Psychoacoustic metrics for assessing the quality of automotive HMIs’ impulsive sounds

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\begin{abstract}
Designing an automotive Human Machine Interface (HMI) falls into a resource intensive and iterative prototyping process, where design inputs also emerge from subjectively evaluating the products. These inputs are defined from the outcome of the automaker’s brand sense appraisal process: achieving a desired and holistic perception of product experience. This work aims at characterizing the acoustic feedback of mechanical push–buttons’ prototypes, parametrizing their sound by an array of acoustic and psychoacoustic parameters. A review of literature published in automotive sound quality was performed, specially addressing impulsive sounds. From this review, a list of metrics for both temporal and spectral content stands as a contribution to methodologies addressing impulsive sounds.

This research made use of a Design of Experiment (DOE), producing 18 minor variations of an automotive push–button, designed for affording different haptic feedback. Yet, the DOE impact on acoustic emissions remained unclear. An experimental procedure allowed the prototypes’ sound characterization with acoustic and psychoacoustic metrics. Parametric data was analysed to assess feedback consistence within each design and sound differences among design variations. The work includes an interpretation of results with perceptual thresholds, including Just–Noticeable Differences (JNDs) for the hearing sense. This work also found discrepancies and reports different interpretations of results when comparing SPL with loudness models, and standardized loudness models with a psychoacoustic model specific for impulsive sounds. It was concluded that both sound duration and the nature of fast-decaying impulsive sounds explains the different results among loudness models. Despite numerical differences, the introduction of JNDs in the interpretation of results showed that the design variations of the prototypes almost do not introduce noticeable differences in the psychoacoustic feedback. Exceptions were found in some designs for a single metric, sound duration.

1. Introduction

In product experience, vision is the primary sense modality used during the act of purchasing and product evaluation [94]. However, in time, both sound and touch actually dominate product experience [32,33].

Product sounds form a particular perceptual subdomain of the environmental sounds [95], chap. 3). Moreover, the structural properties for both the temporal and spectral domain affects how the sound is recognized and later remembered [77]. Product sounds go beyond the sensory domain and provide both cognitive and emotional experiences [8,9,37,76,77,112,120]. Sound design holds particular relevance when the acoustic emissions of a product aim at representing a meaningful interaction feedback. This association of meaning to sound should be a goal introduced in the design process [112].

Product’s physical properties, energy released, and loads applied affect the spectral and temporal properties of its acoustic emissions [58]. Sound is an intrinsic property of a product [78] and changing the sound requires changing the product [77]. However, changing the product may or may not, perceptibly, change the sound it affords. In either case, sound should not be a mindless consequence of a product’s physical output but a part of its design process. Moreover, sound design must be part of emotional design [17,21,22].

If a product affords interactions that integrate acoustic emissions, such sounds contribute to user experience and they can be a subject of brand sense requirements. In this research, it is acknowledged that, when part of the brand sense emerges from acoustic and psychoacoustic parameters, these could then be used as well-defined design requirements. However, knowing which acoustic parameters are relevant for assessing feedback sound quality is a research task by itself.

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https://doi.org/10.1016/j.apacoust.2018.03.007
Received 20 March 2017; Received in revised form 7 January 2018; Accepted 7 March 2018
Available online 23 March 2018
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This work makes use of a case-study, an automotive HMI in development stages. For this product, mechanical push-buttons were designed to afford perceptually different haptic (active touch) feedback. However, these had to conform to a pre-determined brand sense for its acoustic emissions. Whatever design variations were introduced in the prototypes, no perceptually different sounds from a reference design could be accepted. As such, this work aims at selecting and defining an array of acoustic and psychoacoustic parameters, sufficient to characterize rapid decaying acoustic emissions, i.e. impulsive feedback sounds, commonly found in automotive interfaces. Furthermore, the work aims at identifying perceivable sound differences in measured acoustic feedback by interpreting results with human hearing thresholds for each metric. The array results from a literature review in acoustic metrics and psychoacoustic models, as well as previous research from the automotive industry. In order to allow an interpretation and comparison of data from the perceptual perspective, the work is complemented with a literature review of just-noticeable differences in sound perception.

By measuring prototypes acoustic feedback and characterizing acoustic emissions with selected metrics, it should be possible to sufficiently assess sound differences within multiple interactions for the same prototype, evaluating feedback coherence; and among different prototypes, assessing feedback differences. Moreover, if a desired feedback sound is sufficiently defined by the proposed array of parameters, it is also possible to understand which acoustic emissions may fall numerically and perceptually outside a specific brand sense. In the end, by applying it to a case study, this research work aims at providing a sound quality evaluation methodology and an associated experimental procedure, possible to be used in design processes and production quality control for automotive interfaces and other HMIs affording impulsive sounds.

