen for lower frequencies and longer decay times than wood. The absence of a significant effect of the height/width ratio variable was consistent with the absence of significant F and T_e differences associated with this variable. On the contrary area and material type influenced significantly both F and T_e. The orderings of material types in respect to F and T_e did not always correspond to that used by subjects to recognize material from sound. Steel and glass had, coherently with subjects acoustical response criteria, higher frequencies and longer decay times. Coherently glass had shorter decay times, but, contrary to the acoustical criterion used by subjects, lower fundamental frequencies. Plastic and wood material types were found not different in respect to both F and T_e.

Discussion

The almost perfect levels of performance observed in the identification of the material macro–category is consistent with results collected by Gaver [92] with iron and wood struck bars sounds. In his experiment the absence of a significant effect of the length of the bars on material categorization could be due to the fact that subjects were not given the possibility to use the glass and plastic response categories. Results are inconsistent with those collected by Kunkler-Peck et al. [142], where the plexiglass and wood categories were perfectly discriminated. A possible explanation of the inconsistency can be found in the procedural differences between his experiment and ours. Kunkler-Peck et al. generated stimuli live, behind an occlusion screen that precluded sight of the device by participants. Reverberation inside the room or additional signals generated by manipulating the struck plates to prepare trials could provide additional acoustical information than that provided to participants in our experiment.

In the current experiment macro–categorical categorization was independent from variations in the geometrical properties of the plates. Furthermore subjects responses were veridical, and were based on acoustical criteria that reflected the relationship between variations in the sound source and variations in the acoustical signals. Macro–categorical categorization was found to be based more on decay times than frequency and, consistently with results collected on synthetic stimuli [137], [10], it showed that plastic and wood were chosen for lower decay times glass and steel.

The steel versus glass and wood versus plastic categorizations, however, showed a strong effect of the geometrical properties of the sound source, as well as a drastic drop in the veridicality of responses. Plastic and wood sounds were found to be equivalent from the acoustical point of view. Likely participants relied on the only physical dimension that structured significantly the acoustical signal. This, however, does not invalidate the general effect of geometrical properties on material categorization, as it was found in the steel versus glass categorization, where these two materials differed in both F and T_e.

Subjects associated wood to small area plates, and plastic to large area plates. Coherently the first category was chosen for higher frequencies than the latter. This result is consistent with those by Klatzky et al. [137]. A smaller group of subjects showed the opposite response profile, associating plastic to higher frequencies than wood. The presence of opposite response profiles in different subjects could be one of the potential explanations for the discrepancies between Klatzky et al. and Rocchesso et al. [10] results, who observed a weak association of wood with low frequencies.

Glass was associated to smaller area plates than steel. As in the case of the plastic versus wood categorization, frequency played a greater role. The glass response was chosen for shorter decay times than steel, and consistently, glass sounds were found to have shorter decay times than steel sounds. However glass sounds had significantly lower frequencies than steel sounds, while subjects associated glass to higher frequencies than steel. Our results are consistent with those collected with synthetic sounds: both Klatzky et al. [137], as well as Rocchesso et al. [10] found glass to be associated to higher frequencies than steel. Furthermore, the fact that frequency played a greater role than decay times for categorization inside the steel ad glass macro–category aligns with results by Lutfi et al. [163].

