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Original
Sensory evaluation of the sound of rolling office chairs: An exploratory study for sound design / DAL PALU', Doriana; Lerma, Beatrice; Actis Grosso, Luca; Shtrepi, Louena; Gasparini, Mauro; DE GIORGI, Claudia; Astolfi, Arianna. - In: APPLIED ACOUSTICS. - ISSN 0003-682X. - STAMPA. - 130:C(2018), pp. 195-203. [10.1016/j.apacoust.2017.09.027]

Availability:
This version is available at: 11583/2684836 since: 2018-08-29T10:53:06Z

Publisher:
Elsevier

Published
DOI:10.1016/j.apacoust.2017.09.027

(Article begins on next page)

Sensory evaluation of the sound of rolling office chairs: an exploratory study for sound design

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Abstract
Only an infinitesimal part of the sounds from everyday objects that surround us has been designed specifically. This study has dealt with a sensory test for sounds produced by objects interacting with other objects, which can be performed during the concept design phase, where only some parts of the product can be tested. The aim of the study has been to prove the reliability of this preliminary test and compare it to the full-product test condition. The concept for an office-chair was considered, and the sound of a chair-wheel moving across flooring tiles was tested as a simplification of chair-flooring interactions. Sixty participants took part in a listening test and described the acoustic stimuli of the wheels of two office chairs, one of high quality and the other of low quality, rolling over polyvinyl chloride (PVC), ceramic and wood floorings. The listeners were asked to assign descriptors to stimuli from a list of 26 adjectives, according to a forced ordered scale. Comparisons were made with sounds from the rolling of real office chairs. The sound of wheel rolling was prevalently judged "rough" on ceramics, "dull" on PVC and "smooth" on wood, and some cross-modal audio-tactile verbal interactions between the sounds and flooring surfaces emerged. No statistically significant difference was found between the concept and full product test conditions, thus proving the efficacy of the concept sound test during the early design phase.

Keywords
sound design; sensory evaluation; sound descriptor; office chair rolling sound; office environment; flooring

Highlights

- The SounBe toolandmethod has proved reliably in assessing the sound quality of a concept sound;
- The quality of perceived sound, e.g. dull, rough, smooth, can be assessed before prototyping;
- The influence of flooring on the rolling sound of office chairs has been proved both using SounBe and analytically;
- Cross-modal audio-tactile verbal interactions, e.g. wood-rough, smooth-ceramics, have emerged.

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1. Introduction[1]

Everyday life is made up of sounds. Every action a person makes contributes to the creation of a soundscape [1], which is composed of feedback sounds, mechanical sounds, digital sounds, etc. However, it is known that only an infinitesimal part of the sounds to which we are subjected has been designed specifically, with the consequence of people having to cope with ever-increasing noise pollution on a daily basis. Several studies have in fact demonstrated that indoor sound sources, such as scraping sounds from tables and chairs, can affect the global perception of annoyance of the indoor sound environment [2]. The possibility of not only controlling, but also of preventing environmental sounds therefore has a direct impact on human well-being. However, specific tools are required for this purpose.

1.1 Sound descriptive tools

Apart from the acoustical tools that are based on sound wave frequency and amplitude parameters, several other tools have been created to facilitate multi-sensory product design [3], in which particular attention has been paid to the description of the perceived quality of a sound [4,5]. These sound design tools are usually based on sensory tests, and in general adopt semantic differentials [6-9]. Others, instead, adopt descriptive techniques derived from to the well-known food sensory evaluation discipline [10]. For example, in Quantitative Descriptive Analysis (QDA), and specifically in the Individual Vocabulary Profile (IVP) test, participants are required to draw up a consensus vocabulary [11]. The IVP test has been applied and exploited extensively to describe the subjective evaluation of concert hall acoustics [12,13]. On the other hand, tests such as the Sensory Spectrum, which involves participants using a standardized word list [14], are employed in contexts such as wine testing [15]. Since the generation of a consensus vocabulary is a time-consuming procedure, the use of a standardized word list is frequently preferred in product sound quality investigations [16].

Furthermore, two different approaches to the design phase in sound quality investigations can be mentioned: the *ex ante* and *ex post* approaches. Sound quality investigations are usually undertaken on existing, i.e. already produced prototypes or products [17]. When this approach is adopted, the sound design issue is taken into consideration just *after* the design phase. This entails a very long time-to-test, i.e. from the sound design phase to the product testing, as well as very high costs for the test-retest prototyping [18].

As a result of these problems, a "toolandmethod", i.e. a physical device, which is also a working protocol that can be used to perform quali-quantitative analyses, has been developed. This device can be used for the acoustic and sensorial analysis of materials and products during the concept design testing phase [19]. Starting from the assumption that materials are the element in common of any product, allows the sound quality of a product to be assessed without the need of the prototyping phase, with the benefit of shortening the time-to-test and reducing the redesign costs. This toolandmethod has been the subject of a complex experimental campaign, first aimed at verifying the robustness of the device, considering different descriptive methods [9], and then at establishing its effectiveness throughout all the design phases.

In a recently published study, which may be considered as complementary to the present one, a semantic differential technique, applied to office chair rolling sounds produced by the SounBe physical device was tested. The study had two aims: to compare the results of listening tests with semantic differential scales in context, laboratory and SounBe conditions, and to verify the validity of the semantic differential scales on sounds generated with the new tool [9];

In the present exploratory study, the overall effectiveness of the patented toolandmethod has been tested, i.e. taking into account both the physical device and the descriptive protocol derived from the Sensory Spectrum [14]. An experimental application of this sound design method to two different phases of the design process, i.e. the concept phase and the final product in action, thus representing the *ex ante* and *ex post* approaches, respectively, is presented. A real case study has been considered as it may be of interest to firms, researchers and designers.

1.2 Office sounds as a testing ground

[1] The following non-standard abbreviations are used in this paper:
PPTC = Prototype or Product Test Condition; CTC = Concept Test Condition; HLC = high level chair; LLC = low level chair.

