FROM SOUND QUALITY TO SOUND SYSTEMS: A RETROSPECTIVE STUDY

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http://dx.doi.org/10.6036/MN9586

TO CITE THIS ARTICLE:
SANZ, Rosana, MANCHADO-PEREZ, Eduardo, OZCAN, Elif et al. FROM SOUND QUALITY TO SOUND SYSTEMS: RETROSPECTIVE OF SOUND STUDIES APPLICABLE TO PRODUCT DESIGN. DYNA Management, January-December 2020, vol. 8, no. 1, [12 p.]

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1.- INTRODUCTION

The current socio-technological scenario incorporates products with increasingly complex and dynamic information management systems. New functions that require new interfaces, capable of communicating with the user at different levels. In this context, sound is a valuable resource for communicating messages of different nature and critical level. Thus, the sound stimulus takes the form of an alert in the cockpit of an airplane, provides information for the blind at a traffic light, or warns abouts a vital sign variability of a critical patient.

Product sound design (PSD) studies the sounds resulting from its operation, and those intentionally implemented during the design activity [1]. Its contribution to design engineering means accepting sound as a fundamental channel of product communication and, consequently, an essential parameter to be configured during the development process. However, PSD is not yet a sufficiently solid and consolidated discipline [2]. Particularly, design engineering demands specific and dedicated knowledge, which can be applied in a rigorous, systematic and orderly manner. The role of sound has already been approached from various academic disciplines, and applied to different fields such as marketing. However, the available methods and tools differ according to the field of study and are more or less useful depending on the phase of the project in which they are considered (eg., conceptualization, prototyping or evaluation), and there are no specific guidelines for their application during the design engineering process.

Before generating new knowledge in the field, we propose to review, group and classify existing knowledge. The aim of this contribution is to familiarize engineering teams with the specific methods and tools of PSD, and to reconsider the value of sound as a product design specification. The ultimate goal is to assist designers with the product / user interaction process and to provide an orderly review of the main approaches to PSD, also required by the socio-technological context. Thus, an introduction to existing knowledge is offered based on the description and compilation of some of the most relevant studies to date. Six different lines of work are identified that start from different scientific approaches, valuing their interest for design engineering and describing their evolution. The cited academic articles have been selected according to the following criteria: i) must have been published in high-impact journals, included in the Web of Science (WoS) or in a design journal, peer reviewed, and prioritizing those with the highest number of citations, regardless of geographical origin; ii) must contain the word "sound" (or variations) in the title, indicating the authors' commitment to the concept. The result is a map of 54 publications classified in six blocks according to the original field of study and the approach to the concept of "sound and design" (Figure 6). The map distinguishes between theoretical studies and methods or tools. This work was originally presented in Spanish since there is hardly any literature in this language. However, the nomenclature of the different blocks refers to the most characteristic english terms, useful for searching databases such as WOS or

SCOPUS. Thus, this contribution serves as a starting point for future research capable of generating new tools and methods, concluding with some considerations for those who seek to advance in this discipline.

2.- SOUND STUDIES REVIEW AND ITS APPLICATION TO PRODUCT DESIGN

Specialized literature generally studies the physical nature of sound and its effects on product performance. In particular, how variations of certain physical parameters affect the user's experience and perception of everyday products, food, or interfaces. But although psycho-physical methods and psychoacoustic instruments can measure discomfort or preference for a sound, they do not take into account the complexity of emotional / cognitive responses related to the functional and aesthetic characteristics of the product: everyday sounds cause emotions prior to their cognitive interpretation that influence how a listener perceives a sound. Thus, assuming the complexity of the object of study and the substantial differences between the disciplines of origin, the lines of work are grouped into six blocks: *sound quality; sound quality 2.0; product sound design and experience-driven sound design; sonic interaction design; and sound & systems design*. Each block describes the progress made as a chronological structure. The most relevant bibliography is thus summarized, differentiating its context, disciplines involved and respective contributions. The result is a map or graphic representation of the research field that shows its evolution and facilitates its analysis.

2.1.- "SOUND QUALITY". THE ACOUSTIC ANALYSIS AND THE PSYCHOACUSTIC CORRELATION.

Fig. 1. The acoustic analysis and the psychoacustic correlation. Map of contributions.

