Applied Cognitive Psychology, *Appl. Cognit. Psychol.* (2012)

Multisensory Assessment of Acoustic Comfort Aboard Metros: a Virtual Reality Study

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Summary: In this study, a multisensory methodology is used to assess acoustic comfort aboard different real-world metros by means of subjective annoyance and cognitive performance measures. Two experimental conditions were compared: unimodal versus bimodal. Immersive virtual reality was used to simulate journeys aboard metro coaches. Participants performed four tasks (Rey Test, Verbal Fluency, Backward Counting and Auditory Words Discrimination) while listening to metro sounds (unimodal condition) or while listening to metro sounds within a virtual metro coach (bimodal condition). At the end of each journey, participants reported their degree of noise annoyance. The results showed that cognitive performances were worse in the bimodal than in the unimodal condition. Moreover, the bimodal condition affected negatively the capacity to discriminate words and to count backward. However, reported noise annoyance was higher in the unimodal than bimodal condition. The theoretical and practical implications of these findings are discussed. Copyright © 2012 John Wiley & Sons, Ltd.

INTRODUCTION

The electric mass transportation systems, such as the Metros (or 'subways'), have become a fundamental transportation means for millions of people inside and around urban areas all over the world. Metros are seen as the most efficient alternative road transport systems as they allow higher capacity with less land surface use, less environmental impact and lower costs. More than 170 cities have built metro systems, and similar urban rail systems (such as Trams and Light Transit Rails) are currently under construction (http://mic-ro.com/metro/).

Given the large number of daily riders and the increasing time they spend aboard trains (Gershon, Neitzel, Barrera, & Akram, 2006), these transportation systems should ensure an acoustically comfortable environment for passengers (Genuit, 2004). However, recent surveys have shown that noise exposure aboard metro coaches often exceeds the limits recommended by the World Health Organization (1999; WHO). For example, Gershon and colleagues (2006) revealed that inside five different metro coaches in New York city, the mean maximum noise level was 94.9 decibels A-weighted [dB(A)], with a range of 84 to 112 dB(A). Similar noise levels were found by Maffei and colleagues (Maffei, Masullo, & Palmieri, 2009) inside metro coaches of different Italian cities [~80 dB(A)]. According to the WHO, the long-term exposure to these noise levels can significantly contribute to passengers' hearing loss (Gershon et al., 2006; Neitzel, Gershon, Zeltser, Canton, & Akram, 2009). Although several studies about the long-term effects of metro noise on health in outdoor conditions have been carried out, little is known about the effects of noise on passengers aboard metro coaches during transfer time (Parizet, Hamzaoui, & Jacquemoud, 2002). It is reasonable that metro noise can increase passengers' annoyance and disturb cognitive processing involved in secondary activities during the journey, such as reading, taking notes, working with laptops or understanding communications. For example, it may be difficult for passengers to understand important announcements from public address systems (Shimokura & Soeta, 2009).

For all these reasons, it is important assuring a comfortable transfer time aboard metros. However, the lack of a clear definition of acoustic comfort and of sufficient information about the effects of noise aboard metros prevents educated decision making by coach producers (Griffin, 1996).

The aim of this study was to assess passengers' acoustic comfort during simulated audio-visual journeys aboard metros. This will allow us to investigate the effects of different metro noises on passengers, and at an applied level, it will inform coach producers and manufacturers of what acoustic pattern can be considered as more comfortable.

The few attempts to assess noise perception aboard railway systems have focused on the relationship between acoustic parameters of interior high-speed trains and subjective annoyance (Fastl, 2005; Hardy, 2000; Kuwano, Namba, & Okamoto, 2004; Letourneaux, Guerrand, & Poisson, 2000; Parizet et al., 2002). In these laboratory studies, participants were seated in a room and listened to pre-recorded sounds. Sounds were presented through an amplifier and loudspeaker or through headphones for a duration ranging from 10 seconds (Kuwano et al., 2004; Parizet et al., 2002) to 3–4 minutes (Hardy, 2000; Letourneaux et al., 2000). Afterwards, participants had to indicate their degree of annoyance or pleasantness of sounds on a five-step, seven-step or 10-step scale. Usually, participants had to imagine to be aboard a metro (e.g. Kuwano et al., 2004) while seating in a laboratory room (Watts, 1995).

One problem with these laboratory procedures is that they reproduce environmental information in a simplified way as compared with the sensory richness of real-world situations. In particular, unimodal noise assessment methods were used: participants were only presented with metro sounds without contextual visual scenarios. Moreover, measures of acoustic

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comfort were restricted to self-reported annoyance ratings without considering possible effects on cognitive abilities (see Stansfeld & Matheson, 2003).

Audio-visual interaction in sound patterns evaluation

Urban sounds are rarely perceived in isolation but rather apprehended within a global context that includes information from other sensory modalities such as vision and touch. In daily life, passengers hear metro noises while immersed in scenarios characterized by rich multisensory stimuli (e.g. visual appearance of metro coaches, external landscapes, platforms, tunnels and other passengers). These various kinds of information give rise to a multimodal mental representation of the environment, and subsequent evaluations will be based on this representation (Pheasant, Fisher, Watts, Whitaker, & Horoshenkov, 2010; Viollon, Lavandier, & Drake, 2002). For this reason, some theoretical approaches underline that the environment is experienced holistically (Cassidy, 1997). Instead, standard acoustic comfort assessment methods neglect the multisensory nature of environmental perception.

These considerations are reinforced by data coming from neuroscience and cognitive psychology showing that vision and audition are not independent modalities but interact in complex ways (Ernst & Bülthoff, 2004; Frassinetti, Bolognini, & Ladavas, 2002; McGurk & MacDonald, 1976; Shams & Kim, 2010; Warren, McCarthy, & Welch, 1983) even at early stages of signal processing (Watkins, Shams, Josephs, & Rees, 2007). Neurons that respond to multisensory stimulation (e.g. both auditory and visual) have recently been discovered in areas previously thought to be modality specific, such as the somatosensory cortex, as well as in clusters at the borders between the major cerebral lobes, such as the occipito-parietal, occipito-temporal networks (Allman & Meredith, 2007; Wallace, 2004; Wallace, Ramachandran, & Stein, 2004; for a review see Stein & Meredith, 1993) and medio-temporal areas (see Olivetti Belardinelli et al., 2004). It has also been shown that sound can alter visual perception (Shams, Kamitani, & Shimojo, 2002) and that under certain conditions, cerebral areas involved in processing auditory information can be activated in response to sound-implying, but silent, visual stimuli (Meyer et al., 2010; see also Calvert et al., 1997).