1.1. Automotive product sound quality

The automotive context holds special considerations for sound design, with multiple multimodal excitations, resulting in both intentional and consequential sounds [58]. The automotive interior products specifically aimed at providing feedback and interactions to driver and passengers, e.g. Human-Machine Interfaces (HMI), are designed to be operated in a dynamic and noisy environment. Thus, typically, automotive HMIs are multimodal. Vision remains the dominant modality to interact with automotive HMIs [91,99]. Yet, according to available standardization [50,51,52,113], HMI interfaces for secondary and tertiary tasks [107] should be designed to integrate non-visual multimodalities, with the purpose of minimizing cognitive workload and reducing further driving distractions.

HMIs commonly incorporate interfaces, such as push-buttons, rotary switches and sliders. These functional interaction sub-systems have their inherent functional mechanical behaviour providing multimodal feedbacks: force and displacement feedback, auditory cues and visual light indications [9,88]. Auditory cues provide perceptual representations of events in the environment [39], thus should afford a confirmatory feedback of the interaction. Cross modal effects in push-buttons were also found to physically change and improve the interaction [3], with sound augmenting the tactile experience [58].

Publications regarding the influence and adequateness of haptic or acoustic feedback in automotive HMI is scarce [89]. Studies regarding auditory cues in this context include Spence and Zampini [101], Lee and Spence [60] and Treiber et al. [110]; or Politis et al. [86] regarding both vision and the former senses. Damiani et al. [20] and Rydström et al. [90] provide an overview of current automotive trends on human-vehicle interactions.

Beyond driver performance issues, automakers have also understood that interactions between a user and an HMI are a mean to integrate and convey their brand sense [63]. Automakers aim at affording an interaction with their products, distinguishing them from competitors. Specifically, a user should perceive the behaviour of a product as belonging to a certain brand identity. Moreover, by continuously implementing specific feedback along the entire brand’s product line and throughout its evolution in time, the brand sense itself emerges and becomes recognizable [67]. Here, product appraisal [22], brand coherence and experience consistency [96] are fundamental goals, especially for luxury brands [42].

With emotional requirements embedded in the design of automotive products, manufacturers face experiential design challenges from complete sub-systems for HMIs [37,117,118] Technical and design specifications, written in the form of engineering parameters, can define, to some extent, product attributes that address emotional experience and brand sense [66,67,117]. Also, in product experience, it is necessary to consider non-parametric sensorial cues and emotional or satisfactory qualities. However, when these are translated into design requirements [64], they can remain uncertain, informal and not entirely defined [102]. In fact, engineering parameters won’t be sufficient to fully characterize how an interaction is actually perceived [104,115]. Experience requirements are ill-defined in nature, sometimes conflicting among themselves or other requirements [16]. Furthermore, and specifically for sound design, the industry restrains information regarding both tools and methods [77]. The emotional aspects of a product with ill-defined requirements tend to remain vague within the communication between the automaker and its suppliers. In this relationship [4], scheduled evaluation activities are commonly agreed to achieve the full acceptance of a product. When emotional expectations are included, both experimental measurements and perceptual evaluations are performed upon prototypes. In these processes, plagued with uncertainty, resource exhaustive iterations overwhelm the suppliers and the design process itself.

In this research, the feedback afforded to the hearing sense by an automotive HMI is, by itself, an object for quality. The present case-study is a set of push-buttons resulting from a Design of Experiments (DOE). The prototypes have been subjected to design changes to their functional components. While their haptic feedback is intentionally different, their consequent acoustic feedback should not significantly differ from the desired sound. In fact, these consequential sounds should meet the expectations for cognitive experience, the perception of a successful interaction; and an emotional experience, an appraisal for the product itself, as part of the automakers identity. However, product specifications given by the automaker fall short on providing sufficient information as to correctly achieve this sound in early design stages. Experimental and sensorial analysis methods are, thus, performed at the automaker, resulting in an approval/rejection process. This results in a resource exhausting trial and error method for the supplier.

However, if the supplier knows a reference sound conforming to its client automaker expectations and makes use of sufficient acoustic parameters to characterize it, it should be possible to reduce these iterations. Furthermore, psychoacoustics models can be involved in the translation of physical metrics into perceptual metrics. Interpreting these metrics with models of human perception thresholds, just-noticeable differences (JNDs) for this sensorial modality allows identifying perceptual similarities or disparities.

1.2. Metrics for automotive impulsive sounds’ quality

In a literature review, Peeters [84] presented 166 acoustic parameters retrievable from an audio spectrum alone. These are acoustic metrics only. Many more can be added from psychoacoustics [82].

The design of car sounds is widely known ([95], chap. 5), from engine performance to door latches closing sounds that enhance perception of overall quality. The improvement of products’ sound quality led to develop metrics specifically formulated for applications, contexts or even industries. Cerrato [14], in a context specific review, offers an overview of acoustic metrics for automotive sound quality. Duan et al. [27] propose a prediction model for sound quality for automotive
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