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The Sound Quality of Car Horns: A Psychoacoustical Study of Timbre

Guillaume Lemaitre, Patrick Susini, Suzanne Winsberg, Stephen McAdams*
STMS-Ircam-CNRS, 1 place Igor Stravinsky, 75004 Paris, France

Boris Letinturier
SCE-Klaxon, 106 ZI du Clos de la Reine, F-78410 Aubergenville, France

Summary
This paper is the first of a two-part study of the quality of car horn sounds. It aims to provide insights into the design of new sounds: how do we create new sounds that still warn road users against a danger related to a car? In this first part, we study the perception of the timbre of the sounds, grounded in a psychoacoustical framework. We begin to review the approaches to sound quality and choose a framework for our study. Then, after the perceptual validation of the choice of the set of sounds, we ask listeners to categorize all the recorded sounds into main families. Then we model the perception of the timbre of these sounds as three elementary sensations, each correlated with an acoustical descriptor. The results of these experiments suggest that listeners used shared perceptual dimensions along which the sounds were rated. These different dimensions, and the correlated acoustical descriptors rely on the differences between the slight variations of car horn mechanisms. They form the basis for the following study of the invariants that let a sound convey the warning message.

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1. Introduction

The aim of this paper and a companion paper is to study the perceived quality of car horn sounds, in order to help design new sounds, within a psychoacoustical framework. To attain this goal, the study is split into two parts. This first part, reported in this paper, studies the timbre of some car horn sounds. The second part, reported in a forthcoming paper, will define how to create new personalized sounds sharing the properties of the original sounds. To define our approach to this problem, we begin in section 1.1 with a general discussion about timbre, because timbre is a concept that has crystallized the differences between the main approaches (theories) to sound perception. They also form the basis of the different approaches to sound quality that we will then review in the section 1.2.

1.1. Timbre: several standpoints

The notion of *timbre* originates from the Western musical tradition. Although it has been widely discussed by musicians and auditory psychologists, there is no single, widely accepted definition of it [1]. Thus, the most general way to describe timbre is certainly to quote Risset and Wessel [2, p. 113]: “Timbre is a quality of sound. It is the perceptual attribute that enables us to distinguish among orchestral instruments that are playing the same pitch, and are equally loud”. This “definition” illustrates the two aspects that timbre research has explored: (1) timbre is an *attribute* that allows two sounds to be distinguished; (2) timbre allows an instrument to be identified. These are as the “two principle constituents” of timbre reported by Hajda *et al.* [1]. And this has led to rather different research paths.

Timbre as a multidimensional attribute: psychoacoustical definition According to the ANSI definition [3] of timbre, summarized by Krumhansl ([4] p. 44), timbre is “the way in which musical sounds differ once they have been equated for pitch, loudness and duration”. This idea was the first guideline to study sound perception and is grounded on psychoacoustics. Psychoacoustics aims at establishing quantitative relationships between *perceptual attributes* and acoustical properties of the sound signals. Some of these perceptual attributes are singled out in Western culture (duration, loudness, pitch). But once two sounds are “equated” for these attributes, they may be still be perceived as different. It is then said that their *timbres* are different. Timbre is thought to be multidimensional, embedding several perceptual attributes that are collectively referred by this term. To uncover the attributes of timbre, the first studies used the method of semantic differentials [5, 6, 7]. This approach amounts to asking listeners to judge each sound along a set of scales labeled by two opposed adjectives (e.g. “clear/hazy”, “bright/dull”). Sta-

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* now at CIRMMT, Schulich School of Music, McGill University, 555 Sherbrooke St. W., Montréal, Québec, Canada H3A 1E3

tistical techniques are then used to cluster scales into main factors. These main factors are finally interpreted according to the acoustical properties of the sounds. This technique has the main disadvantage that it forces listeners to judge the sounds over a predefined vocabulary (see [4, 8] and [9] for a discussion). Further studies have then used dissimilarity ratings and multidimensional scaling (MDS) techniques [9]. MDS is a three-step procedure. First, listeners have to rate the dissimilarities between each pair of sounds of a set. Then, MDS techniques represent the dissimilarity data by distances in a geometrical space (*perceptual space*). It is assumed that the dimensions of the space represent perceptual attributes. These dimensions are then interpreted by acoustical parameters (called in this case *psychoacoustical descriptors*). Psychoacoustical descriptors are often computed on the basis of physiological models of audition [10]. The multidimensional scaling framework has the great advantage that it does not impose any pre-defined rating criteria on the listener. Furthermore, the increasing sophistication of MDS techniques has led to a refinement of the initial model. Specificities have been added to the model [11], which account for the possibility that a sound may possess some unique feature that other sounds of the set do not share [4]. The possibility of different responses among subjects may also be taken into account [12, 8]. These studies are both *exploratory* (identify the perceptual dimensions and their acoustical correlates) and *confirmatory* (explicitly test the hypotheses formulated by the confirmatory studies in terms of the acoustical descriptors that underly the perceptual dimensions [13, 14]).

Hence the psychoacoustical approach to timbre has singled out perceptual attributes and correlated acoustical properties that allow listeners to rate the dissimilarities among the sounds of a given set. But these results only partially address the issue of identification of a musical instrument. For instance, the *timbre* (according to the psychoacoustical definition of this word) of the different notes produced by an instrument varies with register, intensity, articulation of the notes, instrument, player, room, recording conditions, etc. [15]. To explain how listeners identify an instrument, timbre has to be included in a more global theory of cognition, such as the one proposed by McAdams [16].

Timbre of something: cognitive and ecological approach This leads us back to the first principle constituent of timbre: identification of the event that causes the sound. Indeed, timbre is "what it sounds like" [17, p. 426]. Whereas musical sounds have been studied mostly in the psychoacoustical framework, the identification of environmental sounds has received a great deal of attention from researchers in the fields of cognitive and ecological psychology.

Cognitive psychology seeks to explore the psychological representations of the world. Here again, two approaches can be distinguished.

