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Immersive virtual reality and environmental noise assessment: An innovative audio–visual approach

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ABSTRACT

Several international studies have shown that traffic noise has a negative impact on people's health and that people's annoyance does not depend only on noise energetic levels, but rather on multi-perceptual factors. The combination of virtual reality technology and audio rendering techniques allow us to experiment a new approach for environmental noise assessment that can help to investigate in advance the potential negative effects of noise associated with a specific project and that in turn can help designers to make educated decisions. In the present study, the audio–visual impact of a new motorway project on people has been assessed by means of immersive virtual reality technology. In particular, participants were exposed to 3D reconstructions of an actual landscape without the projected motorway (*ante operam* condition), and of the same landscape with the projected motorway (*post operam* condition). Furthermore, individuals' reactions to noise were assessed by means of objective cognitive measures (short term verbal memory and executive functions) and subjective evaluations (noise and visual annoyance). Overall, the results showed that the introduction of a projected motorway in the environment can have immediate detrimental effects of people's well-being depending on the distance from the noise source. In particular, noise due to the new infrastructure seems to exert a negative influence on short term verbal memory and to increase both visual and noise annoyance. The theoretical and practical implications of these findings are discussed.

1. Introduction

Motorways are considered a fundamental precondition of European prosperity (Ragazzi and Rothengatter, 2005). However, it is of vital importance that they are built with due responsibility for the well-being of the population and the protection of the environment. Indeed, it is well documented that motorways are one of the main sources of noise pollution along with aircraft and railway noise (Baldwin et al., 2004). Many studies have shown that traffic noise has a deep negative impact on individuals' health and quality of life (Ouis, 2001). Chronic exposure to traffic noise has been found to be associated with health problems such as hearing damage, heart disease, sleep disturbance, high levels of perceived annoyance, distraction, emotional problems such as fear and anger, and communication disturbances (Fyhri and Klæboe, 2009; Ljungberg and Neely, 2007; Öhrström, 1995; Ranft et al., 2009; for a review see Ouis, 2001). Moreover, traffic noise can have either a short term negative impact on cognitive capacities (Belojevic et al., 1992; Hygge et al., 2003) or long term negative effects if people are daily exposed to the source of noise (Evans, 2006; Ranft et al., 2009).

For all these reasons, it is necessary to assess, before building motorways, their potential impact on human beings. To this aim, different predicting studies about urban noise perception have been proposed (for a review see Miedema, 2007). Traditionally, noise perception assessment is based on subjective noise annoyance, that is, a self-report measure of displeasure or irritation caused by noise exposure (ISO/TS 15666, 2003). In the standard laboratory methods used to assess noise effects, people have to listen to pre-recorded road traffic noise and afterwards they have to report their degree of perceived noise annoyance on a 5- or 10-step scale (from non-annoying to very-annoying) (Maris et al., 2007; Sandrock et al., 2008, 2010). Otherwise, noise annoyance data are often collected through social surveys (Jakovljevic et al., 2009; Yang and Kang, 2005). In general, researchers have analyzed the relationship between noise annoyance and noise levels in terms of dose–response models and have shown

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that the higher the noise level (e.g. sound pressure level) the higher the number of people that will declare to be highly annoyed (Miedema, 2007; Miedema and Oudshoorn, 2001; Öhrström et al., 2006; Schultz, 1978). The dose–response curve parameters (Miedema and Vos, 1998, 1999) are used by planners and consultants to predict noise effects in future years and to plan noise abatement programs (Gusky, 2004). According to Miedema (2007), the dose–response curves allow an insight about the noise effects in a long term perspective. However, other studies have shown that the reliability of the prediction based on the dose–response curve may be insufficient due to large variations in individual annoyance reactions to the same noise exposure level (De Coensel et al., 2009; Paunović et al., 2009; Shepherd et al., 2010). In relation to annoyance, the literature indicates that only about 10 to 15% of the variability in ratings can be explained by noise level, arguing against the use of dose–response relationship as the sole basis for establishing noise standards. The remaining variability is likely to be explained by a collection of interacting factors including age (Van Gerven et al., 2009), noise source and attitude to noise source (Fields, 1993; Maris et al., 2007), personality (Belojevic et al., 1997, 2003; De Coensel et al., 2009), cognitive performance (Belojevic et al., 2003), time of day (Pirrera et al., 2010) and noise sensitivity (Paunović et al., 2009; Senese et al., 2012; Stansfeld, 1992).

Another criticism of the predicting role of the dose–response curves is that they do not consider the influence of the future visual environment on people's noise annoyance. This could represent a problem in the case of the construction of a new motorway, where both the existing acoustic and visual landscape will be modified. There are a huge number of behavioral and neuropsychological studies showing that visual information influences auditory judgments and vice-versa (Ernst and Bülthoff, 2004; Hunter et al., 2010; Iachini et al., 2012; McGurk and MacDonald, 1976; Ruotolo et al., 2012; Shams and Seitz, 2008; Viollon et al., 2002). 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 et al., 1992; Southworth, 1969; Tamura, 1997). In addition, the influence of visual scenes on sounds has also been found. 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. These findings confirm that the human perception is multisensory by its very nature and that the environment is perceived and represented holistically (Cassidy, 1997; Iachini et al., 2009; Pheasant et al., 2010). It is important to say that the visual preference for existing and future landscapes has been widely studied (Abkar et al., 2011; Wilson, 2002). However, these studies have mainly used photographs and photomontages, and only few researches have focused on the visual preference for landscapes by using an audio–visual approach (Li et al., 2012; Pedersen and Waye, 2007; Pheasant et al., 2010; Viollon et al., 2002; Watts et al., 2010, 2011; Yang and Kang, 2005). Furthermore, only in a few cases has the visual impact of an existing or future infrastructure been assessed by means of a 3D graphic reconstruction in 1:1 scale (Jallouli and Moreau, 2009; Ruotolo et al., 2012). Instead, a more plausible environmental noise impact assessment method should be characterized by the presentation of both future auditory and visual features of the environment and it should explore both auditory and visual people's annoyance.