5.2.4 Damped plates - material, area, and height/width ratio variation

External damping lead to a drop in the macro–categorical recognition performance only for glass plates, while recognition of the macro–category was almost perfect for steel, wood, and plastic sounds. Glass plates sounds were almost always categorized as belonging to the plastic and wood macro–category. The same effects of area on subjects' responses were observed with damped plates sounds. In particular the category steel was chosen for larger area steel plates than the response glass, while the response wood was chosen for smaller area glass, plastic and wood plates than the response plastic. As in the previous experiment the height/width ratio had no effect on participants responses. The steel versus glass and wood versus plastic categorizations were influenced by both the material and area of the plates. The steel versus glass categorization was significantly influenced by variations in area but not in material. The absence of an affect of the material variable is due to the fact that the glass and steel responses were almost never given for damped glass plates. The wood versus plastic categorization was, on the contrary, influenced by both area and material. As in the previous experiment, all categorization contrasts were significantly influenced by both decay times and frequency. Analysis of the macro-categorical categorization revealed, consistently with results from the previous experiment, the tendency to chose the steel or glass response for higher frequencies and longer decay times. The relative weight of F and T_e in determining subjects responses was almost equal. Analysis of the steel versus glass categorization revealed the tendency to chose the category steel for higher frequencies and longer decay times than glass. Differently from the previous experiment, in this categorization decay time played a greater role than frequency. Wood was chosen for higher frequencies and shorter decay times than plastic, where, consistently with previous experiment, frequency played a greater role in determining this categorization. Not surprisingly, external damping produced a decrease in decay times, and a non significant decrease in frequency. Damped glass plates sounds were found to have equal decay times to those of damped wood and plastic ones. Wood, plastic and glass damped plates sounds had, on the average, equal frequencies, while steel sounds had higher frequencies than all these three categories. Steel sounds had the highest decay times, glass and plastic were not different in respect to T_e, while wood damped plates sounds had the lowest decay times. Overall glass damped plates sounds were not different from the plastic ones, so that it is not surprising that they were categorized as being made of plastic or wood.

Discussion

In respect to the considered acoustical variables, damping caused glass sounds to be identical to plastic sounds. In particular, the effect of damping on T_e explains the switch in the recognized macro-category for glass sounds. The same explanation, however, does not account for the fact that steel sounds did not switch material macro-category. In fact damping caused a general decrement in the decay times, well below the values measured on freely vibrating wood and plastic plates sounds. If this parameter was the main cause for categorization within the material macro–categories, steel sounds had to be categorized as being made of wood or plastic, as happened for glass sounds. Further acoustical measurements are required to explain the different results gathered with glass and steel damped plates.

5.2.5 Freely vibrating plates - material, area, and pendulum material variation

Data revealed the same area and material effects found in the first experiment. Once again a small percentage of subjects showed an opposite response profile in respect to the plastic versus wood discrimination. Variations in the material of the percussor were found to have no effects on all the categorization contrasts. Categorization inside the material macro-categories was influenced only by the material of the plates. As in the first experiment, steel and glass were equivalent to each other in respect to the macro–categorical categorization, as well as wood and plastic. The steel versus glass categorization was influenced by area and material, while the wood versus plastic categorization was influenced by area only. Macro–categorical categorization was determined by both frequency and decay time, with the latter having the greatest weight. The glass versus steel categorization was influenced by both the considered acoustical variables, F having a greater weight than T_e. The wood versus plastic categorization, finally, was influenced only by frequency. Variations in the hammer were not associated to significant variations in F and in T_e.

Discussion

There are two alternative ways to interpret the absence of significant effects of the percussor in determining categorization of the material of the plates. The first focuses on the distal stimulus, and outlines subjects ability to distinguish variations in the features of the hammer from variations in the features of the sounding object. The second focuses on the proximal stimulus and outlines the fact that variations in the material of the pendulum were not associated to significant variations in the acoustical features. As found in previous experiments, the extent to how a perturbation variable influences the investigated sound source feature depends on its range of variation. The height/width ratio variable was not significant because it did not lead to significant variations in F and T_e, as compared to the effects associated to variations in the area. For the same reason we should expect that a larger range of variation in the material properties of the hammer would lead to changes in material categorization. This would be possible provided that the acoustical variables used by subjects to categorize material are affected by variations in the hammer material properties. The effects of the hammer on recognition of the geometry-independent properties of the sounding object was addressed with the experiments summarized in section 5.3.