First, representations of sound events may be conceived as being based on a set of properties or features. Identification processing amounts to comparing the properties or features of a perceived sound to the memorized representations, in an interactive process (both top-down and bottom up): this is the so-called **information processing approach**. Sound sources are then characterized by *invariants* of the properties [16]. This has led, for instance, to the study of how acoustical sound properties may be used as cues to perceive the geometry of metal bars [18], or whether listeners are able to guess the size of a ball dropped on a plate from the sound [19].

Another recent approach (**psycholinguistic approach**) postulates that cognitive representations are psychological entities which are not observable directly, but which can be accessed by studying the linguistic devices used by the listeners to describe their experience [20, 21] (although a theory using language as an observable representation of mental representation needs to be further elaborated [22]). It must indeed be noted that Ballas and Howard had already studied the perception of environmental sounds using a linguistic analogy [23]. The results of these studies show that at a basic level, two different linguistic categories of sounds have been distinguished. On the one hand, some acoustical phenomena are processed as identified sound sources (*sound event*). These sound events are further categorized according to the sound producing process, and are cognitively represented along with the appraisal (semantic, hedonic) of the sound source (and not only according to signal similarities). On the other hand, when identification fails, listeners perceive the sound as an abstract sensation (or *amorphous sequences* in the case of environmental sound sequences [20]), which is then described according to the properties of the acoustical signal [20].

These findings coincide with Gaver's ecological distinction between *musical listening* (when listeners focus on qualities of the acoustic signal) and *everyday listening* (when listeners identify the sound event or the sound event properties: interaction, material, shape) [24, 25].

Ecological psychology considers that human perception is focused on the interaction with the environment. Hence, asking listeners to scale abstract qualities of sounds like pitch and loudness is not considered to be relevant at all in this theoretical framework. In its original formulation [26], ecological psychology is formally incompatible with psychoacoustics. It is also formally incompatible with cognitive psychology, for it does not postulate any inferential processing, nor the internal representations of the world postulated by cognitive psychology, but rather a *direct perception* of the world [26]. However, the actual influence of ecological psychology has been less on the theories of cognition than on the research topics: it has redirected attention from laboratory experiments on simple tones to studies of the perception of everyday sound events.

Timbre: an illustration of different theoretical views of sound perception This review of the different approaches to timbre reflects the distinction between three theoretical views on sound perception.

- Psychoacoustics and the “information processing” approach to cognitive psychology: sounds are perceived as attributes (which are actually constrained by the auditory nervous system). The attributes are the information available for further inferential processing. The different stages of processing are mutually influenced (bottom-up and top-down). Timbre is a set of perceptual attributes.
- Ecological psychology: sound sources are perceived directly, as meaningful events, through perceptual invariants of the objects of the world. Timbre is a cue to recognize objects and events in the world.
- “Psycho-linguistic” approach to cognitive psychology: cognitive representations are constructed by the listener. These representations are both constrained by the materiality of the phenomena and by listener knowledge, and are stabilized in linguistic forms.

Sound quality reflects in the same way these different approaches.

1.2. Different approaches to sound quality

The quality of the acoustic environment is currently an important issue. On the one hand, efforts are being made to account for the annoyance caused by noises [27]. On the other hand, designers seek to improve the *sound quality* of industrial products. The idea of sound quality has emerged relatively recently. It refers to the fact that the sounds produced by an object or a product are not, or not only, annoying or unpleasant, but are also for people to interact with an object. In the case of industrial products, it is therefore of major importance to design the sound quality to meet consumer expectations, product uses and brand image. However, in practice there are several definitions of sound quality and several methods to study it. Even if not always mentioned by the authors, these different approaches to sound quality are grounded in different theoretical frameworks of sound perception.

Psychoacoustical approach In the psychoacoustic context, sound quality is defined as a global attribute of a sound or as arising from a combination of attributes. Sound quality can thus be evaluated directly (following Zwicker and Fastl’s approach to *pleasantness* [10, 28]) This is, among other examples, the case in the studies reported in [29, 30, 31]. Listeners have to rate the perceived quality (or inversely the discomfort) of the sounds either with ordinal, analog category, or numerical scales. This evaluation can be made after having heard the sounds or continuously during the sounds [32]. The evaluated quality is then mapped onto acoustical parameters.

A more sophisticated technique is defined in [33] and applied in [9]. It transposes the method used to study the perception of the timbre of musical sounds to sound quality. It is a two-step procedure: dissimilarity judgments and multidimensional scaling techniques first determine the psychological dimensions and correlated acoustical parameters. In a second step, listeners provide preference judgments among the sounds. These preference judgments are then related quantitatively to the psychoacoustical descriptors.

Ellermeier [34] used preference judgments to test the BTL (Bradley-Terry-Luce) model. It tests the assumption that an “unpleasantness” ratio scale can be derived from the preference judgments among a set of environmental sounds (which may not be the case if listeners use different criteria for different sounds). Then this ratio scale is correlated to psychacoustical descriptors, providing a predictive model of the preference judgments.

An alternative method uses semantic differentials. A factor analysis defines a criteria corresponding to sound quality, and to relate it to the sound properties. For example, this method has been applied to car sounds [35, 36]. However, defining the appropriate adjectives to label the scales must be done carefully, because it influences greatly what can be measured [37].

Cognitive and ecological approach Several studies of sound quality refer to both cognitive and ecological psychology at the same time. Actually, in this case, ecological psychology has focused attention on the *possibilities of action* that sound conveys (see Guski [38]). This has led this author to redefine a three-fold definition of sound quality: “(1) suitability, or stimulus-response compatibility, (2) pleasantness of sounds and (3) identifiability of sounds or sound sources” [38]. According to this author, psychoacoustical methods are able to address the second point. The first point leads to focusing the experimental context upon relevant tasks, i.e. tasks that are natural for listeners: dissimilarity judgements, categorization, verbalization [39, 40], imitations [41] or tasks that the listeners are supposed to do in real situations when listening to the sounds. For instance, to study sound quality inside passenger trains, Shafiquzzaman-Khan [42] asked passengers to perform habitual tasks (reading a book, having a conversation, having a rest, etc.) and then to evaluate the ease with which they performed the task.