The office soundscape was selected as the most suitable testing ground for this work because of the ever-increasing number of hours per day spent in offices, and because of the existing relationship between the acoustic conditions of the work environment and workers' health, job satisfaction and wellbeing [20]. The study specifically focused on an accidental temporary and unpredictable activity sound that is always present in offices: the rolling sound of a chair. This sound was chosen considering the high number of minor and micro-movements performed every day by a seated office worker, which are known to be an important source of annoyance in an office [21]. Moreover, the non-stationary and unpredictable nature of these noises [22] has been proved to have a negative effect on working comfort [23], performance and fatigue [24,25]. Furthermore, non-stationary noises in the workspace have been investigated much less than stationary ones [26], and there is still a gap in literature concerning the office chair rolling sound. On the other hand, an extensive amount of literature on the perception of outdoor rolling sounds, e.g. from vehicles, already exists [27-30]. Finally, a new approach towards environmental sound control concerning office furniture is currently under investigation [31], and increasing interest towards the sound design of furniture in different living environments has been observed [32-34]. The application of the concept phase sound design method [19] to the office chair rolling sound represents, for all the above-mentioned reasons, an opportunity for those industries that produce office furniture and flooring to manage the sound sources of their products and improve the indoor acoustic environment of offices.

The aim of this work is to verify the effectiveness of the aforementioned method in two "extreme" conditions, i.e. in the concept testing phase, compared with the more frequently adopted method, which is based on the study of a real prototype or product sound. This has been accomplished by adopting a sound quality investigation approach, derived from the Sensory Spectrum technique [14], based on the selection of three main attributes connected to a sound, taken from a list of standard descriptors. Whether no statistically significant difference occurred between concept and full product test conditions, the efficacy of the concept sound test from the early design phase will be proved.

2. Materials and methods

The present study is a second, complementary part of a wider experimental campaign; the results of the first part have already been published [9]. In the first part of this experimental campaign, the relationship between objective data, i.e. L_{Aeq}, L_{AFmax}, Loudness, Sharpness, Roughness, Fluctuation Strength and Tonality, and subjective data, i.e. ratings on semantic differential scales such as calm-strident, pleasant-unpleasant, smooth-rough and not annoying at all-very annoying, pertaining to the rolling sounds of office chairs was investigated. The research method on which the second part of this study was based instead consists of a comparison of qualitative data, collected during an experiment performed under two different test conditions, that is, with real office chairs and flooring and with a headphone listening test.

2.1 Test conditions

The test was performed, considering the two sound quality investigation methods, under the following two conditions:

- PPTC (Prototype or Product Test Condition)- in this condition the participants were asked to evaluate and describe six different sounds they made while sitting on real office chairs and moving across paved platforms in a dead room, i.e. a silent and soundproof room [17]. Overall, the participants were able to experience, i.e. ecologically perceive [35], the chair and the flooring (not only from a listening point of view, but also visually, haptically, etc.);
- CTC (Concept Test Condition)- in this condition the participants were asked to evaluate sounds, which had previously been produced with a simplified procedure, using a new tool [19], i.e. regardless of the chair. In this condition, the sound of a chair-wheel moving across flooring tiles was produced by an external experimenter in order to simplify chair-flooring interactions. The produced sounds were recorded and then delivered to the participants in the test through headphones. No visual information on the chair or on the flooring was provided to the participants.

The innovativeness of the approach adopted in CTC is that a predictive patented toolandmethod, called SounBe [36], has been adopted to generate a sound, based on the three generating variables of each mechanical sound source: the material, the shape and the gesture. This toolandmethod was conceived to support architects and designers in the delicate meta-project phase of choosing the best material for an object, taking into account the sound aspect as a fundamental project requirement, as well as to assess the sound quality of a product. The physical toolkit is housed in a suitcase-type container. It consists of a variety of instruments that are used to ''sound'' material samples and products (i.e. sticks and resting planes of different materials, a measuring cup, some support bars, etc.), and it allows sounds to be collected and resubmitted to a listener by means of a microphone and headphones. The method, i.e. a protocol, was conceived to analyse and design the sound of an object that interacts with another object through a simplified procedure that splits the sound into its three generating variables, i.e. the material, the configuration form and the exciting mode interaction [9]. A product sound can be generated repeatedly with this toolandmethod, qualitatively assessed and designed before the prototyping phase. For example, the clinking sound of a spoon hitting against a cup can be simplified and approximately recreated by hitting a steel stick against a ceramic plate, thus avoiding the necessity of having a real cup and a real spoon. Once the sound has been obtained from the generating variables, a sound profile can be defined through a standard descriptive procedure derived from the sensory evaluation discipline [36]. It is well known that a specific and shared vocabulary is necessary to verbalize the characteristics of sounds [37]. Semantic descriptors that are used to define the sensorial recall produced by the sounds themselves, are then attributed by a testing panel. Each sound is matched to the descriptor that has been judged the most suitable, and each sound-descriptor matching can be used by architects and designers as starting information on sound perception. In this way, it is possible for sound stakeholders to forecast consumers' perception on the sounds of a product and then design the product, taking into due consideration the results of the test, in the concept design phase.

2.2 Adopted materials

Several materials and objects were collected and adopted, or built *ad hoc*, in order to set up this study.

2.2.1 Office chairs

Two operative chairs were identified as being suitable to represent the typical Italian office chairs (which comply with the UNI EN 1335 norm), on the basis of data on office chair sales in 2014 by Assufficio (the Italian association of office furniture and accessories) [38]. Two types of office chairs were considered, one to represent a high quality level (reported during the experiment as "chair A" and here called HLC) and another to represent a low quality level (reported during the experiment as "chair B" and here called LLC). The levels of the chairs were established on the basis of their selling price and their construction characteristics. Apart from the use of different materials, HLC and LLC also differed from the wheel equipment point of view. HLC was provided with damping wheels, which had a soft rubber covering; LLC was instead provided with non-damping wheels and no rubber covering. Both chairs were used for 30 days before they were examined in the tests, in order to simulate the wear condition of an office chair.
Both the complete chairs and the single wheels were tested in PPTC and CTC, respectively, during the experiment. In CTC, the two office chair wheels were equipped with a handle to facilitate the handgrip (Figure 1).