Consistently, evidence coming from environmental psychology has confirmed the multisensory nature of human perception. For example, several studies have demonstrated that a visual scene is judged as more annoying and unpleasant when presented without sounds or with context-incongruent sounds (Carles, Bernaldez, & De Lucio, 1992; Southworth, 1969; Tamura, 1997). In addition, the influence of visual scenes on sounds has also been found. Viollon and colleagues (Viollon et al., 2002) showed that judgments of a set of sounds were affected by co-occurring visual settings: when participants viewed natural scenes (e.g. woods), sounds that were naturally associated with them (e.g. singing birds) were rated as more pleasant than when these same sounds were matched to visual urban environments.

The audio-visual interaction has also been demonstrated on loudness evaluation, that is perceived intensity of acoustic stimuli. Some studies have shown that visual factors, such as colours, may modulate loudness judgments. For example, colours such as red or pink seem to increase perceived loudness, whereas grey or pale green seem to decrease loudness (Menzel, Fastl, Graf, & Hellbrück, 2008). Consistently, Parizet and Koehl (2011) found that pictures of red trains caused an increase in perceived loudness as compared with pale green trains.

In conclusion, convergent data from different disciplines would suggest that bimodal audio-visual stimuli are essential for a reliable assessment of acoustic comfort (Blauert & Jekosch, 1997).

Acoustic comfort measures

According to the WHO, a healthy environment should trigger good feelings and safety. For this reason, it is limiting to consider an environment as comfortable only on the basis of physical or psychoacoustic parameters (Letourneaux et al., 2000). Instead, subject-centred methodological procedures should be used to develop a suitable measurement procedure (Schulte-Fortkamp, 2002).

In the literature, the most used measure to assess noise impact on individuals (Stansfeld & Matheson, 2003) and to determine the sound quality of a product is subjective noise annoyance (Bodden, 1997; Nor, Fouladi, Nahvi, & Ariffin, 2008; Rossi, Nicolini, & Filipponi, 2003).

Noise annoyance has been subject to extensive scientific research over the last 60 years (Fields, 2001), and dosage–response curves describing the relationship between noise and annoyance have been proposed (e.g. Miedema, 2007; Miedema & Vos, 1998, 2003; Schultz, 1978). In general terms, the measurements of noise annoyance are based on acoustic patterns acquired outside from transportation means (i.e. road, rail and aircraft). These measurements indicate that noise annoyance levels increase with increasing sound pressure levels (SPLs).

However, methods based on self evaluation of annoyance are only informative about the subjective perception of noise and not about relevant psychological, namely cognitive, factors that may characterize noise impact during passengers' transfer time.

The impact of outdoor road traffic, aircraft and railway noise on cognitive performances has been largely investigated (e.g. see Stansfeld & Matheson, 2003). Several epidemiological and experimental studies have shown a detrimental effect of noisy contexts on some cognitive abilities (for a review, see Joseph, Aravindakshan, & Vyawahare, 2000). For example, results from cross-sectional studies have shown a linear exposure effect between chronic aircraft noise exposure, impaired reading comprehension and recognition memory in children (Clark et al., 2006; Stansfeld et al., 2005). Disruptive effects on memory were also found in two laboratory studies where participants, aging from 13 to 65 years, completed 18 memory tests while exposed to meaningful irrelevant speech or to road traffic noise (Boman, Enmarker, & Hygge, 2005; Hygge, Boman, & Enmarker, 2003). Furthermore, Belojevic, Öhrström and Rylander (1992) showed that road traffic noise negatively influenced participants' performance on a verbal short-term memory test and on a mental arithmetic test. Finally, several studies about the exposure to outdoor railway noise have shown impairments in calculation tasks (Ma & Yano, 2004), on children's verbal memory (Hambrick-Dixon, 1986, 1988) and reading abilities (Bronzaft & McCarthy, 1975). Overall, no study has systematically addressed the issue of the influence of noise on cognitive abilities when passengers are aboard metros.

We propose that a more comprehensive definition of acoustic comfort should include perceived well being and cognitive efficiency. Indeed, annoyance ratings and cognitive performances could reveal different patterns of noise effects (Belojevic, Jakovljevic, & Slepcevic, 2003). As a consequence, the assessment of acoustic comfort should concern both subjective (noise annoyance) and objective (cognitive performance) measures of passengers' reactions to noise (see also Schulte-Fortkamp, 2002).

Overview of the research

In sum, the majority of studies about acoustic comfort is based on unimodal acoustic methods that do not consider the contribution of visual scenarios on sound perception. Furthermore, these studies investigate long-term health and cognitive effects of noise exposure and focus mainly on noise effects in outdoor but not indoor conditions. Finally, perceived annoyance assesses only subjective reactions to noise.

In this research, we seek to assess acoustic comfort aboard metros by using a subject-centred methodological procedure that takes into account both subjective reactions and cognitive efficiency. An immersive virtual reality (IVR) technology was used to reproduce as closer as possible the conditions in which metro noise is experienced in everyday life. This technology was chosen because it allows to simulate in a controlled way specific contexts with their visual and acoustic characteristics. Although the graphics depicting virtual environments is still far from being fully natural, immersive virtual technology has two advantages: users are surrounded by the virtual environment and have the impression to be inside the virtual world and users can interact in real time with it. According to Slater (2009), these two characteristics determine the sense of credibility of a virtual scenario, that is the sensation that the simulated world is perceptually convincing and that it can produce events that directly relate to participant's sensorimotor contingencies. One could argue that video recordings of actual metros could be more suitable for the purpose, and some work has shown that this method can be reliably used to assess tranquillity of spaces (Watts, Pheasant, & Horoshenkov, 2010). Video recordings have the advantage of reproducing real-life situations, but participants are outside the represented world and cannot interact with it.