The third point of Guski’s approach emphasizes that identification of the source is the most spontaneous reaction to describe a sound [43]. Several studies of the perception of everyday sounds [44, 45] have typically shown that identification of a sound source is highly dependent on the (auditory, but also visual) context. Experimental paradigms thus have to be designed to direct the listener’s response strategy toward a natural situation: this is the *ecological validity* of the study [21]. Great care is then taken to record and reproduce the sounds with the right context and the right medium [46, 39, 45, 21]. More than a simple methodological refinement, these latter studies introduce a change of paradigm, grounded on the psycholinguistic approach to cognitive psychology: to deal with sound quality of a product, one has to deal with the cognitive representations of this product. These representations are cultural constructions. They cannot be analyzed only from the point of view of the acoustical properties of the sounds.

Semiotic approach The semiotic approach to sound quality considers that a sound is a sign conveying meanings to the listener [47]. For instance, the sound of a rotating hard drive indicates to the user that the computer is working. In this approach, designing the sound quality of an object amounts to fitting the meaning conveyed by the sound to the function of the object. In this case, sounds produced by an object are a part of its global function. The relationship between the sign (i.e., the sound) and the meaning is not inherent in the sound itself but rather assigned to it by the listener. This assignment results from learning (implicit or explicit) and depends on the context [48], which led Jekosh to propose a definition of *product sound quality*: "Product sound quality is a descriptor of the adequacy of the sound attached to a product. It results from judgments on the totality of auditory characteristics of a given sound, the judgments being performed with reference to the set of desired features of the product that are apparent to the users in their actual cognitive and emotional situation" [49, 50]. The semiotic approach to sound quality is cited in many studies, but has actually rarely been applied, except in some cases dealing with warning signals [51].

1.3. Defining an approach to study the quality of car horns sounds

Problematic Car horns are wildly used and widely down-cried. However, they have the capital (and legal) function of warning road users against potential danger. Sound is the function of the product. The sound must be unequivocally interpreted as a warning. But at the same time, car horn builders wish to tune their sounds to match them to car categories and brand identities.

Designing the sound of car horns thus involves a compromise between the need to customize the sound and the necessity of providing efficient warning signals. To fulfill these constraints, car horn builders wish to create new sounds by means of a new device, made of an electronic synthesizer and a loudspeaker (see [52]). In this context, the goal of this study is to identify the invariants of car horn sounds that convey information concerning danger to the listener. This will allow car horn builders to design new sounds still perceived as car warning signals.

The aim is to provide car horn builders with acoustical specifications.

Defining an approach To achieve the goal specified above, we can identify two requirements: (1) We have to provide car horn builders with insights that will allow them to modify the sounds. Our results must therefore deal with the properties of the sound signals. (2) We have to specify what the (acoustical) invariants are that allow the sound to convey a warning. This study is thus grounded in a psychoacoustical framework. We split our approach into two steps. Firstly, we study the timbre (in its psychoacoustical definition) of existing car horn sounds (in this paper). This allows us to identify the acoustical properties of the sounds that allow listeners to characterize the different car horn sounds. Secondly, in a forthcoming paper, we will seek to identify which combination of these properties succesfully conveys a sense of warning.

Following the aforementioned review of the different approaches to sound quality, psychoacoustical methods have the inconvenience of studying sound outside of natural contexts. This is especially annoying for warning signals, as it has been shown that they may be identified differently according to the context in which they are heard [53] (even if, according to the same study, some car horn sounds are very resistant to variations of acoustical context). Furthermore, one may argue that because sound evaluation and identification may be processed according to attributes that are not acoustical (e.g. semantic and hedonic attributes of the cognitive category to which the identified sound event belongs [20]), seeking acoustical invariants of the warning message may be irrelevant. However, as the final goal of the study is to provide insights that will allow designers to create new sounds, i.e. manipulate acoustical properties and only acoustical properties, we believe that psychoacoustics is an appropriate framework, because it is the only one to our knowledge that establishes a quantitative relation between aspects of sound perception and their underlying acoustical properties.

We therefore claim, in line with Susini *et al.* [33, 9] and Caclin *et al.* [14], that the psychoacoustical definition of timbre and the associated experimental methodology are valid for studying environmental sounds. This is because this framework does not try to study the cultural construction of musical timbre, but rather to single out what are the most salient physical features that allow listeners to distinguish sounds of a given homogeneous set.

Framework of the document

This paper has two parts. In the first part (section 2), we describe a free sorting task, that allows us to choose the sound set used for the further experimental studies. In the second part (section 3), we study the timbre of car horn sounds and induce three acoustical descriptors that underly the perception of the timbre of car horns.

2. The sound set

The first step of the study is to choose a representative set of car horn sounds. We describe in the following section how we performed the recordings and select a representative subset of sounds.

2.1. Recordings of car horn sounds

A car horn is a self-oscillating electro-acoustical device. Two main categories exist. The first kind (*horn-like* devices) are based on an electro-dynamical driver and horn. The second kind (*plate-like* devices) are also made of an electro-dynamical driver, but there is a metal plate attached to the membrane. The devices are usually mounted alone (*monophonic* sounds), or in twos or threes resulting in chords (*polyphonic* sounds). Car horn sounds are wide-band signals. They have a harmonic spectrum with a fundamental frequency lying between 300 Hz and 600 Hz (usually around 440 Hz) and a signal-to-noise ratio around 40 dB. This strong harmonicity is due to the self-oscillating mechanism that produces strongly periodic oscillations.