Finally, the prediction models of noise effects are based mainly on subjective evaluations and only a few studies have used more objective measures, such as people's cognitive performances (Elmenhorst et al., 2010; Maffei et al., 2012; Nissenbaum et al., 2012). This is in contrast to some studies showing that noise can have adverse effects on cognitive and subjective measures (e.g. Belojevic et al., 1992; Sandrock et al., 2009, 2010; Stansfeld and Matheson, 2003), whose effects people may not be fully aware of (for a review see Smith and Broadbent, 1991). For example, a person may report that the level of noise is not annoying but objective measures may show a decline of his/her cognitive performances, and vice versa. So, even if subjective reports provide important information, objective measures are necessary to describe the effects of noise on people in a more complete way. Since cognitive processes, such as attention and memory, underlie many tasks in everyday life, the measurement of people's cognitive performances during noise exposure represents a simple and objective method to explore the effects of noise. Furthermore, it is important to highlight that other objective measures have been used to explore this issue, such as psychophysiological measures (e.g. heart rate, blood pressure, muscular tension, etc.). These studies have shown, often with contradictory results (Stansfeld and Matheson, 2003), that noise exposure can also increase heart rate, blood pressure, peripheral vasoconstriction and cortisol levels (for a review see Stansfeld and Matheson, 2003). However, the psychophysiological effects of noise on people have often been observed after long-term exposure to noise (Fyhri and Klæboe, 2009; Ranft et al., 2009). Instead, changes in cognitive performances after short-term noise exposure can give early evidence of potential disturbing effects of noise (e.g. Hancock and Vastmizidis, 1998). In other words, cognitive performances could be considered as early behavioral markers of harmful effects of noise. As a consequence, the assessment of environmental noise impact should concern both subjective (noise annoyance) and objective (cognitive performance) measures of people exposed to the noise source.

In an attempt to overcome all these limitations, we propose here a method to assess the impact of a projected motorway on people that (a) takes into account the multisensory way, i.e. audio–visual, in which individuals interact with the environment, and (b) considers the possible negative effects of noise on both cognitive functions and subjective evaluations. This approach is based on previous studies that have shown the influence of the visual context on noise effects in the case of metro journeys (Iachini et al., 2012; Maffei et al., 2010) and Wind Farm exposures (Ruotolo et al., 2012) that were simulated through immersive virtual reality (IVR).

In this research, the same IVR technology was used in order to reproduce the perceptual richness of the environment while keeping experimental control over the variables of interest. The IVR technology allows the simulation of an artificial world in a 1:1 scale that can give the observer a sense of "being there" (presence) in the environment. Although the graphics of virtual environments are still far from being fully natural, immersive virtual technology has two advantages: users are surrounded by the virtual environment and have the impression of being inside the virtual world; users can interact in real time with it. 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 (Slater, 2009). However, the success of the virtual simulations is mainly due to the fact that these simulated environments are able to provoke responses and behaviors similar to those portrayed in real environments (Bailenson et al., 2003; Jallouli and Moreau, 2009, 2010; Kastanis and Slater, 2012; Lombard, 1995; Meyer et al., 2012; Slater, 2009). One could argue that video recordings or pictures of actual environments or photomontages of future environmental scenarios could be more suitable for the purpose, and some work has shown that this method can be reliably used to assess tranquility of spaces (Watts et al., 2010). Video recordings and pictures have the advantage of reproducing real-life situations, but participants are outside the simulated world and cannot interact with it (Iachini et al., 2012).

In this research, a large rural area located in southern Italy was chosen as case study site. The site represents a real situation where local authorities planned to build a new motorway aimed at reducing the traffic congestion caused by crossing flow through the town.

Virtual models of the area were created that simulated both auditory and visual features, such as traffic noise, trees, cars, etc. These virtual models were presented to participants in two conditions: ante operam scenarios that reproduced the rural area as it was; post operam scenarios that reproduced the same area but adding the projected motorway.

Each ante and post operam scenario could be seen by participants from three different positions placed at different distances from the projected motorway. The three positions were chosen in order to have points where three different levels of impact were expected: PI) facing an existing local road and far from the new motorway (370 m); PII) in a quiet area and at relevant distance from the new motorway (152 m); PIII) in a quiet area and very close to the new motorway (16.5 m).

While immersed in the virtual scenarios, participants had to perform three cognitive tasks: a short term verbal memory task, and two tasks that required the maintenance of information in working memory and the inhibition of disturbing factors. After each virtual scenario immersion, participants were asked to report their degree of subjective visual and auditory annoyance.

On the basis of the literature, we can hypothesize that the noise level due to the new infrastructure should negatively affect both cognitive functions and subjective evaluations. In particular, we predicted higher levels of annoyance, both visual and auditory, and lower levels of cognitive performances in the post operam rather than in the ante operam condition. Therefore, a significant difference between ante operam and post operam conditions is expected. Furthermore, the distance from the noise source should modulate the influence of noise on cognitive and subjective measures, that is, the further the distance the less the disturbance. However, it is possible that noise may exert selective effects on cognitive performances (Belojevic et al., 2003; Iachini et al., 2012; Ruotolo et al., 2012).