2.2.2 Floorings

Three flooring materials, representing some of the most common paving systems in the Italian office landscape, that is, polyvinyl chloride (PVC), ceramics and wood, were selected for the experiment.
Three walkable platforms were prepared *ad hoc* for PPTC. Each walkable platform was made up of an Oriented Strand Board base (2500 x 1250 x 9 mm) equipped with a holding frame, a specific surface paving material and a low-density polyethylene foam underlayer (2500 x 1250 x 3 mm) to reduce vibrations between the platforms and the floating grid in the dead room. The surface area of each platform was paved with each material, in order to create a sort of "runway" on which several different sensory tests could be performed. 'PVC tiles' were arranged in a checkered scheme and fixed to the base with a universal self-flattening

adhesive; 'porcelaingres tiles' were also arranged in a checkered scheme, with 2 mm spacing, and fixed with silicone sealing; finally, 'laminated wood' was assembled with a snap mounting system, according to a deck scheme, and fixed with a Polyvinyl acetates glue.
In the same way as for the office chairs and the office chair wheels, both platforms and the single flooring tiles were tested in PPTC and CTC, respectively, during this experiment (Figure 1).

Figure 1. The materials tested in this experiment. In the picture on the left, the LLC and the HLC and two of the three paved platforms, provided with the wooden flooring and the ceramic flooring, placed on the floating grid. In the picture on the right, the LLC and HLC wheels provided with handles and one piece of each type of flooring.

2.3 Descriptive questionnaire

The core of this experiment consisted of a descriptive questionnaire. It comprised a descriptive procedure derived from sensory evaluation tests [39] that allowed some descriptors to be assigned to a submitted stimulus, on the basis of a forced-order choice between several adjectives presented in a random order.
Several sets of semantic descriptors have been developed in literature to describe a specific acoustic stimulus. For this study, the Von Bismarck set of descriptors, which have specifically been tested on noises and musical sounds [40], was chosen as a reference, considering that office chair rolling sounds are classified as noise. Each adjective had been translated into Italian using general [41,42] and specific [16] English-Italian and Italian-English bilingual dictionaries. Furthermore, each term was validated by a group of 3 English-Italian bilingual subjects, who selected the most suitable translation in Italian from those proposed in the dictionaries (*high/acuto; harmonious/armonico; harsh/aspro; low/basso; beautiful/bello; ugly/brutto; calm/calmo; thick/corposo; weak/debole; soft/delicato; inharmonious/disarmonico; hard/duro; loud/forte; mild/gentile; pleasant/gradevole; rough/irregolare; gentle/lieve; sharp/penetrante; powerful/potente; deep/profondo; smooth/regolare; unpleasant/sgradevole; dull/sordo; thin/sottile; strident/stridente; metallic/tintinnante*).
Furthermore, as demonstrated by Parizet and Nosulenko, the correct understanding, by the participants in a test, of the meaning of the adjectives is a crucial issue, since it could affect the final stimulus ratings [43]. Therefore, each adjective was provided with a short sentence taken from an Italian dictionary [44] in which the descriptor was presented (e.g. *dull/sordo*: "that *dull* sound was barely audible"/"quell suono *sordo* si sentiva appena").
The same descriptive questionnaire was administered under the two different conditions. The participants had to describe each chair-flooring or wheel-flooring item sound considering the whole set of the Von Bismarck adjectives, which were presented in random order, by selecting the three most appropriate descriptors and by ordering them on a 1 to 3 forced ordered scale.

2.4 Participants

A group of 60 participants (30 women and 30 men, $\bar{x}$ = 26.6 years, σ = 6.6 years) was recruited to voluntarily take part in the experiment. At the time of the test, all the participants reported normal hearing conditions and no motor impairment. A between-subject design was set up, i.e. none of the participants took part to the test under both conditions, in order to avoid boredom and fatigue as well as to prevent the participants from becoming experienced in the test. Two sub-groups of 30 randomly assigned subjects were created, one for PPTC (14 women and 16 men, $\overline{x}$ = 28.5 years, σ = 8.3 years) and one for CTC (16 women and 14 men, $\overline{x}$ = 24.7 years, σ = 3.5 years).

2.5 Recording of the stimuli and requested task

Before entering the dead room and starting the test, each participant had to fill in a general questionnaire (sex, age, hearing ability and motor ability), and was instructed on the test procedure through a series of written instructions in which the origin of the submitted sounds was declared [45].

The PPTC and CTC experiments were performed in the dead room of the Laboratory of Applied Acoustics at the Politecnico di Torino, where the background noise level was lower than 20 dB, L_{Aeq} (reverberation time at 0.5-1 kHz equal to 0.1 s). As the source of the acoustic stimuli was different in the two test conditions, the two procedures adopted in the test are presented separately:

- In PPTC (Figure 2), two office chairs were placed at the same height on three paved platforms arranged on the walkable grid. Each participant was asked to sit on a chair and move the chair across the platform, focusing on the sound they heard, and then to describe this sound by means of the adjectives listed in the descriptive questionnaire. Each subject performed the test with both HLC and LLC, on the three paved platforms (2x3), in random order to avoid any possible order effects on the results. Each stimulus was measured by means of a previously calibrated phonometer (XL2 handheld audio and acoustic analyser made by NTi Audio), arranged at a height of 120 cm from the paved platform surface (corresponding to the ear height of a seated office worker, with reference to the 95th percentile of the European population [46]), at the halfway point along the length of each walkable platform;
- In CTC (Figure 2), the previous chair-flooring interaction was simplified by the new toolandmethod [19], in which it was assumed that the chair had still not been fully designed and realized. In this case, the rolling sound source that was evaluated in PPTC was simplified by the material, configuration form, exciting mode interaction [9] as follows: the paved platform material in PPTC was the same as the material of each flooring tile adopted in CTC; the chosen configuration was that of the paving scheme in PPTC, and it was reproduced with three pieces of floorings arranged in the same paving scheme as in CTC; the exciting mode interaction of moving a chair across a paved platform in PPTC was substituted with "sliding an object (i.e. one wheel) on one surface (i.e. the tiles)" in CTC. Three pieces of flooring (i.e. PVC, ceramic and wood tiles) were then arranged on the floor of the dead room on the SounBe tool, according to the same paving scheme as that of the paved platforms (checkered and deck schemes); two sets of office chair wheels, which had previously been removed from the chairs, were equipped with a handle to facilitate hand grip. Each type of flooring was stressed repeatedly by an external experimenter, who had not taken part in the sound quality evaluations, and who was asked to roll each wheel over the flooring, according to the SounBe protocol (Figure 2) [19]. The sounds produced by this action were recorded binaurally using an artificial head (Head and Torso Simulator, HATS, 4128C by Brüel & Kjær) and measured by the phonometer. This procedure was performed with the same reciprocal position scheme between the sound source, the receiver and the phonometer (Figure 2). Since these stimuli were submitted by means of headphones (HD600 headphones by Sennheiser), each acoustic signal recorded with HATS (both for the left and the right channels) was convolved with a Kirkeby inverse filter [47], in order to eliminate any eardrum or headphone effects. The filters were built by applying the Kirkeby reverse filter method [47] to the recorded impulse responses obtained by generating sweeps at both HATS channels through the headphones. An Adobe Audition (version 3.0) software package was used with an Aurora (version 4.4) Alfa plug-in. The edited stimuli were then presented to each test participant in an abstract condition and were delivered by means of headphones in the dead room. Each participant performed the test with both chair wheels on the three floorings (2x3), in a random order to avoid possible order effects.

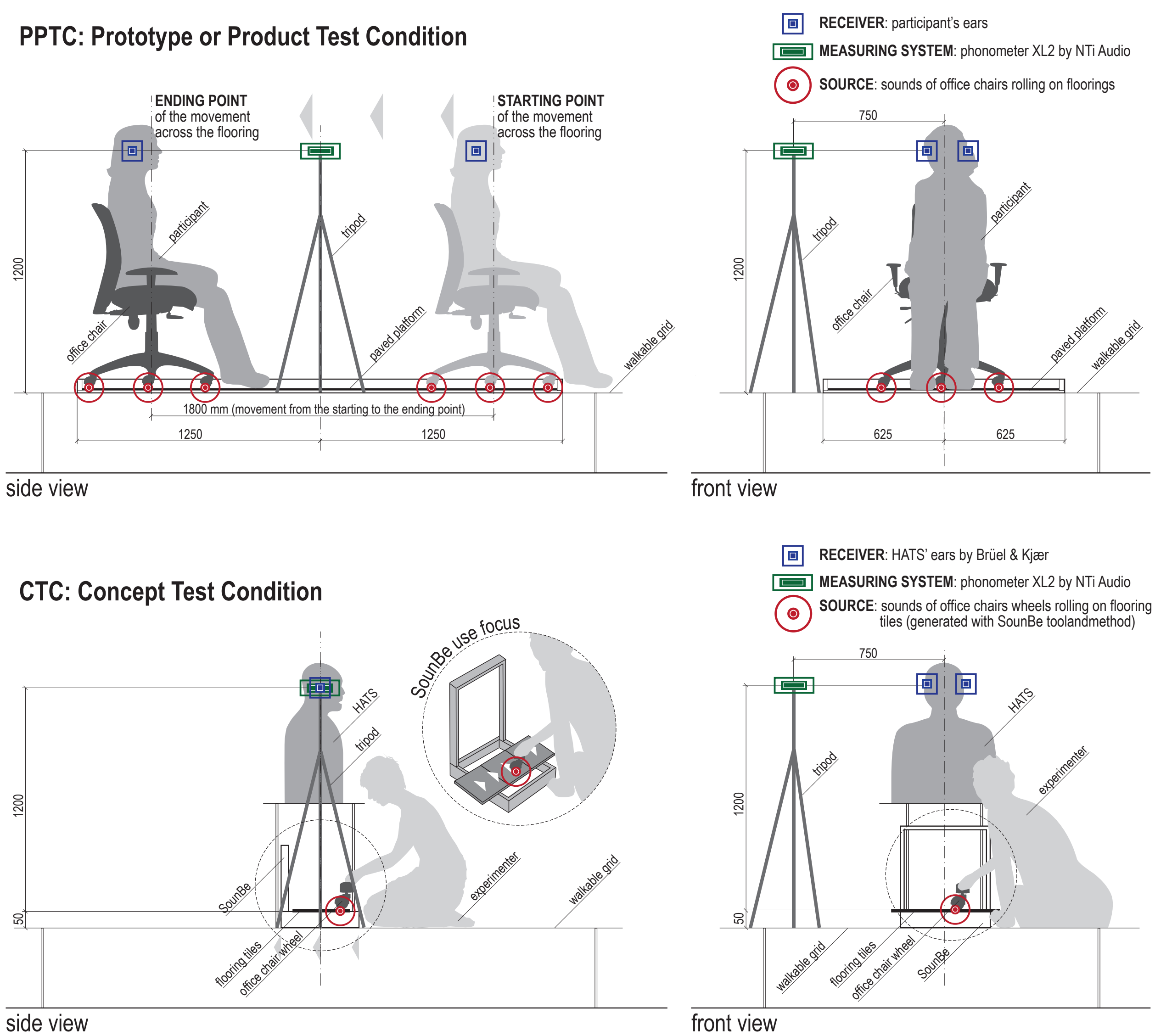


Figure 2. A scheme describing the method adopted to collect the stimuli and all the reciprocal positions of the receiver, measuring system and source in both conditions (PPTC and CTC). In the circle, a specific focus on SounBe toolandmethod use clarifies how the SounBe device was used to produce the sounds in CTC.