This research was based on the comparison of two experimental conditions: bimodal (Audio + Video) versus unimodal (Audio). In line with classic laboratory procedures, in the unimodal condition, participants were only presented with metro sounds via in-earphones (e.g. Parizet et al., 2002). The same sounds were embedded in a 3D graphic reconstruction of a metro in the bimodal condition. In this condition, an IVR system was used to simulate scenarios that reproduced both visual and acoustic aspects of journeys aboard metros.

Sounds from the interior of nine real metros characterized by different acoustic parameters were used (Berlin S3, Berlin U2, Milan L1, Milan L3, Naples L1, New York MQ, Paris L1, Rome LA and Turin L1). Each soundtrack represented a journey between two metro stations. While listening to the metro sounds (unimodal condition) or immersed in the virtual audio-visual scenarios (bimodal condition), participants had to perform an auditory discrimination task and three cognitive tasks that assessed short-term verbal memory, semantic memory and executive control. In this way, the online effects of interior metro noise on cognitive performances could be assessed. As it is common in the literature and suggested by International Organization for Standardization (ISO/TS 15666: 2003), after exposure to each soundtrack, participants had to report their degree of subjective annoyance.

On the basis of the literature, we can hypothesize that the impact of noise on cognitive performances and subjective annoyance should be affected by the presence (audio-visual condition) or absence (audio condition) of congruent visual scenarios; this should be verified by a significant difference between unimodal versus bimodal conditions. Furthermore, the different acoustic patterns characterizing each metro should also affect subjective reactions and cognitive performances. In line with prior evidence (see Stansfeld & Matheson, 2003), more noisy metros (with higher SPLs) should increase self-reported annoyance degrees and have a negative impact on cognitive performances.

METHOD

Participants

Fifty-one students (26 males and 25 females) recruited from the Second University of Naples participated voluntarily in the study. Mean age of the participants was 24.7, $SD = 3.9$ (range 18 to 37 years). Mean education (years of schooling) was 14.4, $SD = 2.9$ (range 13 to 19). They were randomly assigned to one of two conditions: Audio and Audio + Video. All participants reported normal hearing and normal or corrected to normal vision.

Setting and immersive virtual reality equipment

Depending on the condition, the experimental session took place in the anechoic chamber of the Built Environment Control laboratory (Audio condition) or in the laboratory of Cognitive Science and Immersive Virtual Reality (Audio + Video condition) of the Second University of Naples.

The anechoic chamber is a room designed to stop reflections of any sound waves on the boundaries. It is also insulated from exterior sources of noise. The chamber consists of an outer shell of reinforced concrete and an inner room with dimensions 4.4 × 4.4 × 4.5 m, covered by absorbing fibreglass wedges, providing a very quiet environment where hearing tests could be performed by avoiding unwanted sounds perception. The cut-off frequency of the chamber is 100 Hz.

The IVR laboratory is settled in a rectangular room (4.9 × 3.6 × 3.1 m) that allows for extensive movements while participants are connected to the tools of virtualization. It includes a work station linked to the 3D Vizard Development 2009 Edition Virtual Reality Toolkit Devices of the Integrated VR Setups System. Virtual environments were presented through an nVisor SX (from NVIS, Reston, VA) head mounted display (HMD). The HMD presented stereoscopic images at 1280 × 1024 resolution, refreshed at 60 Hz. The virtual scenario spanned 60° horizontally by 38° vertically. Graphics were rendered by an Intel R core (TM) 2 Quad 9300 2.50 GHz and 1.98 GHz processor with an NVIDIA GeForce 8800 graphics card using Vizard software (WorldViz, Santa Barbara, CA). Head orientation was tracked using a three-axis orientation sensor (InertiaCube3 from Intersense, Bedford, MA), and head position was tracked using a passive optical tracking system (Precision Position Tracker, PPT H4 from WorldViz, Santa Barbara, CA). Graphics displayed in the HMD were updated on the basis of sensed position and orientation of the participant's head. In-ear headphone devices were used to integrate auditory information with the virtual environment.

Materials and procedure

The entire experimental setting, materials and procedure were previously tested in two pilot studies (Maffei, Masullo, Alekseeva, Ruotolo, & Senese, 2010; Maffei et al., 2009).

Auditory materials

Data resulting from a previous survey on 17 world great cities' metros were used as basic acoustic stimuli for the study. The original data consisted of binaural audio signals (16 bit/44.1 kHz) that were recorded during metro journeys by a portable two-channel device 'M-Audio Microtrack 24/96' and binaural headphones 'Sennheiser Noise Gard HDC 451'.

In both Audio and Audio + Video conditions, nine Metro lines were chosen: Berlin S3, Paris L1, Turin L1, Berlin U2, Rome LA, Naples L1, New York MQ, Milan L1 and Milan L3. As shown in Table 1, metro lines are ordered according to SPL. The soundtracks covering a journey between two successive stations were extracted from the whole sound records of the metro lines. These soundtracks represented different noise characteristics and specific events (such as rattling, hissing, rumbling, tonal components, etc.). They were selected considering the results of a preliminary psychoacoustic indexes analysis. The psychoacoustic analysis was performed by means of 'dB Sonic' software that provides A-weighted SPL and psychoacoustic parameters such as loudness (N), sharpness (S), roughness (R) and fluctuation strength (F) (see legend in Table 1). Data are reported in Table 1 for each metro soundtrack. Values are the average of the signals at the left and right channels.

Table 1. Acoustic parameters of selected soundtracks

	Acoustic parameters*				
	SPL	N	S	F	R
Metros	dB(A)	Sone	Acum	Vacil	Asper
Berlin S3	65.7	17.65	1	0.26	0.28
Paris L1	71.9	25.1	1.1	0.35	0.26
Turin L1	74.0	33.25	1.25	0.23	0.32
Berlin U2	75.85	33.5	1.1	0.17	0.32
Rome LA	76.25	27.1	1.3	0.31	0.26
Naples L1	80.6	37.95	1.1	0.42	0.31
New York MQ	81.2	47.95	1	0.52	0.36
Milan L1	82.15	46.3	1.2	0.2	0.38
Milan L3	86.2	55.35	1	0.21	0.39

Note:

*Acoustic parameters (Fastl & Zwicker, 2007): SPL, A-weighted sound pressure level (SPL) is a measure of the effective pressure of a sound relative to a reference value. A-weighting is the most commonly used of a family of curves for the measurement of environmental and industrial noises. N, loudness, is the sensation that corresponds most closely to the sound intensity of the stimulus and measures the sound strength relative to a reference value. S, sharpness, is the sensation which is caused to the high frequency component of a noise on the basis of reference values. R, roughness, is a hearing sensation that is created by the relatively quick changes produced by modulation frequencies within a specified range. F, fluctuation strength, is a hearing sensation due to low modulation frequencies. All values correspond to the average of the signals of the left and right channels. Metro noises are ordered according to SPL parameters.