2. Method

2.1. Participants

An a priori power analysis was conducted to calculate the sample size necessary to achieve a power of at least .80 in the within subject ANOVAs. To this aim we used the software G*Power 3.0.10 (Erdfelder et al., 1996). With an expected medium effect size (f = .25), an alpha of .05 and a power of .80, results indicated that a sample of 18 participants was needed. Therefore, twenty university students, 50% females, participated in the experiment, $M_{age} = 25.1$ years, $SD = 2.7$, range 21–31 years. All participants reported normal hearing and regular or corrected to normal vision.

2.2. Setting and immersive virtual reality equipment

The experiment was carried out in the Immersive Virtual Reality laboratory of the Second University of Naples. The laboratory is settled in a sound-proof rectangular room (4.7 × 3.8 × 3 m) that allows for extensive movements while participants are connected to the tools of virtualization. It includes a work station linked to the 3-D 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 a Intel R core (TM) 2 Quad 9300 2.50 GHz and 1.98 GHz processor with a 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 based on sensed position and orientation of the participant's head. In-ear headphone devices were used to integrate auditory information with the virtual environment.

2.3. Materials and setting

2.3.1. Auditory materials

The basic materials used to prepare the audio stimuli consisted of binaural audio signal recordings (16bit/44.1 kHz) collected, in a preliminary phase of the study, by an operator wearing headphones "Sennheiser Noise Gard HDC 451" connected to a portable two-channel device "M-Audio Microtrack 24/96".

In particular, in the rural area under examination, three receiver positions: PI, PII and PIII (see Fig. 1) placed at different distances (370 m, 152 m and 16.5 m, respectively), from the projected motorway were chosen for recording audio signals of the existing background noise.

During the audio recordings, the operator wearing the headphones faced towards the direction of the projected motorway. These recordings represented the exclusive auditory stimuli used for the so called "ante operam scenarios" in the three positions PI, PII and PIII.

Further binaural recordings were taken on a roadside of an existing motorway with characteristics similar to the projected motorway, i.e. type of pavement (traditional asphalt), road slope (flat), surrounding area (few buildings), traffic flow composition (1000 veh/h, 77% of light vehicles, 23% of heavy vehicles) and traffic speed (80–90 km/h). As previously mentioned, during the recordings the operator was oriented perpendicularly to the road. These recordings were representative of the sound emitted from the road source. A recording of a pure tone of 1000 Hz at 94 dB was also taken to calibrate the measure chain of all recorded signals.

In order to simulate the auditory contribution of the sound source (projected motorway) that will reach each receiver point (PI, PII and PIII), a traditional noise model of the post operam situation was built by means of the commercial noise prediction software SoundPLAN 7.0. The model includes both the environmental (e.g. digital ground model, buildings, etc.) and the road source features (traffic flow, speeds, percentage of heavy and light vehicles, etc.). The results of the traditional noise simulation were extracted in terms of one-third octave band noise levels for each receiver position (PI, PII and PIII). Consequently three different transfer functions (one-third octave bands filter attenuations) of the path road source-receiver were considered. The attenuations were then applied as octave band filter to the audio signal recorded at roadside in order to obtain the contribution of the road source at the three receiver points.

To complete the post operam auditory stimuli, the audio signal recordings of the existing background noise in each position were mixed down with the corresponding soundtracks of the road noise contributions. Fig. 2 reports the scheme of audio stimuli construction.

A preliminary analysis of the noise levels and the psychoacoustic characteristics are shown in Table 1. The psychoacoustic analysis was performed by means of "dB Sonic" software that provides A-weighted sound-pressure-level (SPL) and psychoacoustic parameters such as loudness (N), sharpness (S), fluctuation strength (F) and roughness (R) (see legend in Table 1). Detailed data of each parameter are reported in Table 1 as a function of the distances and the scenarios. Reported values are the average of the signals at the left and right channels. The table shows that the introduction of the new motorway's sounds in the post operam scenarios deeply modified the soundscape of the ante operam scenarios with the exception of scenario PI. In the latter case the variation was less relevant due to the presence of an existing road with the associated traffic noise.