2.6 Statistical analyses

Since the procedure adopted in the descriptive questionnaire may be compared with a ranking task, the data collected through the questionnaire were analysed by means of rank-ordered data statistical models [48].

All the information collected in PPTC and CTC was collected in a data matrix, where each row represented one participant; the first, second and third choices of the subjects were assigned 1, 2 and 3, respectively, in the columns corresponding to the participant's evaluations. All the other columns were assigned a value of 4.

Descriptive statistics were computed for the descriptor ranking analysis. As in other investigations of subjective acoustical attributes by means of ranking data [49], an ordered list from the most to the least ranked descriptors for each stimulus was defined by summing the single scores [50]. The descriptors with the largest overall number of scores were assumed as the best ones to describe the stimulus in each condition.

Finally, a further in-depth statistical analysis was performed on the ranking data in order to compare PPTC and CTC. The subsequent statistical analyses were carried out using the SAS® University Edition software package (version 9.4) for statistical analysis. The Exploded Logit model [51] was applied as a series of tests, which had the aim of finding differences, if any, between PPTC and CTC. In order to verify the comparability between the two conditions, this test was repeated several times, in a top-down analysis, from the general data collection to the most specific cases.

The following variables were considered for each analysis: sex (male; female), age (continuous variable), the 26 Von Bismarck descriptors (high; harmonious; harsh; low; beautiful; ugly; calm; thick; weak; soft; inharmonious; hard; loud; mild; pleasant; rough; gentle; sharp; powerful; deep; smooth; unpleasant; dull; thin; strident; metallic), chair (HLC; LLC), flooring (PVC; ceramic; wood) and test condition (PPTC; CTC).

A utility-based regression method, that is, the Mc Fadden approach [52], which is described, for example, in the SAS manual [53], and which is well known and widely used in marketing research, was adopted. The model includes *x* predictors that describe the *i* subject, but which do not vary as the objects vary, *z* predictors that describe the *j* object, but which are the same for all the subjects, and *w* predictors that describe a relation between the *j* object and the *i* subject.

Only the *x* predictors, that is, the only elements upon which the ranking was based, were introduced in this study. Furthermore, several Von Bismarck descriptors with the same ranking were found, and this led to several ties, which was due to the decision to collect only the first three top choices of each subject. A particular likelihood function, implemented by the PHREG SAS procedure [53], was used to resolve the problem of the ties. Since the exact likelihood increased the computation time to a great extent, the Efron approximation was used [54].

3. Results

Results derived from acoustical data and subjective results, i.e. those derived from the descriptive questionnaire, were calculated during this experiment. A direct comparison between PPTC and CTC was then performed.

3.1 Essential acoustical data

With the aim of better describing the characteristics of the stimuli, the essential acoustical data, such as the A-weighted equivalent sound pressure levels and the L_{A5}-L_{A95} [55] values, were calculated on the sounds measured with the phonometer in both test conditions using MATLAB software package (version R2016b) by The MathWorks Inc. These data were obtained on 30 measurements in PPTC (one for each participant in the test) and on 3 measurements in CTC (one for each repetition of the sound recording). The octave band spectra of the stimuli submitted in each test condition were analysed using the Adobe Audition (version 3.0) software package with the Aurora (version 4.4) plug-in. In the case of the octave band spectra, the mean value was obtained from 30 measurements for PPTC and from 3 measurements for CTC. The signals lasted about 4 and 6 seconds in the CTC and PPTC cases, respectively, as indicated in Table 1.

Noise can be assessed in terms of “percentile level”. L_{A5} and L_{A95} represent the A-weighted levels exceeded by 5% and 95% of the time under consideration, respectively. The difference between L_{A5} and L_{A95} gives an indication of the stationarity of the sound [55].

Table 1 shows the A-weighted equivalent sound pressure levels and the L_{A5}-L_{A95} values. In both of the test conditions, the mean value of L_{A5}-L_{A95} is higher for the sounds obtained on ceramics and lower for the sounds obtained on PVC, for both chairs. A similar trend can be found for the A-weighted equivalent sound pressure levels, except for the LLC in PPTC, where the lower value is obtained for the LLC-PVC subgroup.

Table 1. Essential acoustical data, that is, the exposure time to the sounds, the A-weighted equivalent sound pressure levels and the L_{A5}-L_{A95}, are reported for the stimuli submitted during the PPTC and CTC tests.

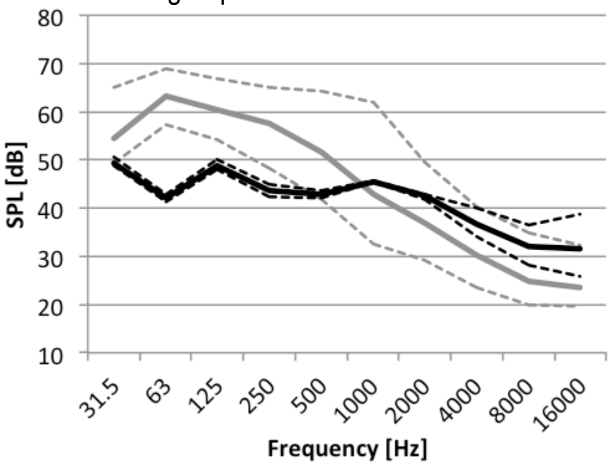
Condition	Chair	Flooring	Time [s]		L_{Aeq} [dB]		L_{A5}-L_{A95} [dB]	
			$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
PPTC	HLC	PVC	6.1	1.74	56.7	6.67	35.0	10.71
		ceramics	6.1	1.34	59.6	6.42	37.1	11.92
		wood	5.7	1.26	55.9	6.03	30.9	10.72
	LLC	PVC	5.5	1.01	56.5	3.99	32.9	9.19
		ceramics	5.3	1.29	60.8	2.92	33.3	11.61

		wood	5.3	1.34	58.5	3.07	32.9	10.20
CTC	HLC	PVC	4.0	0.00	52.3	1.19	33.2	4.87
		ceramics	4.0	0.00	62.6	1.24	45.6	1.25
		wood	3.7	0.58	50.8	4.57	30.9	7.65
	LLC	PVC	4.0	0.00	53.0	1.25	35.9	0.69
		ceramics	4.0	0.00	63.6	0.95	45.8	2.09
		wood	4.0	0.00	49.5	9.06	30.1	8.11