5.2.6 Conclusions

Material categorization was found to be affected by the geometrical features of the sounding object. Analysis of responses revealed that veridicality depended on the level of detail in categorization. Results gathered from freely vibrating plates sounds, in fact, showed that identification of the material macro-categories was almost perfect, and was not influenced by variations in the geometrical properties of the sounding object. Accuracy of categorization inside the macro-categories dropped to chance level, and was strongly influenced by the geometrical properties of the struck objects. The dependence of categorization veridicality on the level of detail is consistent with the free identification results obtained by Gaver [92], who reported that "accuracy [of identification] depends on specificity". The orthodox ecological approach to auditory perception assumes veridicality of recognition and absence of effects of irrelevant sound source dimensions (independence). The correctness of these assumptions have been found to depend on the detail level in material categorization. Recognition of the material macro–category are in agreement with them, while categorizations inside the macro–categories disconfirm them.

An attempt to define an acoustical invariant for material type wasn't performed. However, the significant effects of the investigated perturbation variables on material categorization allow us to conclude that, although an invariant for material type may exist, it is not sufficient to completely explain material recognition. Given the limits of the coefficient of internal friction model [253], it was preferred to characterize acoustical signals using simple acoustical features. Focusing on simple properties confirmed the existence of an ambiguous relationship between objects properties and acoustical signal features [163]. Ambiguous specification of the sound source in the acoustical signal disconfirms the specificity assumption of the orthodox ecological approach. Specific acoustical criteria for material recognition were outlined. These criteria were found, when comparison was possible, consistent with all previous researches conducted using synthetic stimuli.

External damping provided a way to investigate material categorization using stimuli much more adherent to those encountered during everyday life, were externally damped objects are much more common than freely vibrating ones. Furthermore it allowed testing the effect of the decrease in decay times on material recognition via manipulation of the sound source, instead of via manipulation of the recorded signals. This sound source feature have been found to affect material categorization. In particular damped glass plates sounds were categorized within the plastic/wood macro-category. This was explained by the fact that the considered acoustical properties of damped glass plates were equal to those of the damped plastic ones.

5.3 Hardness

In this section we present two experiments concerning recognition of geometry-independent features of the sound source. In the previous experiments the focus of the investigations was on material type, investigated through categorization procedures. Here we focused on hardness, a mechanical material property, and investigated material recognition through scaling.

Scaling of the hardness of the hammer was already studied by Freed [82] with real sounds. Investigated stimuli were generated by striking four cooking pans of variable diameter with six mallets of variable hardness (metal, wood, rubber, cloth-covered wood, felt, felt-covered rubber). Analysis of the performance revealed an appropriate scaling of the hardness of the mallet, independent of the diameter of the pans.

With the present investigations we extended the research by Freed in several directions. Freed addressed hardness scaling of the hammer by using the geometrical features of the sounding object as perturbation variable. We investigated hammer hardness scaling by using both the geometrical properties of the sounding object, as well as its material as perturbation variables. Furthermore we investigated sounding object hardness scaling upon variation in the hammer properties as well as in the sounding object properties. Since all the experiments made an extensive use of perturbation variables, the specificity, independence, and veridicality assumptions of the ecological approach could be tested again. All the experiments were performed using sounds synthesized with the impact model described in chapter 8. Comparison of results presented in this section with those collected by Freed on real sounds allowed addressing again the problems connected to research on sound recognition with synthetic sounds.

5.3.1 Stimuli

Stimuli were generated by varying two parameters that modelled the properties of the sounding object, and one parameter that modelled the properties of the hammer. Sounding object properties were varied by means of the internal friction coefficient $\tan\phi$, assumed to model variations in the material of the sounding object, and by the frequency of the lowest resonant mode F, assumed to model variations in the geometrical properties of the sounding object. Hammer properties were varied through the elasticity coefficient e. A synthesis space was derived by combining a different number of equally log-spaced levels for each synthesis parameter, as described below. For each experiment a different subset of the stimuli from this synthesis space was investigated.

The $\tan\phi$ coefficient varied from 10 (t_1, corresponding to the plastic-wood macro-category in the previous experiments) to 160 (t_3, corresponding to the steel-glass macro-category in the previous experiments), the intermediate level being 40 (t_3). F was varied from 50 Hz (F_1) to 800 Hz (F_3), the intermediate level being 200 Hz (F_2). The elasticity parameter was varied from $5e^6$ (e_1) to $1e^{10}$ (e_5), the intermediate levels being $3.3e^7$ (e_2), $2.24e^8$ (e_3) and $1.495e^9$ (e_4). The lowest value of the elasticity coefficient can be conceived as representing rubber mallets, while the highest value of the elasticity coefficient can be thought as representing steel mallets.