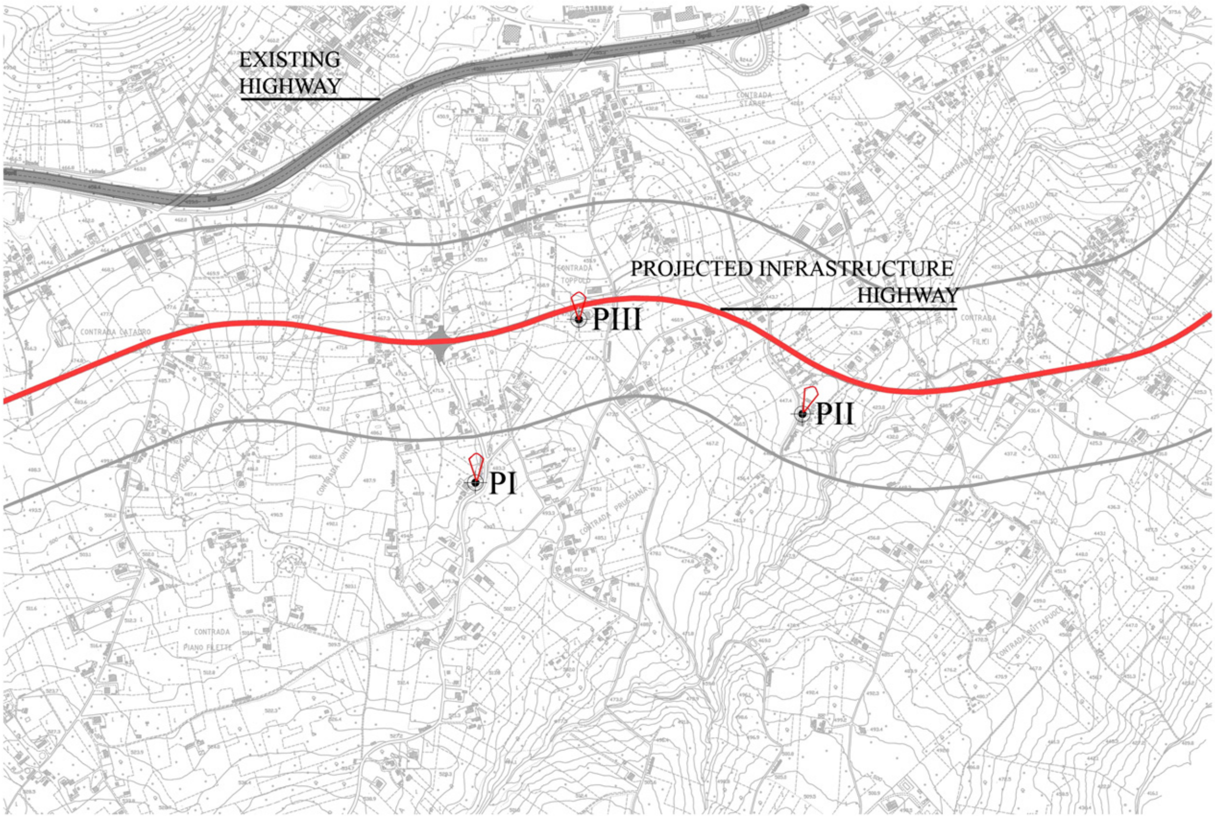

Fig. 1. The figure shows the entire area from a survey perspective. PI, PII and PIII indicate the positions from where participants experienced the virtual scenarios (at 370 m, 152 m and 16.5 m from the projected motorway, respectively). PIII represents the closest position to the projected motorway (the line in dark gray). The cones indicate participants' visual field and gaze direction. As shown on the map, participants faced the direction in which environmental sounds had been recorded.

2.3.2. Visual materials

ESRI ArcGIS was used to build up the visual stimuli. It allowed the visualization of the built environment and the ground of the area. Starting from GIS data and satellite images, the 3D model of the area was created by means of Google SketchUp 3D modeling software. Afterward, video and photo data acquired in the actual rural

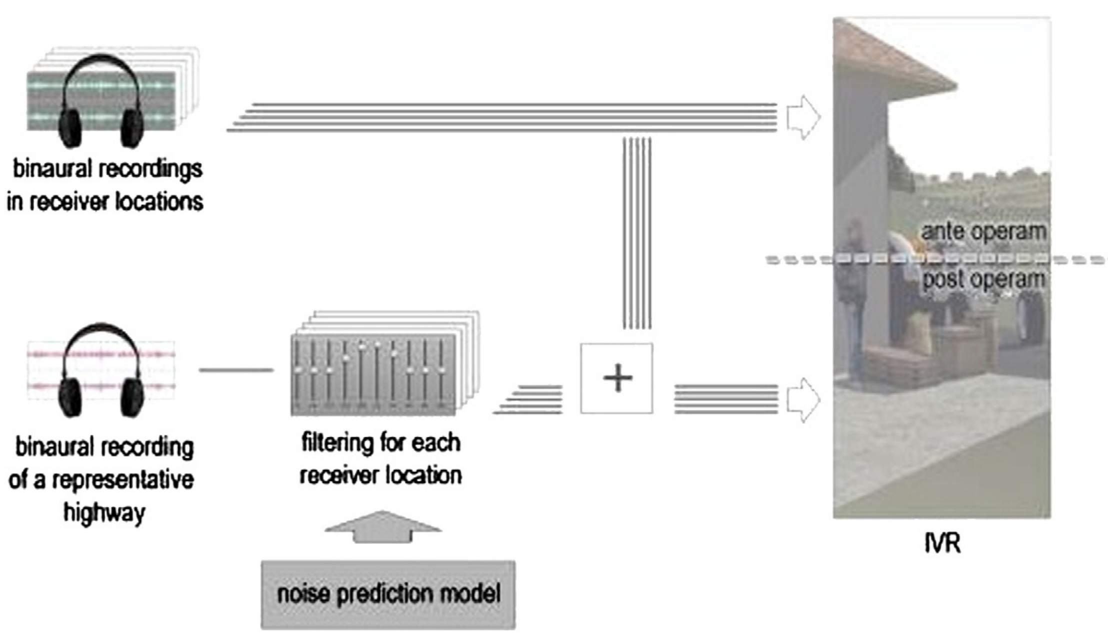

Fig. 2. The figure represents a schematic overview of the audio stimuli construction. As regards the ante operam condition (top of the figure) the audio recordings taken in situ were associated with the congruent visual scenarios. As regards the post operam condition (bottom of the figure), the audio simulations of the future scenarios were created by merging the ante operam audio recordings with the sound tracks simulated by means of a noise prediction software (SoundPlan 7.0). The new soundtracks were then associated with the congruent future visual scenarios.