Influence of the fixation The sound of a car horn is strongly influenced by its fixation. A car horn is usually attched to the body of the car, behind one of the front wheels. When the device is not attached at all, it generates a very weak sound. Recording the horns attached to the body of the car (*car recordings*) is not very practical, however, because it is costly and not very easy to manipulate a car in a specialized hemi-anechoic chamber. For this reason, there is a standardized procedure [54] to record a horn attached to a heavy metal bar in an anechoic chamber (*laboratory recordings*). However the sound emitted by this horn-bar device is quite different from the sound emitted when the device is attached to the car: its fundamental frequency is lowered, and the spectral envelope is slightly changed. To study the perception of sounds, it is very important to assess whether conclusions drawn from experimental studies using these laboratory-recorded sounds can be generalized to situations in which the device is attached to the car body. This issue has been studied in [55]. The conclusions show that the alterations of the sounds introduced by the fixation condition are somehow equivalent for all the devices. This means that, in spite of the fact that the perception of the sound of a given device is changed if the fixation were different, the *difference* between the sounds of two different devices remains perceptually the same. As the study of the perception of timbre described in section 3 will be based only on comparisons between sounds (dissimilarity-rating task) recorded under the same conditions, we decided to work with laboratory recordings.

It must be noted that these sounds are not ecological, because they are not played in a realistic context. Indeed, our experimental protocols are intended to elicit musical listening among the listeners, i.e. we are expecting the listeners to judge the properties of the sound signals. These recordings are thus appropriate.

Recordings and loudness equalization The recording sessions took place in an anechoic chamber. Car horns were attached to a heavy metal bar. The horns were powered by a 12 V car battery. B&K 1/2" microphones were located in front of the horn mouth, 2 m in front and the signal was fed to a DAT recorder (44100 Hz, 16 bits). All sounds lasted approximately 550 ms. 43 sounds were recorded (26 monophonic, 14 polyphonic, 3 electronic prototypes).

In the experiments that we describe, the sounds had been previously equalized in loudness in a preliminary experiment. Listeners were asked to adjust the level of each sound so that they perceived it at the same loudness as a reference sound (1 kHz pure tone at 83 dB SPL).

2.2. Choosing a reduced subset

As 43 sounds are far too many to use in a dissimilarity-rating experiment, we need to sample a subset of sounds, representative of the variety of car horn sounds. The choice of the subset of sounds is based on a sorting task, where listeners have to group together sounds with similar timbres. This sorting task also allows us to assess whether there is categorical classification of the sounds. Indeed, the definition of timbre that we have adopted stands only if the experimental protocol elicits *musical listening* [24, 25], i.e. if the experimental protocol allows listeners to judge the proximities between the sound signals. We thus have to verify that the sounds have not been clustered according to accompanying attributes of identified sound sources, but rather to sound features.

Method *Subjects:* 28 subjects (15 men and 13 women) volunteered as listeners and were paid for their participation. They were aged from 18 to 34 years old. All reported having normal hearing. About half of them were musicians (from amateur to nearly professional level), and the other half had no musical education. Most of them were students from the various universities of Paris. Five subjects were audio specialists.

Stimuli: The 43 sounds (described above) were played at a loudness equivalent to 83 phons.

Apparatus: The test took place in the IAC sound-attenuated rooms at Ircam. The experiment was run on a Personal Computer under Linux, and the graphical interface was implemented under Matlab. The sounds were amplified through a Yamaha P2075 amplifier and sent to Sennheiser HD 520 II headphones.

Procedure: The subjects were all given written instructions explaining the sorting task (see appendix A). Emphasis was placed on what timbre is not (neither pitch nor perceived duration nor loudness). The subjects saw a white screen on which stars labeled from 1 to 43 were drawn, each star corresponding to a sound. The labeling was different for each subject. They could hear the sound by double-clicking on a star. Subjects were asked to move the stars in order to group together the sounds they heard as having the same timbre. They were allowed to form as many groups as they wished and to put as many sounds in each group as they desired. It has been remarked that this procedure actually amounts to collecting timbre proximity data for large sets of stimuli [1, 56, 9]. The data for each subject consisted of an incidence matrix, i.e. a matrix in which a *one* indicates that the two sounds have been classified together and a *zero* that they have been classed in different groups.

Analysis of the results The individual incidence matrices (coding the set partitions of each subject) are summed. A co-occurrence matrix is then obtained by summing the incidence matrices. The co-occurrence matrix represents how many subjects have placed each pair of sounds in the same category. This can be interpreted as a proximity matrix [57]. Sorting data are usually visualized by means of tree representations. However, among the 12341 triplets that can be formed among 43 sounds, 100% of the data follow the triangular inequality, but only 68.8% follow the ultrametric inequality. This latter property suggests that the sorting data cannot be represented properly by a tree representation: if the sorting data would fit perfectly a tree representation, 100 % of them would follow the ultrametric inequality [58]. Thus, a better representation of the sorting data is theoretically made of points in a low-dimensional geometrical space [59]. However, as our goal is not to interpret precisely the proximity data, but rather to find a heuristic to select a subset of sounds, we prefer to use a hierarchical tree representation, as suggested by Kruskal [59].

The hierarchical tree representation of the data (Figure 1) was derived using an unweighted arithmetic average clustering (UPGMA) analysis procedure. In such a representation, the distance between two objects is represented by the height of the node which links them [58]. Because the ultrametric tree representation is not valid in this case, the distances given by the tree are *not* to be interpreted as representing the true distances among the objects.

At this stage of the analysis, we can observe a rather homogeneous tree. There is no particular reason to cluster at any given level. In order to evaluate the most stable level of clustering across listeners' responses, a bootstrap algorithm [60] is performed over the data. As a result we found the nine classes, as illustrated by the symbols and the circled figures in Figure 1.

Discussion Twenty-two sounds are finally sampled from the nine families of Table I (marked by the circles in Figure 1). They form a subset that is both representative of the variety of the car horns and not too large in number.

If we try to interpret the tree derived from the sorting data, three large clusters can be distinguished. One cluster (classes 2-5-7-9) includes all the monophonic horn-like sounds. Another cluster (classes 1-6) includes all the polyphonic sounds, and the latter cluster (classes 3-4-8) includes all the monophonic plate-like sounds. The distinction between monophonic and multiphonic sounds, and between horn-like and plate-like sounds is therefore quite clear.