Immersive virtual reality stimuli

In the Audio + Video condition, 3D graphic virtual reality scenarios of a metro and platform were created. The graphic model was designed by means of the 3D modelling free software Google Sketch Up 7.0 (http://sketchup.google.com/intl/en/index.html) simulating geometrical constructions according to actual dimensions, sizes and colours. Each metro coach measured 16 × 3 × 3 m. Along the virtual platform (measuring 100 × 5 m), several avatars simulated passengers waiting for the train. The coach was coloured in light grey and yellow, the seats were grey, the roof, doors and accessories were light grey, and the floor was iron-like. In the metro coach, nine avatars were seated, whereas three avatars were standing. The train travelled between two stations inside a 185-m-long tunnel. On these scenarios, the WorldViz software virtual reality development interface allowed for simulating the movement of train, avatars, the opening/closing of doors and the changing of the environment outside the metro coach during the tunnel passage.

Cognitive tasks

To evaluate the influence of metro noise on cognitive processes, three typical tasks from neuropsychological literature that could be easily adapted to the experimental situation were chosen. The tasks explored the following cognitive domains: short-term verbal memory (Rey Auditory Verbal Learning Test), semantic memory (Verbal Fluency by letters test) and executive control (Backward Counting). An auditory discrimination task (Intelligibility) was also used.

Rey test (Rey). This test is an efficient neuropsychological instrument for evaluating verbal memory (Rey, 1959; Spinnler & Tognoni, 1987). It provides scores for assessing immediate and delayed memory about new verbal learning. The test consists of the oral presentation of a list of 15 words, at a rate of one per second, and participants have to reproduce from memory as many words as possible independently of their order in the list. In our modified version, we only tested the capacity to recall in short-term memory verbal items visually presented at a rate of one per second. On the basis of the criteria adopted in the original list, for the present study, 10 lists of 15 words each were devised and matched for length, syllable number and word frequency to the original list. Afterwards, participants had to reproduce as many words as possible. Overall, testing time was 30 seconds (15 seconds presentation; 15 seconds retrieval). For each participant, the total number of correctly reproduced words was computed (score range: 0–15 for each list).

Verbal Fluency by letters task (VF). This test explores the extension and recall concerning the long-term lexical-semantic store (Borkowsky, Benton, & Spreen, 1967; Iachini, Poderico, Ruggiero, & Iavarone, 2005; Spinnler & Tognoni, 1987). Furthermore, the test seems also to tap executive functions because the subject, after the run-in, has to self-generate the list without external cues (Shallice & Burgess, 1991). In the original version, participants are required to produce, in 60 seconds, as many words as possible beginning with a given letter, by avoiding proper and geographical names and verbs. In our version, 10 letters were selected (S, C, A, P, I, M, D, T, B and F) on the basis of the word frequency and were visually presented. For each letter, participants had 30 seconds to complete the task. The total number of produced words was computed.

Backward Counting task (BC). This task taps executive functions and requires high attentional resources. Indeed, the task requires to self-generate correct digit numbers and to inhibit wrong information. In its original version, participants are asked to count backward in units of seven, such as 100, 93, 86 and so on (Ganguli et al., 1990). In our version of the task, 10 starting numbers were considered: 64, 68, 72, 76, 81, 83, 84, 90, 93 and 96. Each starting number was visually presented. The total number of correctly generated numbers was computed.

Intelligibility task (I). This task is used to evaluate the effect of noise masking on verbal communication by means of auditory words discrimination (Bradley, Reich, & Norcross, 1999; Finitzo-Hieber & Tillman, 1978; Houtgast & Steeneken, 1985). Ten sets of six words (words with meaning) were recorded with an ISI of 1 second and mixed with noise tracks. For each set, participants were presented with six auditory words, one per time, and were asked to repeat each of them immediately after. The total number of correctly reproduced words was computed (score range 0–6).

Subjective evaluation

Self-report evaluation of the degree of noise annoyance for each scenario was devised according to ISO/TS 15666 (2003). Participants were asked to evaluate the degree of annoyance on a 10-point Likert scale from 1 (‘not at all’) to 10 (‘extremely’).

Procedure

Before starting the experimental session, participants were asked to fill out a consent form and a demographic survey. Afterwards, they were given written instructions describing the experimental procedure that were also orally repeated by the experimenter. Each condition was preceded by a training session in which participants were submitted to the entire procedure. In this way, they got acquainted with the experimental setting, the virtual scenarios (in Audio + Video condition) and the cognitive tasks.

Audio + Video condition. The experimental session was carried out in the Laboratory of Cognitive Science and Immersive Virtual Reality. Participants were led in a premarked starting position where they had to wear both the HMD and the in-ear headphones. Afterwards, they were immediately immersed in a virtual scenario reproducing a typical subway metro station, standing on the platform in front of the metro. The experimenter invited participants to get into the virtual metro and to sit down on one of the metro seats of the coach. The virtual metro seat corresponded to a real chair placed in the premarked position. If the entire procedure was clear, the testing phase began.

Audio condition. The experimental session was carried out in the anechoic chamber of the Built Environment Control Laboratory. Participants wore the in-ear headphones and seated in front of a computer screen. The procedure and materials were the same as in the Audio + Video condition. The only difference concerned the fact that no visual virtual scenario was presented apart from the metro soundtracks and that the items of the cognitive tasks were shown on the computer screen. Also in this condition, if the entire procedure was clear, the testing phase began.