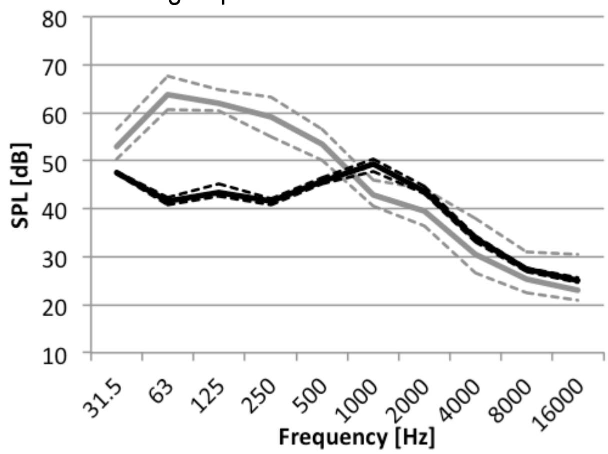
Note: PPTC = Prototype or Product Test Condition; CTC = Concept Test Condition; HLC = high level chair; LLC = low level chair; $\overline{x}$ = mean value; σ = standard deviation.

Figure 3 shows the mean octave band spectra and the maximum and minimum values of each subgroup, e.g. HLC-PVC, in the two conditions, i.e. in PPTC and in CTC. The graph suggests similar spectral behaviour between PPTC and CTC as far as the sounds on PVC and wood are concerned for both chairs, especially at the high frequencies. On the contrary, at lower frequencies, these subgroups seem to differ more when PPTC and CTC are compared, probably due to the differences in the size of the flooring samples and in the introduced forces. Furthermore, when the spectra obtained with HLC and LLC are compared visually, no large differences can be observed. This suggests a greater influence of the flooring factor than the chair factor on the spectral analysis, a result that requires further verification.