The tool of semantic differential is the starting point to study the structure of meaning (Figure 1). The first studies analyze the formation of judgments on everyday objects from the general field of perception, to later relate it to its acoustic properties [3,4]. His research focuses on a limited set of everyday sounds that are studied in depth. The spectrum / temporal properties of the signal are analyzed from the science acoustic (applications of high and low frequencies or temporal properties in the identification of the sound). From the social sciences appears the concept of soundscape. The auditory and perception system in humans adapts in response to natural stimuli to detect information that alerts of situations of danger or distress, or as a response to protection and survival needs. In its application to product design, sound is one of the common channels of communication of critical events. The

psychoacoustic approach is used to measure the level of sound acceptance or the level of (un) pleasure it causes. However, the emotional effects of sound are not restricted solely by psychoacoustic values (eg., a sound is sharp and therefore unpleasant).
One of the most important contributions of this period is Gaver's *The Sonic Finder* audible interface, designed to communicate the most relevant events of the Macintosh computer desk [5]. Inspired by real sounds, their sound representations transmit information analogously to visual icons, being a pioneer in the use of sounds to facilitate user / machine interaction.

2.2.- "SOUND QUALITY 2.0". ANALYSIS AND EVALUATION OF PERCEPTION AND HEARING COGNITION.

Fig. 2. Analysis and evaluation of perception and hearing cognition. Contribution map

The theoretical start from acoustic, perceptual and cognitive perspectives demonstrates the need to broaden the field of analysis and achieve a hybrid theory for the characterization of sounds, as well as the importance of contextual information, especially for sounds with high causal uncertainty. The investigations (*Figure 2*) focus on the analysis of the potential meanings associated with simple sounds. The term *trendsons* appears to refer to the design and hierarchy of the sounds necessary to monitor workspaces [6,7], and the potential of different notifications to communicate warning or alarm messages (auditory alarms / warnings) is studied. Acoustic parameters are modified and the perception of the degree of urgency or importance is evaluated. In addition, some studies appear that consider the semantic level of sound [7]. [8] review the definition of the term *sound quality* (indicated on our map as *sound quality 2.0*) defining a set of *qualities* which imply the adequacy of the product and its sound to a series of preset specifications.

For decades, acoustic engineering was limited to reducing the energy emitted by the product in terms of dB, (volume). The multidimensional character of the product sound is now considered, covering the physical event (acoustic waves) and the auditory event. The observation of the cognitive process of judgment replaces the process of psychoacoustic measurement and the block "cognition, action and emotion" is added, linking the perception of physical attributes and their judgment. The auditory perception relies on a complex interaction between auditory, non-auditory stimuli, the expectations of the listener and their mood. For future contributions, 3 levels of knowledge and experience are defined for the study of sound. Thus, the so-called sound quality is defined by factors i) physical, ii) psychoacoustic and iii) psychological. According to this, it would be impossible to define a global method to evaluate any sound without considering cognitive influences (the image of the sound source: it is a sports or a family car), factors related to the situation in which the product emits the sound , the user / source interaction (we expect an acoustic reaction when we accelerate a car) and the user experience (their expectation can influence the evaluation), as well as the multidimensional nature of all these factors.

As an alternative, [9] proposes the evaluation of a specific type of sound in a specific situation, keeping all non-acoustic factors constant, so that the different evaluations result purely from acoustic variations. [9] Classify the methods of signal analysis (level, spectrum, etc.) and a set of psychoacoustic indices that allow an instrumental prediction of attributes in the process of sound perception (loudness, roughness, sharpness, tonality, pitch); as well as indexes for global measurements (pleasure, discomfort, sound quality ...). The semantics of sound acquires relevance from the study of the meanings associated with 3 groups of differentiated sounds: *sound sounds, environmental sounds,* and *musical sounds* [7]. It is evident that the meaning of the attributes varies depending on the context of study [10].

Bodden uses the term *Active Sound Design* to refer to the sound not resulting from the operation of the product (it will receive other future meanings). Depending on the operation of the product presents two disadvantages: i) it limits the possibilities of sound design, and ii) it generally translates into an increase in costs by implying modifications on the source (changes in mechanical function). The options are thus extended considering as an alternative the sounds generated and superimposed on the original sound. [11] considers the sound superimposed on appliances as an opportunity for differentiation from the competition. The number of attributes assignable to the product sound is expanded and quantitative methods are presented to assess its suitability. Lyon proposes to list the descriptive words of the sound (lexicons) according to: i) those that produce the sound (the bell); ii) those that describe the response to sound (alarm); and iii) those that describe the sound itself (the hum).