Table 1
Acoustic parameters of selected soundtracks.

			Acoustic parameters*				
			SPL	N	S	F	R
Position	Distance^ (meters)	Scenario	dB(A)	SoneGF	Acum	Vacil	Asper
PI	370	Ante	70.3	30.1	1.2	0.1	0.4
		Post	70.3	30.7	1.2	0.1	0.4
PII	152	Ante	53.8	10.5	1.4	0.0	0.3
		Post	60.8	20.2	1.3	0.1	0.3
PIII	16.5	Ante	53.8	10.5	1.4	0.0	0.3
		Post	71.6	41.2	1.3	0.2	0.4

^Distance from the motorway; *acoustic parameters (Fastl and Zwicker, 2007): SPL, A-weighted sound pressure level 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 by 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. Points are ordered according to the distance from the projected infrastructure. The table shows how the motorway sound contribution introduced in the post operam scenarios significantly affects the sound characteristics of the ante operam scenarios only when the receiver point is not yet influenced by existing traffic noise (e.g. PI).

area were matched to the basic 3D model and other dynamic (cars, animals, people, etc.) and static elements (plants, sky, shadows, etc.) were added to make the virtual environment as realistic as possible (see Table 2 and Fig. 3).

For each position (PI, PII and PIII), ante operam and post operam scenarios were developed. In total, 3 ante operam and 3 post operam scenarios were simulated (see Fig. 4).

The audio and visual stimuli concerning each point were merged with WorldViz Vizard 3.X Development Edition software for immersive representation by means of a Virtual Reality System that considered at the same time the noise source and the participant position.

2.3.3. Cognitive tasks

To evaluate the influence of noise on cognitive processes, participants had to perform three cognitive tasks while immersed in each virtual scenario. Three typical tasks from neuropsychological literature that could be easily adapted to the experimental situation were chosen. For each task, six different versions that could be associated to each ante operam and post operam scenario and one version for the training session were developed. Furthermore, these tasks were chosen because they tap cognitive processes underlying common tasks in everyday life (i.e. short-term memory, attention and executive control).

2.3.3.1. Rey test (ReyT). This test is a classical neuropsychological instrument for evaluating short term verbal memory (Rey, 1959; Spinnler and Tognoni, 1987). It provides scores for assessing immediate and delayed memory of verbal information. The test consists of the oral presentation of a list of 15 words, at the 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 tested only the capacity to recall in short-term memory verbal items visually presented, at the rate of one per second. On the basis of the criteria adopted in the original list, 6 lists containing 15 words each were devised for the present study 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 s (15 s presentation; 15 s retrieval). For each participant, the total number of correctly reproduced words was computed (score range: 0–15 for each list).

2.3.3.2. Backward counting task (BC). This task taps executive functions and requires high attentional resources. In its original version, participants were asked to count backward in units of seven starting from a given number (e.g. 100, 93, 86, … and so on; Ganguli et al., 1990) within 30 s. In our version of the task, six starting numbers were considered: 64, 72, 81, 83, 93, and 96. Each starting number was visually presented. The total number of correctly generated numbers was computed.

2.3.3.3. Go–no-go task (GnG). This task taps the ability to select an appropriate response to a target stimulus and to inhibit the response to a non-target stimulus (Kiehl et al., 2000). In this study, participants were requested to clap their hands when one red dot appeared but not to clap their hands when two dots appeared (the task lasted 30 s).

2.3.4. Subjective evaluations

Individual noise subjective reactions to the audio–visual scenarios were assessed by means of a dedicated questionnaire devised according to ISO/TS 15666 (2003). The questionnaire comprised a question about the visual features (on a scale from 0 to 10, “How much did the visual aspects of the scenario annoy you?”) and a question about the audio features (on a scale from 0 to 10, “How much did the auditory aspects of the scenario annoy you?”).

2.4. Procedure

Before entering the virtual reality laboratory, participants were asked to fill out a consent form and a demographic survey. In the virtual reality laboratory, they read written instructions about the tasks which were then repeated orally by the experimenter. All participants had to put on the HMD and the in-ear headphones. Afterwards, a training session started (see Fig. 5). During the training session, participants explored a virtual environment and carried out all the tasks, as for a normal experimental session. When exploring the environment, participants could freely walk within the virtual scenarios since the virtual technology updated the virtual environment as participants moved through it. When carrying out the cognitive tasks, participants were instructed to face the direction in which the environmental sounds had been recorded by asking them to stand

Table 2
Audio and video (static and dynamics) stimuli included in the ante and post operam scenarios.

	Stimuli									
	Traffic	Sheeps	Dogs	People	Hills	Sky	Dwellings	Trees	Wind	New motorway
Ante operam	A	A	A	VS	VS	VS	VS	VS	A	
Post operam	A	A	A	VS	VS	VS	VS	VS	A	A-VD

A = audio; VD = video dynamic; VS = video static.