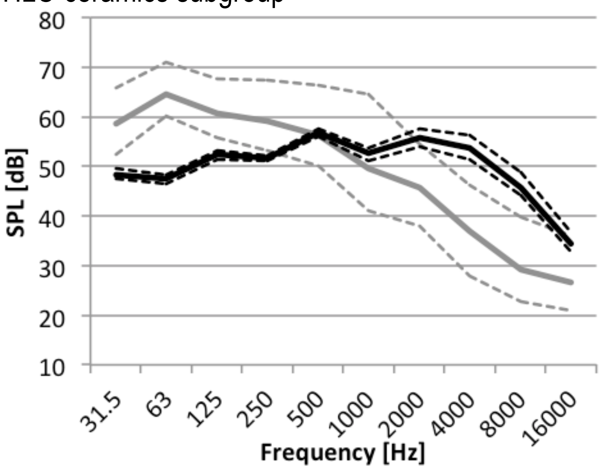
HLC-PVC subgroup



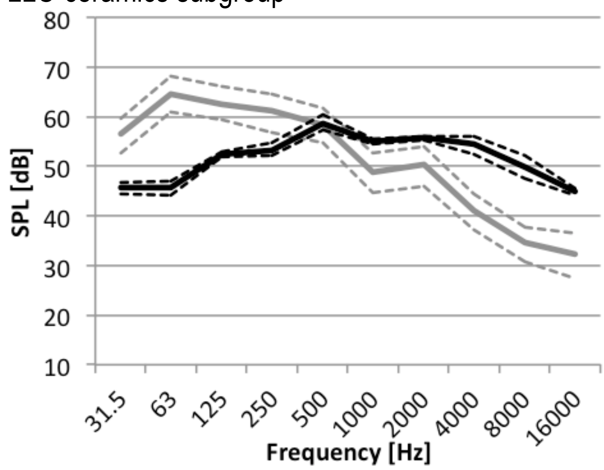
LLC-PVC subgroup



HLC-ceramics subgroup



LLC-ceramics subgroup



HLC-wood subgroup

LLC-wood subgroup

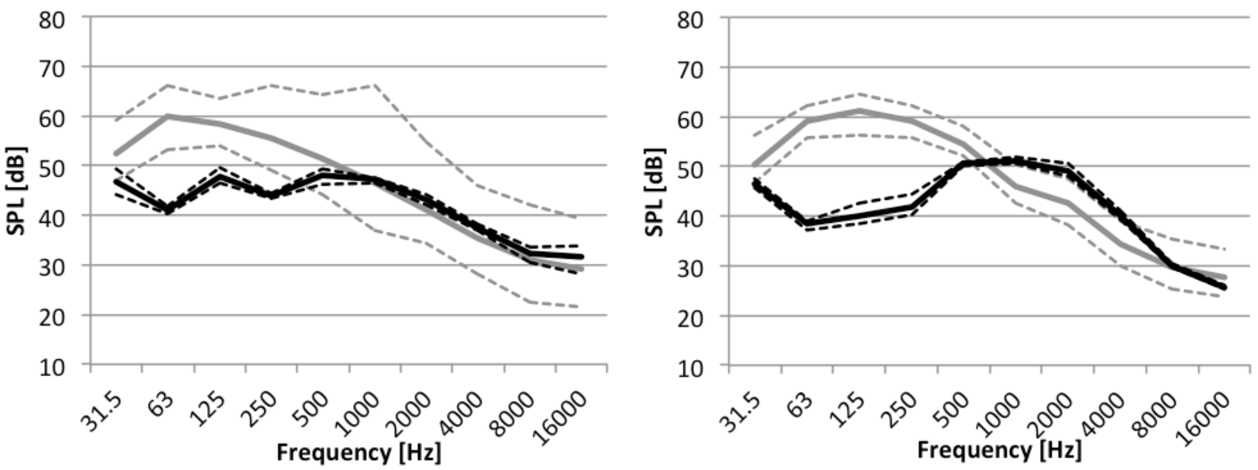


Figure 3. The mean octave band spectra of the stimuli submitted during the test, organized in six subgroups (HLC-PVC; HLC-ceramics; HLC-wood; LLC-PVC; LLC-ceramics; LLC-wood). The spectra indicated with thick grey and black lines correspond to PPTC and CTC, respectively. The thin dotted grey and black lines represent the maximum and minimum values of each spectrum in the PPTC and CTC, respectively.

3.2 Descriptor ranking

The descriptor ranking analysis led to the data shown in Table 2. Four of the six comparisons between sounds submitted under different conditions show a perfect correspondence between the first rated descriptors (adjectives in bold in Table 2). A quite good correspondence is shown in the case of HLC on wood, where the first rated descriptor in PPTC corresponds to the second rated descriptor in CTC. Just in one case is there no correspondence between the first rated descriptors. The second and third rated descriptors define the complementary "profile" of the perceived sound, and thus complete the perception with further collateral attributes. Overall, the total scores show a rather focused voting strategy in both PPTC and CTC. In fact, when the equally rated adjectives are included, the top-three voted adjectives obtained from 65 to 95 scores out of a possible maximum score of 180, which corresponds to a range comprised between 36% and 53% of the ratings. This means that only a small number of adjectives, such as those presented in this study, are needed to describe the sound of a product with a good approximation.

Table 2. The most frequently rated recurrent descriptors in PPTC and CTC are shown in bold. The scores assigned to each descriptor are shown in brackets.

Subgroup	Condition	First rated	Second rated	Third rated	Total
HLC-PVC	PPTC	**dull (24)**	thick (21)	smooth (20)	65
	CTC	**dull (28)**	calm (27)	low (20)	75
HLC-ceramics	PPTC	**rough (34)**	hard (25)	unpleasant (18) thick (18)	95
	CTC	**rough (32)**	metallic (24)	strident (22)	78
HLC-wood	PPTC	**smooth (33)**	deep (15)	calm (14) sharp (14)	76
	CTC	rough (22)	**smooth (13)** gentle (13) inharmonious (13)	low (12)	73
LLC-PVC	PPTC	deep (28)	smooth (24)	thick (19)	71
	CTC	dull (25)	rough (23)	gentle (18)	66
LLC-ceramics	PPTC	**rough (49)**	inharmonious (24)	loud (21)	94
	CTC	**rough (27)**	unpleasant (20)	sharp (18)	65
LLC-wood	PPTC	**smooth (36)**	thick (26)	sharp (22)	84

CTC	**smooth (22)** gentle (22)	calm (18)	soft (15) mild (15)	92

Note: HLC = high level chair; LLC = low level chair; PPTC = Prototype or Product Test Condition; CTC = Concept Test Condition.

3.3 Prototype or Product Test Condition vs. Concept Test Condition

In the subsequent analyses, the predictors with lower *p*-values than 0.05 were assumed to be statistically significant, and the effect of factors, such as sex, age, typology of chair, typology of flooring and test condition, were studied. Details on the statistics and the SAS programmes are available on demand from the third author of the paper.

The global null hypothesis of no difference in any of the predictor coefficients over 9360 observations was tested using the Wald test, and a *p*-value equal to 0.87 was obtained, so that the null hypothesis cannot be rejected.

Marginal tests on several binary predictors (male vs. female; age; HLC vs. LLC; ceramics vs. PVC; wood vs. PVC; CTC vs. PPTC) were conducted. All the *p*-values exceeded 0.38. Since the focus of this analysis was on finding differences, if any, between PPTC and CTC, it can be concluded that no significant differences between the two tested conditions were found.

A subgroup analysis was performed in order to determine whether certain baseline characteristics could affect the outcome of the previous global analysis, and in particular to establish whether a significant difference between the two tested conditions could be found within the data subgroups. Since 2 types of chairs (HLC; LLC) and 3 types of floorings (PVC; ceramics; wood) were present, 6 subgroups were obtained.

In the subsequent analyses, the model was the same as the one already described, with the only difference being that the type of chair and type of flooring were no longer predictors. Moreover, the exact formula was used to compute the likelihood function [53], since the number of observations was reduced to 1560.

As reported in Table 3, the minimum *p*-value obtained with these analyses was 0.06, which is greater than 0.05. Therefore, it can again be assumed that there were no significant differences between PPTC and CTC for any of the subgroups when this model was used.

Table 3. Linear hypothesis tests on the global null hypothesis on the 6 data subgroups (1560 observations for each group).

Subgroup	Chi-squared Wald	*p*-value
HLC – PVC	25.28	0.45
HLC – ceramics	22.50	0.61
HLC – wood	29.34	0.25
LLC – PVC	37.09	0.06
LLC – ceramics	21.60	0.66
LLC – wood	33.53	0.12

Note: HLC = high level chair; LLC = low level chair.

Strictly speaking, the statistical methods applied here only demonstrate that the hypotheses that there are differences between PPTC and CTC cannot be rejected. This does not constitute positive evidence of the absence of differences. However, in the absence of clear and widely accepted limits of equivalence between sound conditions, this is the best supportive evidence that could be provided towards this goal.

4. Discussion

The presented results offer the possibility of discussing the following themes: the effect of the chair and the flooring factors on office chair rolling sound descriptions, the role of the methods compared in this study in the sound quality investigations, and the industrial consequences of the findings.