The relevance of these contributions lies in the acceptance of the multidimensionality of the product sound, which requires knowledge of three areas: i) *acoustics*, and their study from mechanical engineering; ii) *psychoacoustics*, or relations between acoustic input and perception; and iii) *cognitive*, such as the psychological processes that guide the judgment of the qualities / quality of sound. The combined study of these three levels defines the concept of *quality of sound 2.0*, but research continues to focus on how the variation of the signal allows to predict psychoacoustic parameters.

2.3.- “PRODUCT SOUND DESIGN” AND “EXPERIENCE-DRIVEN SOUND DESIGN”. THE ROLE OF SOUND IN DESIGN AND PRODUCT EXPERIENCE.

Fig. 3. a)Product Sound Design y b)Experience-driven sound design. Contribution map

The congruence between the concept of product and the combination of its visual, auditory, tactile and olfactory properties attributes to it the meaning it deserves. The consideration of auditory properties as another key aspect to be developed is generalized under the term "*product sound design*". From here (Figure 3a), various contributions observe the lack of theoretical references and specific tools to implement the sound when designing a product. The perception of hedonic attributes of the product is considered as a complex set of sensory experiences, whose components are identifiable and quantifiable. [12] suggest a method of sensory evaluation to analyze the relationship between the physical characteristics of a product and the perceived hedonic attributes. As a quantifiable method of the emotional quality of a product, [13] consider the different sensibilities of the users according to gaps in perception and their own individual ambiguity. In contrast to the approach that generalizes human sensitivity using average statistical results of sensory tests, new methods quantify emotional quality from the analysis of differences between listeners [14].

Terms are provided that differentiate the sounds derived from the functionality of the product from others specifically carrying meaning [1]. The first, *consequential sounds*, produce complex sound waves (without sinusoidal form), lack a temporal-spectrum structure and the user understands them as noise. However, the consequential sound of a washing machine also provides information about its washing cycles. *Intentional sounds* are selected or made with a communicative purpose. They have a defined spectrum-time structure, are musicalized and imply meanings for the user (in the case of a traffic light: "you can pass"). Both can support functional or hedonic meanings, while some being more specifically associated with one type of sound than the others. When giving importance to the semantic association [15, 16] it is considered that any sound emitted by the product should be foreseen to anticipate the user's response, orienting the design towards those values that we wish to communicate [16,17]. This ensures not only user satisfaction, but also that users´ response guarantees the fulfillment of the assigned mission.

The studies cover the complementary roles of the auditory experience and the user's response [18], (Figure 3b). The adequacy of the quality of the product sounds leads to an improvement in the experience both ergonomically and emotionally. PSD is finally considered as a multidisciplinary activity that relates psychology, engineering and acoustics with hybrid disciplines such as psychoacoustics and musicology [19]. The overall product sound experience integrates the emotional [20], semantic [21] and sensory [22,23] experience. Sound no longer has only a utilitarian function. The multimodal experience in which sound is combined with other sensory modalities, allows alternative feedbacks and facilitates the understanding of the message in different contexts, and for different users. For example, sound notifications are combined with visual alerts in the car navigator to adapt to the most critical driving conditions [20]. The sound of the product can reinforce brand values by complementing corporate graphic image resources, and plays a cultural role capable of inviting and excluding users.

2.4.- SONIC INTERACTION DESIGN. THE USER-MACHINE INTERACTION THROUGH SOUND.

Fig. 4. Sonic interaction design. Contribution map

The *screen-based interfaces* for human-machine interaction have been widely analyzed from the field of computing and the psychology of perception [24], which deserves its consideration as a specific block (Figure 4). The current interfaces integrate more efficient, usable and productive sensors, actuators and computing units. In a context in which the visual medium predominates, sound is a common complementary channel in user-machine interaction. *Sonic Interaction Design* (SID) explores the way in which sound can transmit information, meaning and aesthetic and emotional qualities in digital contexts. It is a discipline that combines the design of sound displays, sonification methods as a means of data representation, sound and musical computing and the study of the underlying processes of perception and action [25]. Based on the knowledge available in these fields of study, the SID community proposes the design process based on the iteration of the stages of sketching, prototyping and evaluation, and advocates the confluence of disciplines that add value to sound design solutions in the interaction experience [24, 26, 27].