If we go deeper into the details, some horns are distinguished from the others: one new sound (class 5), which was at the time of the study only a prototype, and a ship horn (class 9) are separated from more common horns.

Hence two main conclusions can be drawn from this experiment. Firstly, the properties of the proximity data indicate that they would fit a low-dimensional Euclidean representation of this data far better than a tree representation. This suggests that listeners have sorted the sounds according to a small number of perceived attributes of the sounds. This tends to prove that the experimental conditions have oriented the listeners toward musical listening. Secondly, the analysis of the hierarchical tree drawn from the data (although it is a poor representation of these data) indicates that these proximities, and the perceived attributes of the sounds, distinguish the different car horn mechanisms. This suggests that the small number of attributes used to class the sounds are representative of the different car horn mechanisms.

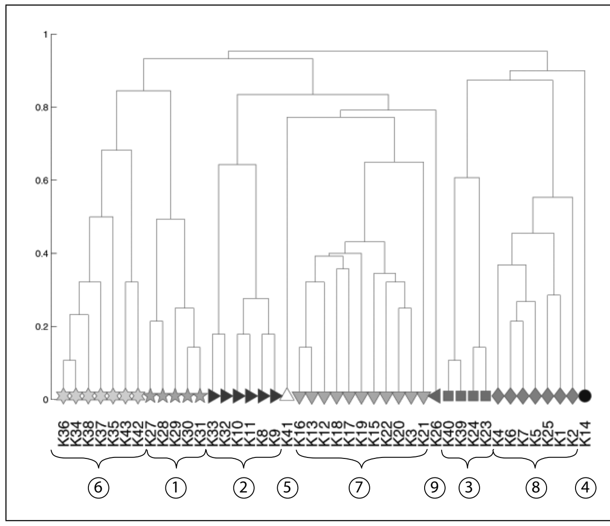

Figure 1. Hierarchical tree representation of the results of the sorting task. Symbols and circled figures refer to the classes labeled in Table I.

Table I. The nine classes of car horn sounds.

Class	Class label	Horns
1	Standard polyphonic plate-like	K27-31
2	High-pitched horn-like	K8-11, K32-33
3	Special plate-like both mono- and polyphonic	K23-24, K29-40
4	Low-pitched horn-like	K14
5	Prototype (imitation of a monophonic horn-like)	K41
6	Standard polyphonic horn-like	K34-38, K42-43
7	Standard monophonic horn-like	K3, K12-13, K15-21, K26
8	Standard monophonic plate-like	K1-2, K4-7, K25
9	Ship horn	K26

3. The timbre car horn sounds

3.1. Timbre space

According to the psychoacoustical definition of timbre used in this study, timbre is what still may permit a listener to differentiate two sounds once they have been equalized in duration, loudness, and pitch. Following the multidimensional scaling approach described in the introduction, we first collect dissimilarity judgments.

Dissimilarity judgments *Subjects:* Forty-one subjects (20 men and 21 women) volunteered as listeners and were paid for their participation. They were aged from 18 to 34 years old. All reported having normal hearing. About two thirds of them had received musical training. The majority of the students were from the various universities in Paris.

Stimuli: Twenty-two sounds were chosen from the nine classes obtained from the classification task. They were played at the same level as in the previous experiment (83 phons).
Apparatus: Same as in previous experiment.
Procedure: Subjects all received written instructions explaining the task (see Appendix B). They were told that they were to make judgments on the timbre. The meaning of the word timbre (neither pitch, nor perceived duration, nor loudness) was explained to them. Particular emphasis was placed on ignoring pitch [61].

All 231 different pairs (AB or BA pairs are considered as equivalent) among the 22 sounds were presented. At the beginning of the session, the subject listened to all of the samples in random order to get a sense of the range of variation possible. Next, five training trials were presented to familiarize the subject with the rating task. On each trial, a pair of sounds was presented, separated by a 500-ms silence.

The subject saw a horizontal slider on the computer screen with a cursor that could be moved with the computer mouse. The scale was labeled "Very Similar" at the left end and "Very Dissimilar" at the right end. A rating was made by moving the cursor to the desired position along the scale and clicking on a button to record it in the computer.
Coherence of the responses: An analysis of the correlations between the responses of the subjects revealed that one subject was correlated negatively with the others. This subject was removed from subsequent analyses, since this negative correlation indicated that he had judged similarity instead of dissimilarity.

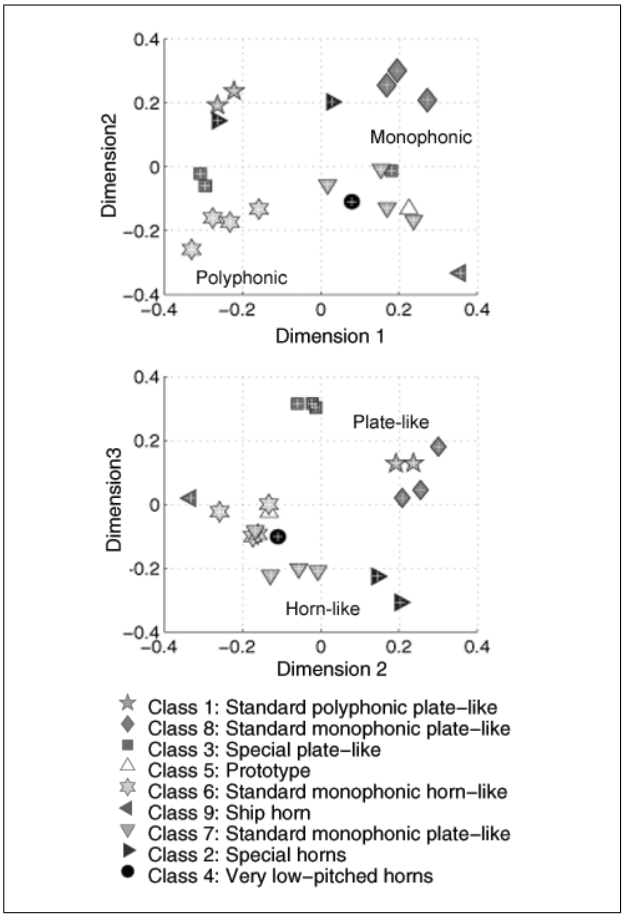

Figure 2. 2D projections of the 3D-perceptual space. Symbols refer to class labels in Table I.