Testing phase

In both conditions, all participants were submitted to 10 scenarios: nine associated with the soundtracks of corresponding metros (Berlin S3, Paris L1, Turin L1, Berlin U2, Rome LA, Naples L1, New York MQ, Milan L1, Milan L3) and a completely silent control one (Control). Each scenario corresponded to a soundtrack covering a journey (in Audio) or a virtual journey (in Audio + Video) between two metro stations. Each scenario lasted approximately 2 minutes. The control conditions consisted of the presentation of the cognitive tasks without wearing the in-ear headphones (control for the Audio condition) or during a virtual journey in a metro without associated sounds (control for the Audio + Video condition). Within each scenario, participants had to perform the four cognitive tasks (Rey, I, VF and BC). The beginning and the ending of each cognitive task were indicated with a green and red squares, respectively. The intertask interval lasted 5 seconds. The first green square appeared 10 seconds after the beginning of the journey. Immediately after, a cognitive task had to be performed. This procedure was repeated for each task, that is four times within each journey. Materials of the Rey test (i.e. words), VF (i.e. letters) and BC (i.e. numbers) were visually presented at the centre of the visual scenario (Audio + Video) or at the centre of the computer screen (Audio) (see Figure 1 for an example). In the Rey test, the list of 15 words was visually presented at a rate of one per second (15 seconds). After that, participants had to reproduce as many words as possible within 15 seconds until the red square appeared. As regards the BC, the starting number was visually presented, and participants had to count backward aloud by seven within 20 seconds. In the VF task, the target letter appeared, and participants had to generate as many words as possible within 30 seconds. Finally, in the Intelligibility task, the six words were aurally presented at a rate of one per second, and participants had to immediately reproduce each of them.

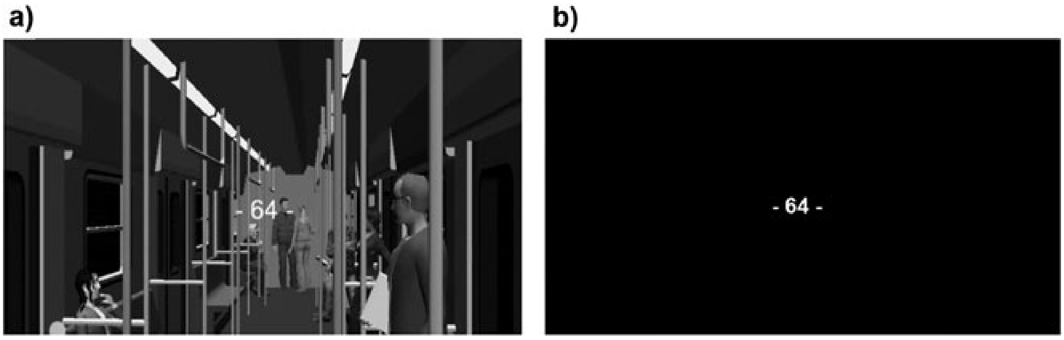

Figure 1. The figure depicts what participants saw during the cognitive tasks. An example from the Backward Counting task is given for both experimental conditions: (a) in the bimodal condition, participants saw at the same time the virtual metro coach and an item of the task; (b) in the unimodal condition, participants just were presented with the item of the task at the centre of a monitor screen

The order of presentation of the scenarios was quasirandomized. The order of cognitive tasks was counterbalanced within each scenario and across subjects. In this way, any spurious effect deriving from sequence and order factors was prevented.

In both Audio and Audio + Video conditions, at the ending of each scenario, participants were required to fill out a self-report questionnaire assessing their degree of noise annoyance.

For each participant, the mean duration of the experiment was about 70 minutes.

Data analyses

To see the general effect of the Audio versus Audio + Video conditions on cognitive performances and perceived annoyance, two MANOVAs that treated the experimental conditions (Audio and Audio + Video) as a two-level between-subject factor and the cognitive performances or annoyance ratings as dependent variables were performed.

To analyze main and interactive effects of experimental conditions and scenarios on each cognitive performance, as follow-up tests, four separate mixed factorial 2 × 10 ANOVAs that treated the experimental condition (Audio and Audio + Video) as a two-level between-subject factor and scenario as a 10-level within-subject factor (Control, Berlin S3, Paris L1, Turin L1, Berlin U2, Rome LA, Naples L1, New York MQ, Milan L1, Milan L3) were carried out on single tasks. The mean correct responses of the cognitive tests (Rey, Intelligibility, Verbal Fluency and Backward Counting) were used as dependent variables.

To analyze subjective annoyance, one 2 × 9 mixed factorial ANOVA with the experimental condition as a two-level between-subject factor and scenario as a nine-level within-subject factor (the same nine metros without the control scenario) was carried out as a follow-up test. The ratings of annoyance were used as dependent variable.

In all ANOVA analyses, the Bonferroni correction was used to analyze post-hoc effects, and the magnitude of the significant effects was indicated by partial eta squared (η_p^2).

Finally, to investigate the effect of SPL and other psychoacoustic parameters on cognitive measures and subjective annoyance ratings, scores were averaged over subjects as a function of each scenario. Then correlation analyses between acoustic parameters of each metro and mean scores of the objective and subjective measures were carried out.

RESULTS

Analyses on cognitive performances

The MANOVA showed a significant overall effect of the experimental condition on the cognitive performances, Wilks' lambda = .002, $F(9, 40) = 7.882$, $p < .001$, multivariate $\eta_p^2 = .972$. As shown in Figure 2, cognitive scores were better in the Audio condition than in the Audio + Video condition.

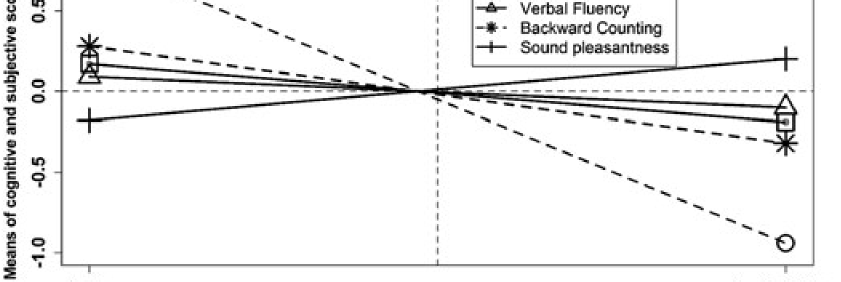

Figure 2. Standardized ratings of cognitive performances and sound pleasantness as a function of experimental conditions. To compare the pattern of the different measures, raw scores were standardized. To illustrate the different effect of the experimental conditions on the considered measures, the subjective annoyance was reversed and expressed as subjective sound pleasantness

The ANOVA on the Rey Auditory Verbal Learning Test showed that short-term verbal memory was not influenced by the Condition, $F(1, 49) = 1.695$, $p = .204$, $\eta_p^2 = .033$; the Scenario, $F(9, 441) = 1.716$, $p = .083$, $\eta_p^2 = .034$; or the Condition × Scenario interaction, $F(9, 441) = 0.852$, $p = .568$, $\eta_p^2 = .017$.