5.3.2 Sounding object hardness

Categorization of the sounding object material was shown to be influenced by both the material and the geometrical properties of the sounding object. We expected that scaling of a material property of the sounding object to be dependent on both these modelled features of the sound source.

Methods

Ten subjects participated to the experiment. All of them reported normal hearing. Three levels for each synthesis parameter were chosen, namely F_1, F_2, F_3, t_1, t_2, t_3, e_1, e_3 and e_5. This resulted in a stimuli set that comprised 27 sounds. Subjects were told that they would have been presented several sounds generated by striking sounding objects of variable hardness with hammers of variable hardness. They were asked to rate the hardness of the sounding object on a numerical scale ranging from 1 (very soft materials) to 100 (very hard materials). Before the experiment started they were presented several real examples of variable hardness sounding objects struck with variable hardness mallets. Each of the 27 stimuli, presented in randomized order, was judged three times by each subject. Stimuli where presented through Sennheiser HE60 headphones connected to a Sennheiser HEV70 amplifier. The amplifier received the output signal of a Sound Blaster Live! Soundcard.

Results

Average hardness ratings were analyzed by means of a repeated measures ANOVA, with frequency, internal friction and hammer elasticity as repeated

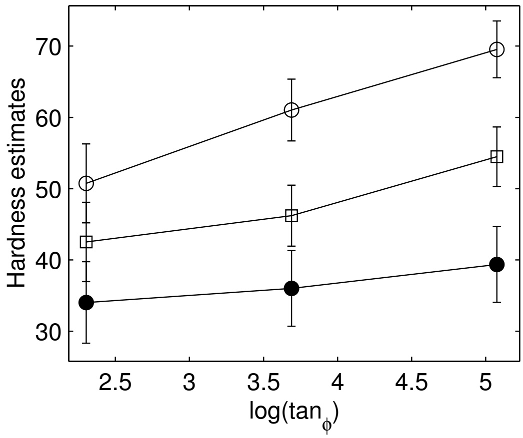

Figure 5.1: Average sounding object hardness estimates on a 1-100 scale ($1 =$ very soft $100 =$ very hard), as a function of the internal friction coefficient. Filled circles: e_1; empty squares: e_3; empty circles: e_5.

measurements factors. The 3-way interaction between the synthesis parameters, as well as the 2-way interaction between frequency and internal friction coefficient, were not significant ($F_{(8,72)} = 0.898$, $p = 0.523$; $F_{(4,36)} = 1.698$, $p = 0.172$). The interaction between the elasticity parameter and frequency, as well as that between the elasticity parameter and the coefficient of internal friction were significant ($F_{(4,36)} = 3.563$, $p = 0.015$; $F_{(4,36)} = 3.860$, $p = 0.010$). Simple effects of the coefficient of internal friction and of the elasticity parameter significantly influenced average hardness estimates ($F_{(2,18)} = 6.600$, $p = 0.007$; $F_{(2,18)} = 19.686$, $p < 0.001$). The simple effect of frequency was not significant ($F_{(2,18)} = 1.144$, $p = 0.341$).

Figure 5.1 shows the interaction between $\tan\phi$ and F, by plotting average hardness estimates as a function of $\tan\phi$, with F as factor. Figure 5.2 shows the interaction between the F and e factors, by plotting average hardness estimates as a function of the F parameter, with e as factor.