CLASCAL analysis CLASCAL, a multidimensional scaling (MDS) technique, is described in detail in [12]. We only give here a short description. In the CLASCAL model, dissimilarities are modeled as distances in an extended Euclidean space of R dimensions. In the spatial representation of the N stimuli, a large dissimilarity is represented by a large distance. The CLASCAL model for the distance between stimuli i and j postulates common dimensions shared by all stimuli, specific attributes, or *specificities*, particular to each stimulus, and latent classes of subjects. These classes have different saliences or weights for each of the common dimensions and for the whole set of specificities. For the t^{th} latent class, the distance between two sounds i and j within the perceptual space is thus computed according to Equation 1:

$$d_{ijt} = \sqrt{\sum_{r=1}^{R} w_{tr}(x_{ir} - x_{jr})^2 + v_t(S_i + S_j)}. \qquad (1)$$

In this equation d_{ijt} is the distance between sound i and sound j, t is the index of the T latent classes, x_{ir} is the coordinate of sound i along the r^{th} dimension, w_{tr} is the weighting of dimension r for class t, R is the total number of dimensions, v_t is the weighting of the specificities for class t, and S_i is the specificity of sound i.

The class structure is latent: there is no a priori assumption concerning the latent class to which a given subject belongs. The CLASCAL analysis yields a spatial representation of the N stimuli on the R dimensions, the specificity of each stimulus, the probability that each subject belongs to each latent class, and the weights or saliences of each perceptual dimension for each class. We found a spatial model with three dimensions, specificities and six latent classes. We chose the model configuration by comparing *Bayesian Information Criteria* BIC [62] across models, as well as performing Hope's test [63].

Interpretation To check the coherence between sorting task results and MDS analysis, we represent the projections of the sounds on the D1-D2 and D2-D3 planes in Figure 2. The symbols are identical to those of Figure 1 and Table I (specificities are not represented). This reveals that the first dimension distinguishes monophonic and polyphonic sounds, and that the plate-like and horn-like sounds form two distinct groups in the D2-D3 plane.

The distribution of the sounds along the three dimensions is rather homogeneous. This property is very important, for it indicates that the dimensions of the perceptual spaces are continuous dimensions, and do not simply reflect some binary categorization of the sounds. This allows us to compute correlations with these dimensions.

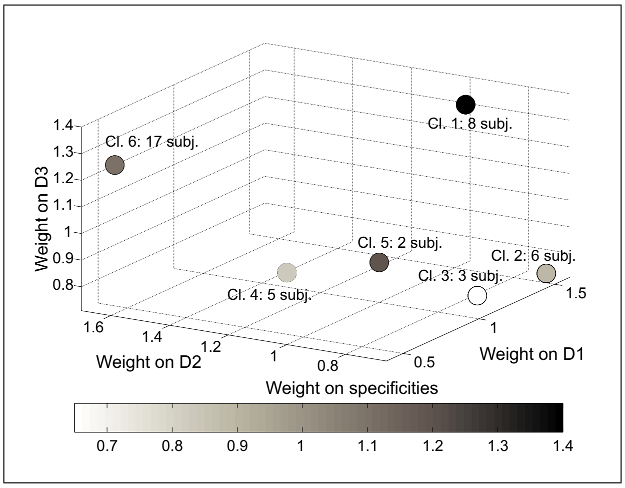

Figure 3. Representation of the weight of each dimension and specificities for the six latent classes.

Subjects belonging to each latent class weight the common dimensions differently. The large number of latent classes make it difficult to characterize different response strategies. The different weights of the dimensions and specificities are represented for each of the six latent classes in Figure 3. One remark must be made, however: this figure shows a clear distinction between subjects who tend to favor dimension 3 (classes 1 and 6: 25 subjets) and subjects who attach less perceptual importance to this dimension (classes 2 to 5: 16 subjects). It should be noted that these categories are not related to the variables *age*, *genre*, *profession*, *musical* or *audio training* of the subjects.

3.2. Acoustical correlations

The next step of the timbre study is to give a physical interpretation of the perceptual dimensions revealed by the MDS analysis. Acoustical descriptors found to be relevant for timbre perception in previous studies are computed [61, 64, 65, 10]. They are based on physiological models of the auditory system. Due to confidentiality restrictions, descriptor computation details will not be explicated, but this in no way detracts from the theoretical import of the findings.

Dimensions Three descriptors were found to match the perceptual dimensions.

The first descriptor is related to the amplitude modulation rate of the temporal envelope (expressed in asper). It has been identified as corresponding to the perception of *roughness* [64]. The first panel of Figure 4 shows the regression line of the first dimension onto the roughness descriptor.

The correlation coefficient is highly significant (r(20)=-0.9, p<0.01), but the spreading of the points around the regression line suggests that the relationship would be closer to a power law than to a linear law. Non-linear regression shows a better regression spreading for a power law with an exponent 0.2. Such correcting factors have been found in other models of roughness [66].