The ANOVA on the Intelligibility task showed that the capacity to discriminate words was influenced by the Condition, $F(1, 48) = 191.053$, $p < .001$, $\eta_p^2 = .799$; the Scenario, $F(9, 432) = 86.101$, $p < .001$, $\eta_p^2 = .642$; and the Condition × Scenario interaction, $F(9, 432) = 14.007$, $p < .001$, $\eta_p^2 = .226$. The mean comparison revealed that participants in the Audio condition ($M = 4.2$) were more accurate than participants in the Audio + Video condition ($M = 2.3$). The post-hoc analyses for the Scenario effect revealed that the various scenarios affected differently the mean number of correctly recognised words (with at least $p < .05$). In particular, the higher the SPL, the lower the intelligibility. Of course, the performance was more accurate in the control than in all other scenarios ($ps < .05$). Table 2 presents the means for each metro. Condition × Scenario interaction revealed that no significant differences between the Audio and Audio + Video conditions for control metro, New York MQ and Milan L3 metros (see Figure 3).

As regards the Verbal Fluency task, the ANOVA showed a main effect of the Scenario, $F(9, 441) = 4.095$, $p < .001$, $\eta_p^2 = .077$), but neither the main effect of the Condition, $F(1,49) = 0.447$, $p = .507$, $\eta_p^2 = .009$, nor the Condition Scenario interaction, $F(9, 441) = 0.972$, $p = .463$, $\eta_p^2 = .019$, were significant. The post-hoc analyses revealed that verbal fluency was lower in metro Milan L1 ($M = 8.06$) than in metro Turin L1, Rome LA and Paris L1 ($M = 10.27$, $M = 10.09$ and $M = 9.79$, respectively), $ps < .05$. No other significant differences were observed (see Table 2).

The ANOVA performed on the Backward Counting task showed that the mean amount of correctly counted numbers was influenced by the Condition, $F(1, 49) = 4.975$, $p = .030$, $\eta_p^2 = .092$, but neither by the Scenario, $F(9, 441) = 1.447$, $p = .166$, $\eta_p^2 = .029$, nor the Condition × Scenario effects, $F(9, 441) = 1.183$, $p = .304$, $\eta_p^2 = .024$. The mean comparison showed that the Audio condition was better ($M = 5.6$) than the Audio + Video ($M = 3.9$) condition.

Analyses on subjective annoyance

The MANOVA showed a significant overall effect of the experimental conditions on annoyance ratings, Wilks' (lambda) = .451, $F(9, 41) = 5.535$, $p < .001$, multivariate

Table 2. Mean correct responses to cognitive tests and noise subjective measures as a function of metro

	[a]Metro									
Measures	Control scenario	Berlin S3	Paris L1	Turin L1	Berlin U2	Rome LA	Naples L1	New York MQ	Milan L1	Milan L3
Cognitive tests										
Rey test	4.73	5.19	4.50	4.73	4.78	4.86	4.49	4.93	4.96	5.01
Intelligibility*	5.59	5.36	4.68	3.13	2.85	3.48	1.19	3.25	2.41	0.41
Verbal Fluency*	8.90	9.50	9.79	10.27	9.21	10.09	8.94	9.46	8.06	9.07
Backward Counting	5.05	4.43	4.98	4.81	4.84	4.78	4.43	4.59	5.18	4.94
Self-ratings										
Noise Annoyance*	–	4.27	4.78	5.19	5.18	5.16	6.53	5.43	5.40	6.96

Note:
[a]Metro lines are ordered by sound pressure level (from the lower 'Berlin S3' to the higher 'Milan L3').
*The Scenario effect was significant ($p < .05$). In general, the higher the SPL the lower the intelligibility. As regards Verbal Fluency, Milan L1 was less accurate than Turin L1, Rome LA, and Paris L1. Finally, perceived annoyance was higher in Naples L1 and Milan L3 and lower in Berlin S3 than all other metros.
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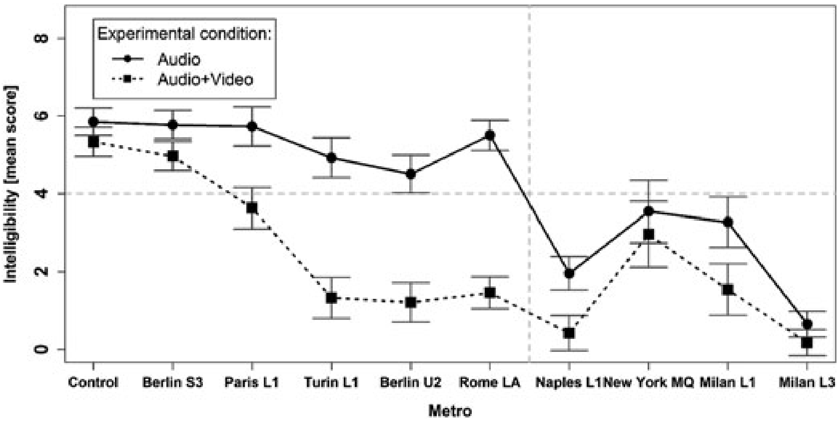

Figure 3. Mean correctly recognized words at the intelligibility task as a function of metros and experimental conditions. Metro lines are ordered by sound pressure level. Error bars represent 95% confidence interval of the mean values

$\eta_p^2 = .549$. Overall, the level of perceived annoyance was higher in the Audio condition than in the Audio + Video condition.