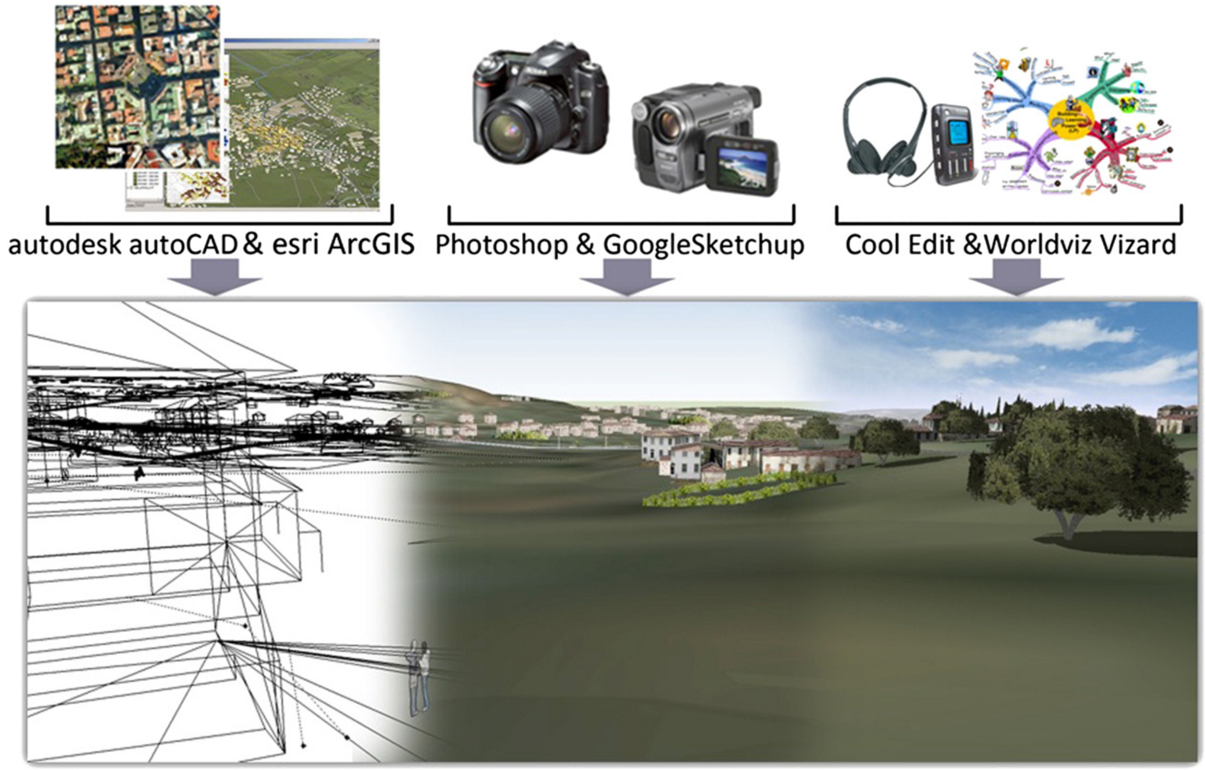

Fig. 3. The figure shows the tools, software and materials used for visual stimuli construction. The basic 3D model of the area was created by means of Google SketchUp 3D modeling software (bottom-left of the figure) by using GIS data and satellite images of the area (top-left of the figure). Afterwards, video and photo data acquired in the actual rural area (top-center of the figure) were matched to the basic 3D model (bottom-center of the figure) and other dynamic (cars, animals, people, etc.) and static elements (plants, sky, shadows, etc.) were added to make the virtual environment as realistic as possible (top- and bottom-right of the figure).

still at a pre-marked position. Only in this phase, feedbacks were given about performances. Afterwards, participants were requested to take off the helmet and report their degree of auditory and visual annoyance in the questionnaire. Moreover, participants were asked if they felt physically "present" in the virtual environment and if they felt the virtual scenarios as realistically as natural ones. All participants gave an affirmative answer to both questions. If the tasks and the procedure were clear, the testing phase started. Participants were "immersed" in the virtual scenarios as soon as they wore the HDM. The HDM did not allow for vision of external/physical world stimuli, but only visual and auditory stimuli of the virtual environment could be perceived.

The testing phase consisted of 6 scenarios (3-distance [PI, PII and PIII]×2-condition [ante operam and post operam]), each lasting 3 min. Within each scenario, participants had to perform the three cognitive tasks (ReyT, GnG, and BC). The beginning and the end of each cognitive task were indicated with a green and a red square, respectively. The inter-task interval lasted 15 s. The first green square appeared 30 s after the beginning of the virtual immersion. Immediately after, a cognitive task had to be performed. This procedure was repeated for each task, that is, three times within each scenario. After the last task, participants experienced the virtual environment for 30 s and then the virtual presentation stopped. The order of presentation of the scenarios was quasi-randomized. 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.

At the ending of each scenario, participants were required to fill out a self-report questionnaire assessing their degree of visual and noise annoyance.

2.5. Data analyses

To analyze the main and interactive effects of distances and conditions on each cognitive performance, three separate within-subject factorial 3×2 ANOVAs, that treated distance as a 3-level factor (PI, PII, PIII) and condition as a 2-level factor (ante- and post operam), were carried out on cognitive tasks. The correct responses to the ReyT, BC, and GnG task were used as dependent variables. To analyze both subjective visual and noise annoyance, the same model of ANOVA was carried out on visual and noise annoyance ratings. In all ANOVAs, the conservative Bonferroni correction was used to control for Type I error in post hoc tests, and the magnitude of the significant effects was indicated by partial eta squared (η^2_p). Finally, to investigate the effect of SPL and 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 scenario and mean scores of objective and subjective measures were carried out.

In all analyses an alpha value of .05 was used to determine significant differences.