Estimates of the hardness of the sounding object increased for increasing $\tan\phi$ and e. The slope of the functions that relate sounding object hardness estimates to $\tan\phi$ increases with increasing mallet hardness, so that we can conclude that the $\tan\phi$ coefficient induces higher changes in the hardness estimates for higher e values. Analysis of the interaction between e and F shows

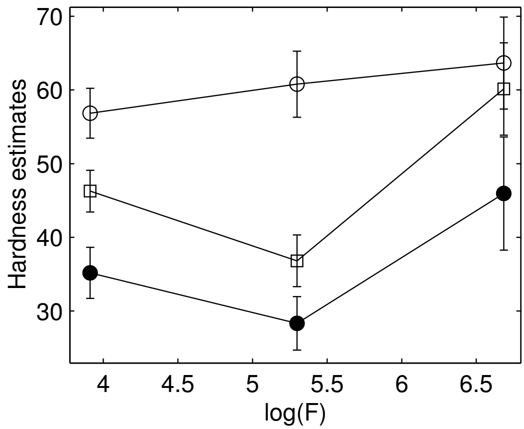

Figure 5.2: Average sounding object hardness estimates on a 1-100 scale ($1 =$ very soft $100 =$ very hard), as a function of frequency. Filled circles: e_1; empty squares: e_3; empty circles: e_5.

the same general effect of e on the sounding objects hardness estimates. This latter interaction has however a different origin than the one between $\tan\phi$ and F, which was due to a non parallelism of monotonic psychophysical functions. In this case it is due to a change in the shape of the psychophysical functions. In particular the effect of F on the hardness estimates is found monotonic for the highest e value used, non-monotonic for lower values of the e coefficient. In this latter case intermediate F levels (200 Hz) lead to a strong decrease of the sounding object hardness estimates.

Discussion

Materials with low $\tan\phi$ coefficient values (plastic, rubber) were estimated as the softest, while materials with high $\tan\phi$ coefficient values (steel, glass) were estimated as the hardest. As for the material categorization experiments, recovery of the material of the sounding object was found to depend on material (as modelled by $\tan\phi$) and on the geometrical properties of the sounding object (as modelled by F). These findings suggest also that the $\tan\phi$ measure alone is not sufficient to explain material recognition. The reported change of the effects of F with variable e is surprising and has no explanation. The analysis of the acoustical structure of stimuli, as well as a replication of this study with real sounds will allow outlining the causes of this effect. The significance of the effects of the elasticity coefficient points toward an inability of subjects to distinguish material properties of the mallet from material properties of the sounding object. This is particularly evident if we conceive an increase in the e coefficient as modelling hammers of increasing stiffness (i.e., from rubber to steel). When commenting the results of material type categorization with variable pendulum material, we hypothesized that a higher range in the variation of the material properties of the hammer would have led to significant changes in the recognized material. The significant effect of the e parameter on sounding object hardness estimates provides a partial confirmation to this hypothesis.

5.3.3 Hammer hardness

The final experiment investigated estimation of the hardness of the hammer upon variations in the properties of the sounding object.

Methods

Two stimuli sets were investigated. In both cases all the five levels of the e parameter were used. In the first set the $\tan\phi$ parameter was fixed to t_2, while all three levels of F were used. In the second F was kept constant at 200 Hz (F_2), while all the three levels of the $\tan\phi$ parameter were used. The combination of these synthesis parameters produced two sets of 15 stimuli. Procedure was identical to that used in the previous experiment, the only difference being that subjects were asked to rate the hardness of the hammer. All the stimuli, presented in randomized order, were judged three times by each subject. The two sets of stimuli were presented in separate sessions. The order of the sessions was counterbalanced between subjects. Ten subjects participated to the experiment. None of them participated to the previous experiment. All of them reported normal hearing.

Results

Average hardness ratings were analyzed by means of a repeated measures ANOVA. For the variable F set, average hardness ratings were significantly influenced by e ($F_{(4,36)} = 8.597$, $p < 0.001$), but not by F ($F_{(2,18)} = 2.269$, $p = 0.132$) or by its interaction with the e ($F_{(8,72)} = 1.379$, $p = 0.220$). Figure 5.3 plots the average hardness estimate as a function of e, with F as factor.