The ANOVA carried out on the self-reported ratings of annoyance showed that the mean ratings were influenced by the Scenario, $F(8,\ 392) = 13.787$, $p < .001$, $\eta_p^2 = .220$, and the Condition × Scenario effects, $F(8, 392) = 4.968$, $p < .001$, $\eta_p^2 = .092$, whereas the Condition effect was not significant, $F(1,\ 49) = 1.933$, $p = .171$, $\eta_p^2 = .038$. The post-hoc analyses for the Scenario effect showed that the perceived annoyance was higher in metro Naples L1 ($M = 6.5$) and in metro Milan L3 ($M = 6.9$) and lower in metro Berlin S3 ($M = 4.3$) than all other metros (see Table 2). The post-hoc analyses for the Condition × Scenario effect showed that perceived annoyance was significantly higher in metros Naples L1 and Milan L3 in the Audio condition ($M = 7.5$ and $M = 8.0$, respectively) than in the two correspondent scenarios in the Audio + Video condition ($M = 5.5$ and $M = 5.9$, respectively, for Naples L1 and Milan L3; see Figure 4). No significant differences were observed between the two experimental conditions in the other scenarios.

Correlation analyses

The correlation analyses showed that in both experimental conditions, there was a general association between specific acoustic parameters and both cognitive scores and subjective annoyance ratings (see Table 3). However, some differences between the experimental conditions emerged indicating a modulation tendency of visual components on the effects of the acoustic parameters. Indeed, the presence of a congruent visual context seemed to mitigate the negative impact of acoustic parameters on cognitive performances and perceived annoyance.

In both experimental conditions, data showed that SPL was positively associated with Annoyance, $r = .858$, $p < .01$ for Audio condition and $r = .700$, $p < .05$ for Audio + Video condition. SPL was negatively associated with Intelligibility, $r = -.870$ for Audio condition and $r = -.776$ for Audio + Video condition. Moreover, in the Audio condition, Loudness (N) showed the same pattern of SPL (Intelligibility: $r = -.864$; Annoyance: $r = .824$, $ps < .01$), Roughness (R) showed a negative relation with Intelligibility and Verbal Fluency ($r = -.767$, $-.779$, respectively, and $ps < .05$) and a positive relation with Annoyance ($r = .694$, $p < .05$). In the Audio + Video condition, there was a negative association between the Fluctuation strength (F) and the Backward Counting performance ($r = -782$, $p < .05$).

DISCUSSION

The main goal of this study was to assess acoustic comfort aboard metros by means of an audio-visual methodology. Noise effects on both perceived annoyance and cognitive performances during simulated metros journeys were measured.

Table 3. Correlation of acoustic parameters with cognitive tasks and subjective evaluations of annoyance as a function of experimental condition (Audio and Audio + Video)

	[a]Acoustic Parameters				
	SPL	N	S	F	R
Measures	dB(A)	Sone	Acum	Vacil	Asper
Audio					
Cognitive tasks					
Rey test	−.118	−.039	−.317	−.073	.037
Intelligibility	−.870**	−.864**	.355	−.045	−.767*
Verbal Fluency	−.549	−.653	.378	.206	−.779*
Backward Counting	.450	.329	.634	−.050	.156
Subjective evaluation					
Noise Annoyance	.858**	.824**	−.297	.106	.694*
Audio + Video					
Cognitive tasks					
Rey	.034	.234	−.162	−.447	.563
Intelligibility	−.776*	−.625	−.325	.233	−.465
Verbal Fluency	−.335	−.255	.050	.092	−.303
Backward Counting	.058	.177	−.118	−.782*	.361
Subjective evaluation					
Noise Annoyance	.700*	.527	.175	−.020	.245

Note:
[a]Acoustic parameters: SPL, sound pressure level; N, loudness; S, sharpness; F, fluctuation strength; R, roughness;
*$p < .05$;
**$p < .01$.

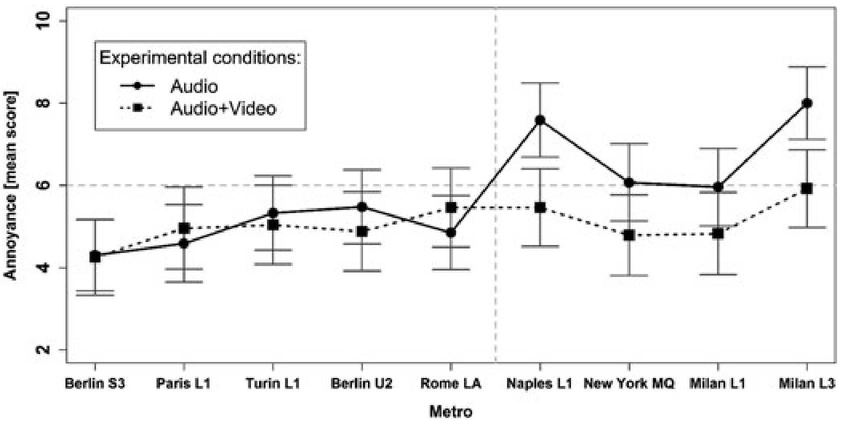

Figure 4. Mean annoyance ratings as a function of metros and experimental conditions. Metro lines are ordered by sound pressure level. Error bars represent 95% confidence interval of the mean values

To this end, we compared two different approaches: a traditional approach, based exclusively on the presentation of acoustic stimuli (Audio), and a bimodal approach based on the presentation of acoustic and visual stimuli by means of an IVR System (Audio + Video). Soundtracks from the inside of several real-world metros and visual scenarios reproducing a typical metro were used. In the bimodal condition, participants were immersed in virtual scenarios that combined the metro sounds with a 3D congruent visual presentation reproducing a realistic metro. Moreover, measures of cognitive performances along with traditional self-report measures (annoyance) were used.

In line with previous literature, results showed that in both Audio and Audio + Video conditions, perceived annoyance was influenced by metro noise levels; metros with more noisy acoustic patterns (i.e. Naples L1, New York MQ, Milan L1 and L3) produced higher annoyance ratings than all remaining metros. This suggests that the use of the IVR does not alter the direct relationship between annoyance and noise largely reported in open-field and laboratory studies (e.g. Miedema, 2007; Miedema & Vos, 1998). However, results also showed a significant difference between the two experimental conditions. In particular, the presence of congruent visual information mitigated subjective noise annoyance. Specific analyses showed that the influence of the audio-visual presentation was maximized as the degree of metro noise increased, in particular with a SPL value greater than 80 dB(A) (as in Naples L1, New York MQ, Milan L1 and L3).