3. Results

3.1. Analyses on cognitive performances

The ANOVA on ReyT scores showed that short-term verbal memory was influenced by the condition, $F(1, 19) = 6.942$, $p = 0.016$, $\eta^2_p = 0.268$. Participants in the ante operam condition ($M = 5.3$; $SD = 1.3$) were more accurate than in the post operam condition ($M = 4.7$; $SD = 0.9$). This means that the visual and auditory aspects

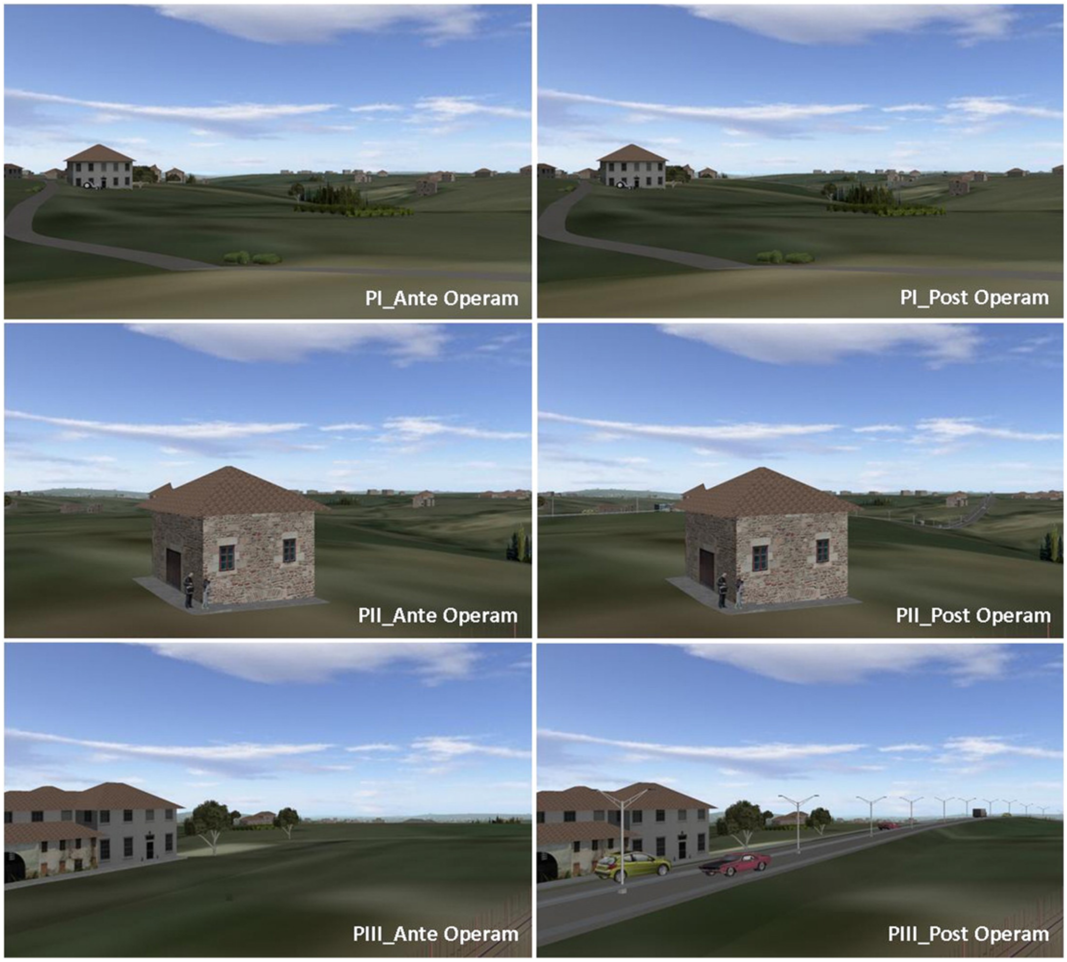

Fig. 4. The figure shows what participants could see from each position PI, PII and PIII in the ante and the post operam conditions according to the fields of view indicated in Fig. 1.

of the motorway had a negative impact on participants' short-term verbal memory. Moreover, participants tended to be less accurate as proximity to the sound source increased, although the distance factor only approached significance, $F(2, 38) = 2.691$, $p = 0.081$, $\eta^2_p = 0.124$. The interaction condition × distance was not significant, $F(2, 38) = 1.874$, $p = 0.167$, $\eta^2_p = 0.090$.

The ANOVA on the BC task showed that the mean of correctly generated numbers was not influenced by the considered factors, condition, $F(1, 19) < 1$, distance, $F(2, 38) = 1.50$, $p = 0.236$, $\eta^2_p = .073$, and condition × distance, $F(2, 38) = 1.550$, $p = 0.225$, $\eta^2_p = 0.075$.

Finally, the ANOVA on the Go–no-go task showed that the mean accuracy was not influenced by the considered factors: condition, $F(1, 19) < 1$; distance, $F(2, 38) < 1$; and condition × distance, $F(2, 38) = 1.947$, $p = 0.157$, $\eta^2_p = 0.093$.

3.2. Analyses on subjective annoyance

The ANOVA on visual annoyance showed that post operam scenarios were rated as more visually annoying than ante operam scenarios, $F(1, 16) = 16.90$, $p < 0.001$, $\eta^2_p = 0.514$ (see Table 3). Furthermore, an interaction between condition and distance was found, $F(2, 32) = 4.295$, $p = 0.022$, $\eta^2_p = 0.212$. The post hoc analysis showed that post operam scenarios were rated as more annoying than ante operam scenarios in the PII and PIII positions (with at least $p < 0.05$), whereas no difference between ante operam and post operam scenarios in PI was observed. As expected, participants rated as more visually annoying those scenarios where the new motorway could be seen, that is from 152 (PII) and 16.5 m (PIII). Finally, in the ante operam condition no differences were observed between the annoyance ratings of the three scenarios (see Table 3).