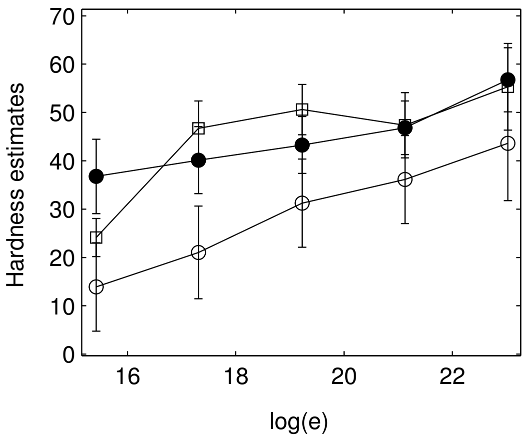

Figure 5.3: Average hammer hardness estimates on a 1-100 scale (1 = very soft 100 = very hard) for the variable F set. Filled circles: F_1; empty squares: F_2; empty circles: F_3.

As shown, hammer hardness estimates increase with increasing e. The psychophysical functions for the different F levels appear greatly overlapped. A tendency of the hardness estimates to decrease for the highest F value (800 Hz) is observed. Contrasts were performed to test whether the estimates given for F_1 and F_2 differed significantly from those given for F_3. This additional test revealed the difference to be non significant in both cases ($F_1 - F_3$: $F_{(1,9)} = 1.903$, $p = 0.201$; $F_2 - F_3$: $F_{(1,9)} = 3.371$, $p = 0.100$;). Thus we can conclude that F did not significantly influence the hammer hardness ratings.

For the variable $\tan\phi$ set, average hardness estimates were significantly influenced by e ($F_{(4,36)} = 6.905$, $p < 0.001$) as well as by $\tan\phi$ ($F_{(2,18)} = 43.315$, $p < 0.001$). The interaction term proofed slightly significant ($F_{(8,72)} = 2.109$, $p = 0.046$). Figure 5.4 plots the average hammer hardness estimate as a function of e with $\tan\phi$ as factor.

As shown, hammer hardness estimates increase with increasing e and with increasing $\tan\phi$. As can bee seen in Figure 5.4 the interaction term is due to an increase in the slope of the psychophysical function for increasing $\tan\phi$ values. As observed with the previous experiment, the higher the $\tan\phi$ value, the higher the range in the hammer estimates. The same effect was observed with in the previous experiment, but in reference to the sounding object hardness

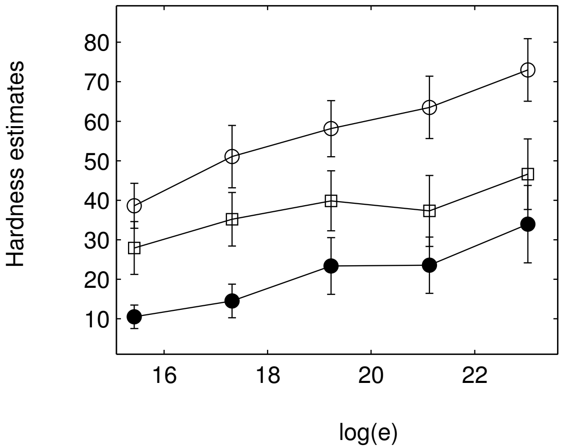

Figure 5.4: Average hammer hardness estimates on a 1-100 scale (1 = very soft 100 = very hard) for the variable $\tan\phi$ set. Filled circles: t_1; empty squares: t_2; empty circles: t_3.

estimates.

Discussion

For both sets of stimuli an increment in e was associated with an increment of the hardness estimates. The absence of significant effects of frequency on hammer hardness ratings is consistent with results reported by Freed on real sounds [82]. This result points toward the independence of recognition of hammer geometry-independent properties from the geometrical properties of the sounding object. Results collected with the variable $\tan\phi$ set of stimuli point toward a dependence of the recognition of the geometry-independent features of the hammer on the geometry-independent features of the resonator.