2.5.- SOUND AND SYSTEMS DESIGN. THE CRITICAL SOUND.

Fig. 5. Sound and systems design. Contribution map

More and more products integrate intelligent data management systems, capable of being shared for different purposes and user profiles [28]. This implies a high number of events to be communicated, so the sound channel is very profitable i) in those cases where visual attention is not guaranteed, ii) as a resource for differentiation or iii) when the message contains different layers of information. For example, a warning light indicates that we should use the car's seat belt and a variable sound provides a nuance of urgency. Sound is especially valuable in critical and technologically advanced contexts (such as ICUs, aviation control towers or nuclear plants) where communication through alarms is common for operators [29]. In these high demanding environments, alarms must be designed so that they accurately represent system messages and also cause the required action according to the level of criticality of the event [30]. In critical contexts, not responding to an alarm properly can imply consequences as important as the loss of life or the abortion of a mission.

In recent years (Fig. 5), efforts are focused on characterizing communication processes in highly demanding environments, equipped with new data processing solutions. The user's response to the alarm is studied and obstacles are identified for the fulfillment of the mission. In the latter period, the study of sound fits into a holistic approach to the product (system or service), unifying knowledge and seeking common languages for the exchange of information [31, 32].

3.- RESULTS AND DISCUSSION

From the theoretical and empirical research compiled, there is a trend to focus on the analysis of the acoustic and psychoacoustic quality of sound, considered as an isolated characteristic of the product. This perspective is justified because human hearing is based on common physiological reactions, and the psychoacoustic response corresponds to a predictable sensory level. However, these metrics do not consider the meaning of a sound, and a complete product experience requires congruence between the concept and its sound properties at a functional, aesthetic, sound quality and emotional level.

As a partial response to this need, alternative perspectives appear that explore how sounds caused by real events or objects involve semantic associations related to the listener's life experience; and studies on product sound perception that appreciate differences between sensory judgments and semantic or meaning attribution, which advances that the attribution of meaning to a sound results from the sum of perceptual and cognitive elements during stimulus processing.

Understanding the complexity of associating meanings with the product sound drives to a third phase of the PSD. It is studied how the modification of the auditory signals associated with the operation of the product influences the user's perception of its qualities. Going deeper into this possibility, it is observed that a sound can be associated with the identity of a brand, at the same level as a corporate graphic resource. Sound can be designed to attract the consumer from a more complex emotional level, contributing to connote a series of complementary attributes or qualities. This appreciation allows us to assess the enormous potential that sound design has for the industry.

From now on, the study of sound for its application to product design is shown as an activity that integrates knowledge from a variety of disciplines, which leads to a remarkable growth in the number of scientific contributions from different approaches. One of the most promising comes from communication theories. The fields of acoustics, psychoacoustics, mechanical engineering, psychology, ergonomics and musicology contribute significantly (from proven methods and tools) to the optimization of the design of a product sound. But the theory of communication provides an integrating vision that allows all these aspects to be linked to each other and relate them to the subsequent emotional response and / or on the user's level of action. This multidisciplinary vision is especially relevant in critical environments, where the complexity and volume of information are high, and where there is a need to prioritize events according to their urgency and criticality.