4.1. The choice of the descriptors and the flooring effect

The choice of a small number of descriptors allows a synthetic and effective sound profile of each stimulus to be created [4], which in turn provides useful information for a sound quality investigation. For example, as presented in Table 2, the choice of the most frequently rated adjectives for the ceramic and wooden flooring, which were judged “rough” and “smooth”, respectively, suggests an important cross-modal interaction between tactile and auditory cues related to flooring surfaces, as already pointed out in literature [56]. Furthermore, the similar description for the high and low quality level chairs on the same flooring indicates a greater influence of the flooring factor than the chair factor, as confirmed by the spectral analysis in Figure 3.

It is conceivable that future research should move towards investigations on the effects of rolling sounds, both outdoors and indoors, in a similar way to the verbal data approach adopted to assess the outdoor soundscape [57]. For example, the rolling sounds of suitcases, which only affect old city soundscapes, or the acoustic environment in railway, metro or airport halls could be investigated.

4.2. A predictive sound design method for sound quality investigation

Apart from the investigation on the perception of office chair rolling sounds, this exploratory study has also offered the occasion to verify the efficacy of the proposed concept phase sound design method [19] through a comparison with a real product in action, which was assumed as a reference. A comparison between real and reproduced sounds seems to be a difficult task, considering the need for a holistic approach, due to the multisensory nature of human perception [58]. Unlike what could have been expected, the statistical analysis found no significant differences between PPTC and CTC, as shown in Table 3. It is plausible to suppose that this result has been achieved in part thanks to the test instructions that were given to the subjects, where the source generating the set of sounds had previously been explained. It has in fact been proved that verbal information positively influences the comprehension of sounds, but does not modify the sound ratings themselves [45]. Furthermore, considering the similarity between the selected descriptors in PPTC and CTC (Table 2) and the spectral differences between sounds, in particular those on low frequencies (Figure 3), it can be argued that low frequencies only affect the perception of this kind of sound slightly. This could mean that the sound perception, in this case, was mainly related to the highest frequency components. Further studies could consider other sounds with different spectra; the relationship between objective and subjective data has already been investigated in a complementary study based on data collected in the same experimental campaign as this work [9].

The results of this exploratory study prove the efficacy of the proposed method to investigate the sound quality of a product during the concept design phase, thus preventing the expensive and time consuming test-retest activities on real prototypes or products that frequently entail ignoring the sound design phase [18]. With this method, a firm that produces office furniture, for example, could benefit from the preventive analysis of different chair rolling sounds and could then orientate the chair design towards the less annoying or better-judged sounding product. This care towards sound design has a direct effect on workers’ comfort and wellbeing [20]. Finally, the novelty of this approach lies in the profitability of the adopted method, derived from sensory evaluation tests by researchers, designers and firms interested in assessing the perceived qualities of the sound of a product that still does not exist, with the consequence of an improvement in everyday soundscapes [1].

4.3 The industrial application of these findings

This research has dealt with office chair rolling sounds, considering the proved drop in satisfaction and performance for employees, which is concurrent with the increasing noise [59]. Companies that produce office furniture could invest in more pleasant-sounding products, in order to improve the environmental soundscape of offices for workers [33]. However, it is also possible to hypothesize research on other living environments and products in the future [60].

Recalling some considerations made by Lyon, it is generally true that when discussing the sound attributes of their products, companies frequently talk about how quiet they are [18]. However, sound quality can be considered as an opportunity to communicate the special attributes of a product, i.e. changing the way the product is multisensory perceived [61]. One of the most common attributes conveyed in the past by sound behaviour was that of the hedonic and luxury attributes, as in the case of sensory marketing research [62]. Today, an unlimited number of other attributes can be identified and conveyed, starting from the consumers' preference [63], and can easily be tested during the concept phase.

Although these findings are promising, they also suffer from some limitations. For example, sensory description is known to be affected by significant cross-cultural differences [64]. This issue suggests the necessity of performing investigations with subjects who are representative of a specific culture, since the same sound stimulus submitted to testers from different cultural backgrounds could be perceived in very different ways.

Finally, a suggestion for a future study arises from the fact that the perception of a stimulus can be context sensitive, i.e. the description of a sound can differ, depending on the environment in which the evaluation takes place [58]. The current study was performed in a dead room. A similar study on refrigerator noise investigated in both an anechoic chamber and in a real living environment revealed that the subjective ratings on semantic differentials were reliable, despite the different testing locations [65]. However, it could be interesting to demonstrate the validity of the proposed method through a comparison with sounds obtained in a real office, while taking into account the typical background noise.

5. Conclusion

The following main results have been obtained from the present exploratory study:

- The proposed method, derived from sensory evaluation tests, allows the sound perceptive qualities of a product to be forecast, starting from its generating variables. The reliability of this preliminary test, compared to the full-product test condition, has in fact been proved;
- The perceived sound qualities of a product can be assessed before the prototyping phase, i.e. already in the concept design phase, by adopting this effective low cost and time-saving sound design method;
- Cross-modal audio-tactile verbal interactions, related to chair rolling on different flooring surfaces have been found (e.g. the *smoothness* of the wooden surface or the *roughness* of the ceramic surface).

In future studies, the efficacy of the concept phase sound design method will be proved through investigations on other sounds in different contexts. Furthermore, investigations on the pleasantness of sounds will be undertaken, and correlations with psychoacoustic measures will also be tested. Finally, other standard descriptors, or a descriptor list generated by the participants and specific for a certain set of stimuli could be tested.

Acknowledgements

The authors would like to thank the Ares Line and Scamet Italia companies for having provided the office chairs used in this study. Special thanks are due to Giuseppina Emma Puglisi and all the technical team of the Department of Energy at the Politecnico di Torino for their collaboration during the experimental phase. The authors are also thankful to Eleonora Buiatti for the suggestions that have greatly helped to improve the research. Finally, many thanks are due to all the students and participants who took part in the test, as well as to Francesca Arato, co-inventor of the method in the preliminary stage of this research.

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