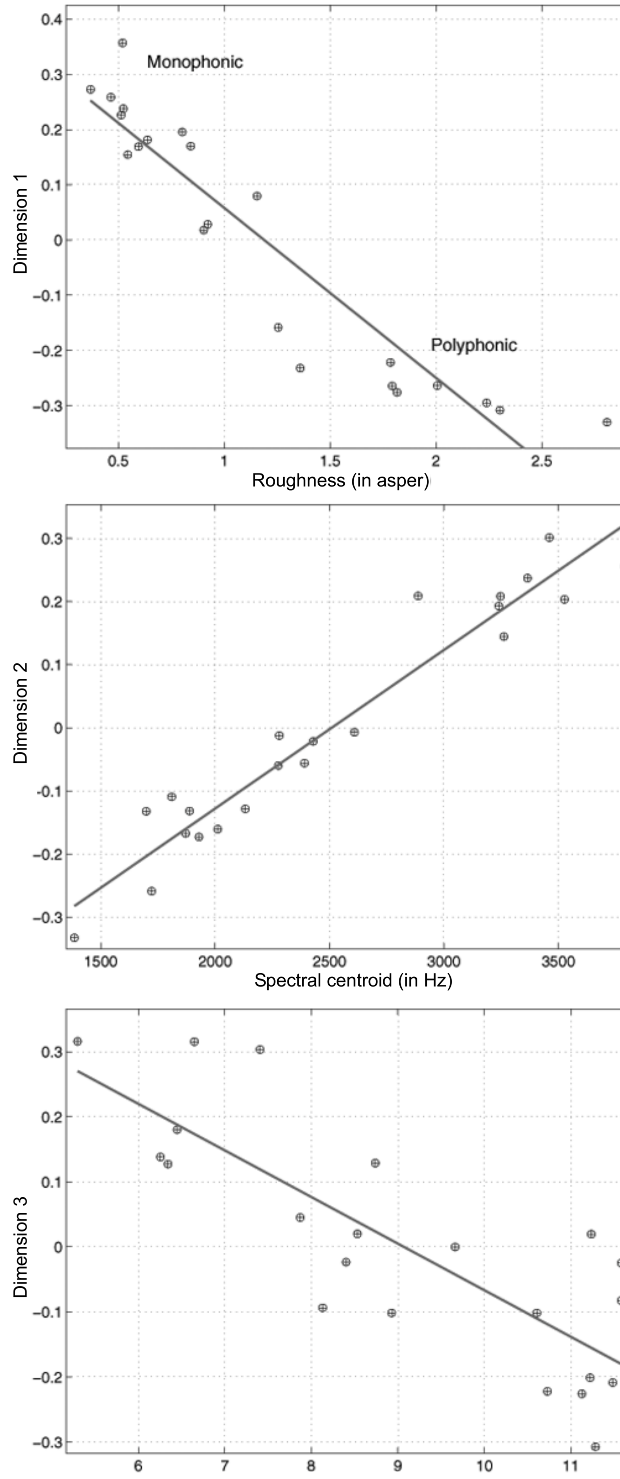

Figure 4. Correlation of the three perceptual dimensions onto the acoustical descriptors.

The second descriptor is spectral centroid (in Hz), and is related to the spectral distribution of energy of the sound. It has been identified as corresponding to the perception of *brightness* [10]. The correlation coefficient is highly significant (r(20)=0.9 p<0.01). The points are uniformly spread around the regression line, as shown in the middle panel of Figure 4.

Table II. Correlation coefficients between the perceptual dimensions and the acoustical descriptors. df=20; *: p<0.05; **: p<0 n.s.: not significant.

Descriptor	D1	D2	D3
Spectral centroid	0.0 n.s.	**0.9****	0.1 n.s.
Spectral deviation	0.3 n.s.	-0.4*	**-0.8****
Roughness	**-0.9****	-0.1 n.s.	0.3 n.s.
Roughness$^{0.2}$	**-0.9****	-0.1 n.s.	0.2 n.s.

Table III. Square roots of specificities.

Class	Horn	$\sqrt{spec.}$	Class	Horn	$\sqrt{spec.}$
1	K27	0.03	6	K37	0.00
1	K29	0.23	6	K42	0.23
2	K10	0.04	7	K3	0.09
2	K32	0.00	7	K18	0.04
3	K24	0.00	7	K21	0.06
3	K40	0.03	7	K22	0.04
3	K39	0.00	8	K1	0.00
4	K14	0.37	8	K2	0.18
5	K41	0.44	8	K5	0.05
6	K35	0.13	8	K25	0.06
6	K36	0.12	9	K26	0.00

The third descriptor is related to the fine structure of the spectral envelope. We call it *spectral deviation* (in sones). Its computation is based on the smoothness of the output of the filter-bank. A descriptor of the same kind has been previously found to account for the perceived difference between the timbre of a clarinet and a trumpet [67]. The correlation between the third dimension and spectral deviation is also significant (r(20)=-0.8, p<0.01). The points are uniformally spread around the regression line, as shown in the last panel of Figure 4.

Table II shows the correlation between those descriptors and the dimensions.

Specificities: The square root of the specificity values (distance-like) are listed in Table III.

The specificity values are very weak, except for two sounds K14 (class 4) and K41 (class 5). The specificity value indicates that in addition to the common dimensions possessed by the stimuli, they also possess some unique or specific attribute or attributes which contribute to the distance between them and other objects as shown in Equation 1. It is not possible to systematically explore the reason why these two sounds have higher specificities, because of the uniqueness of specificities [1]. We can, however, formulate some hypotheses. Sound K14 has a fundamental frequency far lower than other sounds and sounds "dirty", mainly because of the presence of sub-harmonic partials in its spectrum. Sound K41 is a prototype, the spectrum of which is low-pass filtered. Furthermore, these two sounds were alo set apart in the tree representation (Figure 1).

Discussion Acoustical descriptors were found that explain a significant portion of the variance in the positions of the car horn sounds along the perceptual dimensions. The descriptor of roughness matching the first dimension characterizes the distinction between monophonic and multiphonic sounds. It should be pointed out that listeners appear to have performed a continuous rating from pure periodic sounds (one single harmonic series) to sounds made of the addition of two periodic sounds. The spectral analysis of the intermediate sounds reveals that they are made of harmonic series based on the fundamental frequency, added to a second attenuated sub-harmonic series, which progressively increases the perceived roughness.