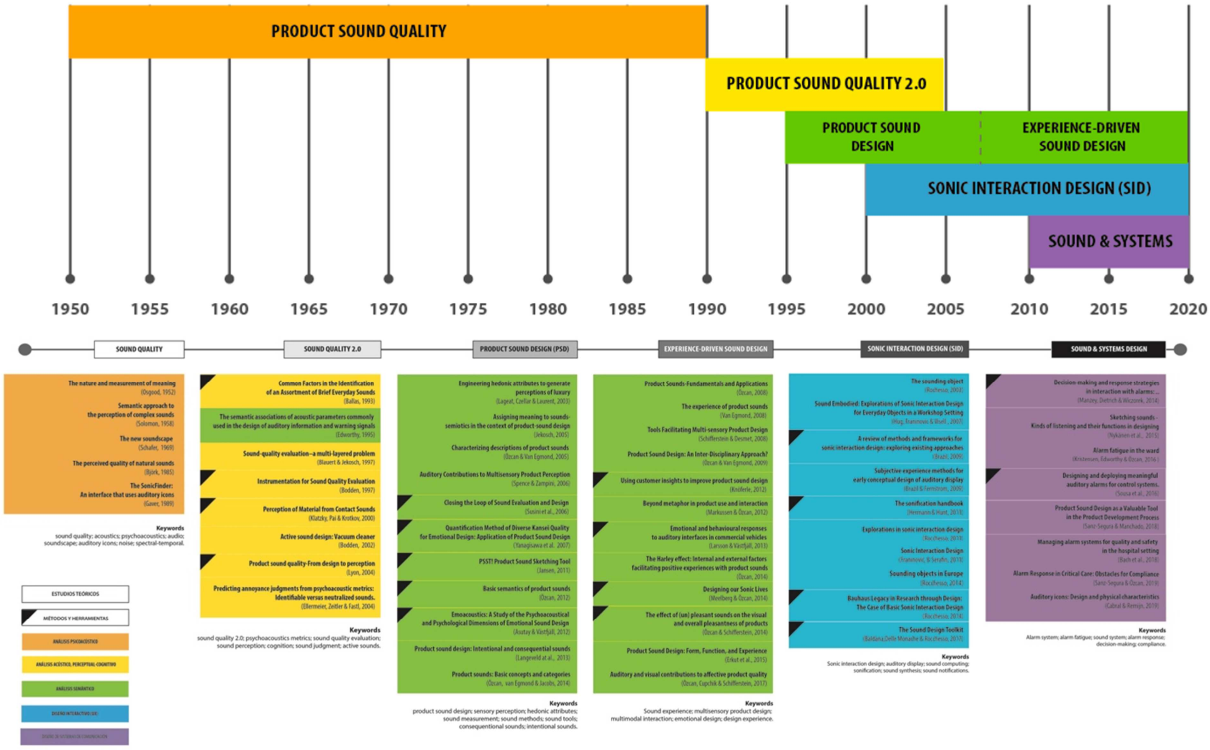

Fig. 6. Retrospective of sound studies applicable to product design.
Chronological chart of fields of sound study and unified map of relevant contributions.

4.- CONCLUSSIONS

Sound has a recognized value and potential as a communicative resource for product / user interaction. In spite of this, knowledge of the main theoretical and practical contributions existing is still scarce among the design and development teams. Proof of this is the practical absence of accessible literature in languages as common as spanish that facilitates its dissemination among development and research teams related to engineering in general and industrial design in particular. Especially from the perspective of perception and experience of use resulting from the user-product interaction. Similarly, design engineering lacks academic and professional level of a vocabulary agreed and validated in the field of sound applied to product (not even in english). As in other disciplines, the consolidation of knowledge and experience in the field must precede the establishment of a common and homogeneous language; or at least, unanimously in the way of designating certain parameters, in terms of nomenclature, methods, tools, and the applicable methodology itself.

From the review and analysis of the literature specialized in design and sound studies, a map of publications has been presented that includes, from its beginnings to the present, a retrospective of the most relevant studies and milestones in this field of research, applicable to the field of design engineering, and classified into 6 large blocks. This contribution provides the starting point and general knowledge base for researchers, professionals or design engineering students who wish to explore this field of study. This knowledge is especially relevant in today's socio-technological contexts, which demand the development of increasingly complex interfaces, and methods and tools to evaluate the efficiency and congruence of the sounds assigned to the different functions of the new products.

The evolution of the research compiled shows that the process of assigning sound to a product, on which its practical utility depends, ultimately lies in an adequate characterization of its communicative capacity. As a summary, the analysis of this ability to communicate implies a holistic vision that combines the different disciplines of study: i) the sound must be recognized and identified by the user from the characterization of its physical properties ii) must be able of transmitting the functional characteristics, mode of use, and attributes of the product and iii) must trigger a complex cognitive process that will end with the development of the action or response required to the user.

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