5.3.4 Conclusions

Independently of the fact that subjects were asked to estimate the hardness of the sounding object, in the first experiment, or of the hammer, in the second experiment, the effects of the $\tan\phi$ and of the e variables appeared undifferentiated. In both cases, in fact, hardness estimates increased for increasing

$\tan\phi$ and e values. This is surprising, given that subjects were informed that both the features of the sounding object and of the hammer were varied in the stimuli, that the two tasks were executed by different groups of subjects, and that all of them were given real sounds examples of hardness variations in both the sounding object and in the hammer. This fact would then indicate an inability of subjects to distinguish geometry-independent features of the hammer from geometry-independent features of the sounding object. The frequency of the signal was found to have different effects, depending on whether listeners were asked to estimates the hardness of the hammer or of the sounding object. Hardness estimates of the hammer were found independent from F, which was assumed to model the geometrical features of the sounding object. In contrast F led to significant changes in the estimates of the hardness of the sounding object, in a non–monotonic fashion. This difference reveals the existence of different acoustical criteria for the recognition of the features of the hammer and of the sounding object. However acoustical measurements on the stimuli are necessary to extensively explain subjects responses.

All these results are not consistent with the assumptions of the orthodox ecological approach to sound source recognition. Perturbation variables were found to lead to significant variations in the recognition of the investigated sound source features. Again the validity of these results could be objected because collected with synthetic stimuli. The substantial coincidence of results gathered with this model and results collected by Freed [82] with real sounds, however, suggests the possibility to replicate all these findings with real sounds.

5.4 Overall discussion

Several experiments investigated recognition of two geometry-independent features of the sound source: material of the sounding object and hardness of the hammer and of the sounding object. Given that material represents variations in different mechanical properties, such as hardness, we expected to find similar effects for the recognition of both these features. As expected, both sets of experiments revealed that recognition of these geometry-independent features of the sounding object were influenced by its geometrical properties. Hammer properties influenced hardness scaling but not material categorization. This was explained by the fact that the range of variation in the hammer properties was lower in the first than in the second of these experiments.

Hardness scaling studies revealed the inability of subjects to distinguish variations of the geometry-independent features of the hammer from variations in the geometry-independent features of the sounding object. Even though acoustical analyses for the hardness scaling experiments were not performed, data collected with real sounds by Freed [82] provide a basis to explain, in part, this inability. In this study one of the acoustical parameters that influenced hammer hardness estimates was the slope of the spectral level over time function. This acoustical parameter is strongly related to the T_e parameter used in our material categorization study, as both measure the decay velocity of signal amplitude. Amplitude decay velocity, then, was found to account for material categorization of the sounding object and for hardness estimates of the hammer. Given that material categorization and hardness scaling of the sounding object are related each other, it follows that the overlap of the hardness estimates of the sounding object and of the hammer is partially explained by the fact that both rely on the same acoustical index.

As pointed out above, the only difference between the criteria used to recognize the hardness of the sounding object and the hardness of the hammer stands in the different effects of the geometrical properties of the sounding object, as modelled by the F variable. In fact, this perturbation variable was found to strongly influence the first type of recognition but not the second one. Thus, even though geometry-independent features of the sounding object are confused with geometry-independent features of the hammer, the criteria upon which their recognition is based differ in respect to the influence of the geometrical features of the sounding object.

In all experiments we investigated the recognition of the features of the objects, using a constant type of interaction between them, impact. All the observed effects of the perturbation variables point toward a revision of the veridicality and independence assumptions of the orthodox ecological approach to sound source recognition, in reference to how we recover the features of objects, rather than those of the interaction between objects.

Finally in both sets of experiments, the correspondences between results gathered with real sounds and results gathered with synthetic stimuli support research in sound source recognition conducted with synthetic stimuli. These two approaches likely highlight different aspects of the investigated phenomena. Research carried with real sounds allows direct investigation of the relationship between the physical features of the sound source and recognition, while research carried with synthetic stimuli allow only indirect investigation of this relationship. On the contrary the first type of researches does not allow precise control of the acoustical features, while research conducted on synthetic sounds does. For this reason this latter type of researches makes investigation of the relationship between the acoustical level and sound source recognition straightforward.

The observed misalignments between the physical sound source features, being them real or modelled, and the recognized ones, claim for a general definition of the criterion that we should follow to ascertain the validity of a synthesis models. What we propose is that perceptually effective synthesis models should be able to reproduce the same biases observed in investigations conducted with real sounds.