The second dimension is correlated with a descriptor related to the spectral energy balance (spectral centroid). The third dimension appears related to a descriptor characterizing fine-grained spectral aspects (spectral deviation). Combinations of these two descriptors (spectral centroid and spectral deviation) hence distinguish perceptually between the acoustic signals of horn-like and plate-like devices, allowing us to describe what distinguishes the two main families of car horn sounds, from a perceptual standpoint. These results are crucial for the designer of new car horn sounds, since they provide clues to design new sounds sharing the characteristics of the main families of the

4. Conclusion

This paper is the first of two studying the quality of new car horn sounds. This first paper focuses on the timbre of the car horn sounds, in a psychoacoustical paradigm. We follow here a framework that was originally designed to study the timbre of musical sounds. We first have reviewed different approaches to sound quality. These approaches are grounded in different theoretical approaches to sound perception: psychoacoustics, cognitive psychology (information processing approach and psycholinguistic approach) and ecological psychology. These different approaches are illustrated in the different definitions of *timbre*: timbre may be considered either as a grab-bag term actually corresponding to different sound sensations (psychoacoustical approach) or as a cue to sound source identification (cognitive and ecological approaches).

Two experiments are reported in this paper.

First, we have asked listeners to freely sort car horn recordings into groups with similar timbres. This sorting task allowed us to extract a subset of sounds that is both representative of the variety of the different sounds and limited in number. It has also allowed us to formulate two assumptions: (1) a small number of independent attributes underlies car horn timbre, and (2) these dimensions are representative of (caused by) the different sound-production mechanisms. In a second step, we have applied the multidimensional approach to musical sound perception. Listeners rated the dissimilarities of each pair of sounds of the selected set. Multidimensional scaling techniques model the dissimilarity judgments as the integration of three continuous perceptual dimensions (shared by all the sounds) and specifities (particular to each sound). The continuous perceptual dimensions were correlated with appropriate acoustical descriptors. Latent class analyses revealed that different classes of subjects weighted the dimensions and specificities differently. However, we were unable to interpret these different weightings in terms of the biographical factors at our disposal.

Several conclusions are to be drawn from these results. From a general standpoint, a major result is the importance of the perception of the sound producing mechanism. The categorization experiment indeed revealed that the categories of car horns made by the listeners are best represented by a small number of dimensions, and that these categories correspond closely to the different kinds of devices. These categories were preserved both in the sorting task and in the dissimilarity ratings. Furthermore, these categories are defined by the common dimensions shared by the sounds and are correlated with the acoustical descriptors.This is may be because the mechanisms of car horns are globally the same: a membrane is set into vibration and is loaded by two kinds of resonators. These resonators may change the spectral envelope, but sounds can still be compared along a set of shared dimensions. Similarly, mounting the horns in twos or threes results in forming chords, but because car horn sound spectra possess several harmonic series, even if sounding alone, car horn sounds are perceived along a common dimension. Thus, musical listening, elicited by our experimental protocols, was an appropriate paradigm to single out the acoustical parameters relevant to the different sounds. Of course, as the experimental tasks were based on sound comparisons, we have emphasized the properties shared by the sounds. We do not have any information about what distinguishes car horn sounds from other sounds that, for instance, may be heard on the street.

However, at this point, we have not yet addressed the problem of the *sound quality* of the car horns. The next step will be first to define a relevant experimental task to study sound quality. This has to be done according to the function of a car horn: warn people against a danger from a car. In a following paper, we will therefore investigate the acoustic invariants that let a sound convey the car horn warning message to road users.

Appendix: Verbatim of the experimental instructions provided to the subjects

(Translated from the French)

A. Sorting experiment

Goal of the study

The goal of this experiment is to study different families of car horns. Your task amounts to grouping together sounds with similar timbre.

Procedure

You will sit in front of a white computer screen. Forty-three green stars are randomly spread across this screen. They correspond to the car horn sounds. You can listen to the sound by double-clicking on the star. You can listen to the sounds as many times as you wish. Your task is to group together sounds with similar timbre. You can form as many groups as you wish. You can select and move clusters of sounds by dragging a rectangle around them. There is no “correct” answer, since we are interested in your personal judgment.

Remark on the notion of timbre

You have to group together sounds with similar *timbre*. Timbre is what allows you to distinguish between two sounds having the same duration, the same intensity and the same pitch. For instance, two musical instruments playing the same note, with the same intensity and of the same duration do not sound identical. What distinguishes them is referred to here as “timbre”. Timbre may also be called the “color”, “texture”, ... of the sound.

These sounds are supposed to have the same intensity. You may however feel that certain sounds are louder than others. We ask you to not take into account intensity in your judgments.

Similarly, the sounds do not have all the same pitch. They “play different notes”. Here again, we ask you to not include these differences of pitch in your judgments, but rather to focus on timbre.

B. Dissimilarity ratings experiment

Goal of the study

The goal of this experiment is to study the perception of the timbre of the car horns. Your task is to judge the dissimilarity that you perceive between two sounds.

Procedure

You will sit in front of a computer screen.

There are twenty-two car horn sounds in the test. They all last about half a second. At the beginning of the test, you will be provided with twenty-two buttons, which allow you to listen to the twenty-two sounds and to familiarize yourself with them. Then you will be provided with each one of the 231 possible pairs of sounds among the twenty-two sounds. For each pair of sounds, the interface looks similar: there are two buttons labeled “listen again” and “validate”, above a cursor with the labels “very different” and “very similar” at each extremity. When you click on the “listen again” button, you can hear the two sounds. You can listen to the pair of sounds as many times as you wish. The cursor allows you to rate the dissimilarity between the sounds. When your are sure of your rating, click on the “validate” button. This moves to the next pair of sounds. Before the real test, you will be provided with six pairs of sounds to familiarize yourself with the interface in the presence of the experimenter.

Remark on the notion of timbre

You have to group together sounds with similar *timbre*. Timbre is what allows you to distinguish between two sounds having the same duration, the same intensity and the same pitch. For instance, two musical instruments playing the same note, with the same intensity and of the same duration do not sound identical. What distinguishes them is referred to here as “timbre”. Timbre may also be called the “color”, “texture”, ... of the sound.

These sounds are supposed to have the same intensity. You may however feel that certain sounds are louder than others. We ask you to not take into account intensity in your judgments.

Similarly, the sounds do not have all the same pitch. They “play different notes”. Here again, we ask you to not include these differences of pitch in your judgments, but rather to focus on timbre.

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