The presence of visual scenarios in combination with acoustic patterns also influenced cognitive performances. However, it is worth noticing that the effect was the contrary of what was found with perceived annoyance. Overall, participants' performances were worse in the bimodal than in the unimodal condition, as if the presence of more contextual stimuli disturbed the cognitive processing. Furthermore, the negative effect of noise on cognitive performances was selective. Analyses revealed that when acoustic patterns were combined with visual information, they had a more detrimental effect on a resource demanding task like Backward Counting and on the capacity to discriminate words, than on short-term verbal memory and semantic memory. An effect of the different acoustic patterns characterizing each metro on semantic memory and word discrimination also appeared. As expected, the effect indicated that as far as metro sounds became more noisy, as defined by higher SPLs, the capacity to retrieve verbal information from long-term memory and to discriminate words decreased. In general, metros with an SPL greater than 80 dB(A), such as Naples L1, New York MQ, Milan L1 and L3, showed the highest negative impact on performances. Instead, soundtracks from Berlin and Paris metros seemed to ensure an easier verbal communication on board. Finally, an interaction effect between auditory scenarios and conditions appeared only for the capacity to discriminate auditory words. Participants' capacity was lower for all scenarios in the bimodal condition with respect to the unimodal condition, except for some of the more noisy scenarios, that is New York MQ and Milan L3.

Putting together the results about annoyance and cognitive performances, Berlin S3 and U2 and Paris L1 seem to represent a good example of acoustic comfort aboard metros. From an applied point of view, studying the technical characteristics of these kinds of metro, such as railway route design, train speed, type of boogie, type of wheels, type of brakes, type of suspension, type of metro car, track gauges and so on, can provide useful guidelines for coach producers.

Overall, the comparison between the two approaches shows that the presence of contextual visual information associated with metro sounds influences the impact of noise on individuals. This is consistent with the literature showing that the impact of noise does not rely exclusively on acoustic parameters but is influenced by contextual visual features (Pheasant et al., 2010). The fact that even the capacity to discriminate auditory words was more disturbed when the metro sounds were associated to their virtual visual metros than when they were not may be interpreted as a strong support of the audio-visual interaction during noise perception. Indeed, in this case, visual information was clearly irrelevant to the purpose of the task, but nevertheless, it influenced the auditory perceptual processing.

From a theoretical point of view, the overall findings are consistent with the idea that humans perceive the environment holistically (Cassidy, 1997). In turn, they are in line with the literature showing that auditory and visual information interact closely along all stages of stimuli processing (Ernst & Bülthoff, 2004; Stein & Meredith, 1993).

From a practical point of view, the results suggest that acoustic comfort assessment methods should be more biologically plausible, that is should take into account the multisensory way in which sounds are processed in real life. In this perspective, the IVR technology could represent a useful way to define more reliable norms about acoustic comfort. Instead, norms based on standard audio only methods could be less consistent with what happens in real contexts. We must recognise, however, that the graphic poverty of virtual reality simulations may undermine the naturalness of the situation. Therefore, we must be cautious in generalizing the results obtained. An optimal research strategy should also include a controlled experimental procedure in more ecological situations. In line with the study carried out by Watts and colleagues (2010), the results obtained by means of the IVR should be compared with what happens in real-world metros. Even in this case, we should consider that the complexity of the real environment and the occurrence of unexpected events might make the interpretation of the data rather complex or lead to designs that can be insensitive to the phenomena of interest (Davies & Logie, 1993). Therefore, more studies combining audio and visual information and based on different methods (IVR simulations, video recordings and ecological settings) would be necessary to find out appropriate acoustic comfort thresholds in different contexts.

Previous studies about acoustic comfort considered mainly participants' self-reported annoyance, whereas cognitive components have generally been neglected. However, many studies have demonstrated that environmental noise has a deep negative impact on cognitive performances (for a review, see Belojevic et al., 2003). Moreover, it has been argued that annoyance ratings and cognitive performances do not necessarily yield an identical pattern of noise effects on passengers (Belojevic et al., 2003). Consistently, our pattern of data revealed that the bimodal condition as compared with the audio only condition had a negative effect on cognitive performances but a positive effect on perceived noise annoyance. The presence of simulated visual features seems to disturb the cognitive tasks. If we define acoustic comfort in terms of perceived well being and cognitive efficiency, this implies that comfortable acoustic scenarios should allow for low annoyance ratings and good cognitive performances.

As regards the selective effect of noise patterns, with and/or without visual information, on cognitive performances, it is not easy to propose an exhaustive interpretation. To our knowledge, there are no published studies exploring the influence of visual features on cognitive tasks performed under noisy conditions. Studies that use unimodal audio methods are often contradictory. In some cases, noise seems to produce a negative effect on cognitive tasks, whereas in others, the effect disappears (for reviews, see Belojevic et al., 1992; Belojevic et al., 2003). This could be due to the presence of many factors such as characteristics of the acoustic parameters, cognitive demands of the tasks, environmental features and personality traits (Belojevic et al., 2003; Senese, Ruotolo, Ruggiero, & Iachini, 2012). Therefore, more studies are needed to better understand how the aforementioned factors may modulate the effect of noise on humans.

CONCLUSIONS

Overall, the results revealed that participants' cognitive performances were worse when soundtracks were associated to their natural visual contexts than when they were not. On the contrary, participants reported to be less annoyed by metro noise when they were immersed in the virtual visual metros. Visual context then seems to modulate the effect of noise on people. If we assume that the virtual audio-visual condition is closer to everyday metro journey conditions, these findings suggest that a bimodal method that takes into account the audio-visual way in which sounds are processed in real life is necessary to assess acoustic comfort aboard metros. To this end, the IVR technology may represent an optimal ally because it is able to provide auditory and visual simulations of metro journeys. Furthermore, virtual stimulations received by the participants facilitate the sense of immersion; that is, users feel like being part of the simulated 'universe' that they can explore by moving around, although the range of movements are still limited. These simulations could be useful to device prototypes of comfortable acoustic environments.

ACKNOWLEDGEMENTS

This research was supported by Research Grant from Second University of Naples, D.R. 1158/2010.

We are really grateful to Seckin Basturk, PhD student in Environment and Structures Representation, Protection and Safety at the Faculty of Architecture of the Second University of Naples, Italy, for useful technical support in setting up the virtual reality scenarios.

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