The ANOVA on noise annoyance showed a main effect of the condition, $F(1, 19) = 24.929$, $p < 0.001$, $\eta^2_p = 0.567$. Noise annoyance was higher in post operam scenarios than ante operam scenarios (see Table 4). This indicates that the introduction of a motorway in the environment chosen for the research negatively affected participants' evaluation of the acoustic landscape. A main effect of the distance was also found, $F(2, 38) = 8.758$, $p < 0.001$, $\eta^2_p = 0.316$. The post hoc analysis showed that the PI and PIII scenarios were rated as more annoying than the PII scenarios (with at least a $p < 0.05$). Finally, an interaction effect between condition and distance was found, $F(2, 38) = 9.786$, $p < 0.001$, $\eta^2_p = 0.340$. The post hoc analysis showed that post operam scenarios were rated as more annoying than ante operam scenarios in the PII and PIII positions (with at least $p < 0.05$), whereas no difference between ante operam and post operam scenarios in the PI was observed (see Table 4). This means that the sound from the new motorway also increased participants' noise annoyance ratings when they were closer to the noise source with respect to the scenario PI.

The correlation analyses confirmed the general association between acoustic parameters and subjective annoyance ratings; overall the higher the acoustic parameters the higher the subjective annoyance (see Table 5). The only exception was the sharpness parameter that showed a reverse pattern for both annoyance measures. In particular, the higher the sharpness, the lower the annoyance ratings.

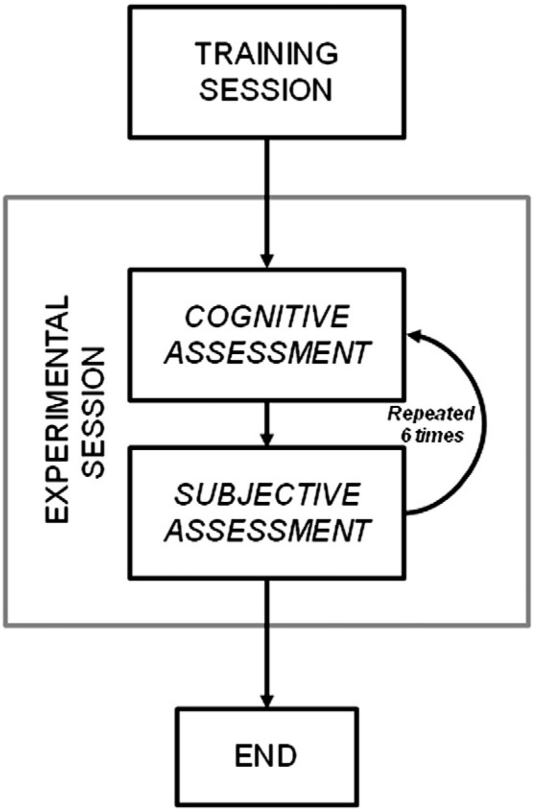

Fig. 5. The figure shows a schematic representation of the experimental flow. The experimental session started with the training session, then cognitive and subjective measures were collected for each scenario. Thus, participants repeated the cognitive and the subjective assessment six times. Afterwards the experiment ended and participants were debriefed.

This result was probably due to the fact that ante operam scenarios were generally rated as less annoying than post operam ones. Ante operam scenarios with respect to post operam scenarios were characterized by lower levels of all psychoacoustic parameters with the only exception of the sharpness.

4. Discussion

This study assessed the effects of a projected motorway on people's noise and visual annoyance and cognitive abilities by adopting an audio–visual immersive virtual reality approach. The immersive virtual reality equipment allowed the presentation of combined auditory and visual features that reproduced an actual case study landscape (without motorway) and the same landscape with the projected motorway. All the visual scenarios were combined with the appropriate audio patterns that considered at the same time the noise source and the participant's position. While immersed in each virtual scenario, participants performed three cognitive tasks that assessed short term verbal memory and executive control. Afterwards, they reported their degree of noise and visual annoyance.

As regards cognitive performances, results showed that the introduction of the motorway had a negative effect on short term verbal memory (ReyT), while it did not affect performances on executive control (BC) and attention (GnG). More specifically, participants' short term verbal memory was less accurate in the post operam than in the ante operam conditions, and when participants were closer to the noise source. This result is in line with the literature showing a difficulty in episodic and semantic memory due to road traffic noise exposure (Hygge et al., 2003), but contrasts with several studies showing that the impairment of short term verbal memory performance is mainly due to the concurrent perception of speech noise in background (Salamé and Baddeley, 1982; Szalma and Hancock, 2011). On a theoretical level, this result is in line with studies showing that non-speech noise, such as road traffic noise, has negative effects on short term serial recall of words. According to Jones (1993), this could be due to task-irrelevant information disrupting the retrieval of relevant verbal material. However, future studies are needed to explore what specific characteristics of road traffic noise are responsible for its rapid negative effects on short-term verbal memory. On the practical level, the negative effects of noise on verbal memory may have important consequences in daily life. Some studies have shown that when exposed to noisy contexts people can maintain their performance at higher levels if they are motivated to do so, but maintaining performance has a physiological cost (Miedema, 2007). In daily life people are not always motivated to invest the required effort and are not willing to pay the cost in the form of fatigue. Therefore, the most important consequence may be that people chronically

Table 3
Mean (SD) visual annoyance ratings.

Condition	Distance			Total
	PI^	PII	PIII	
Ante operam	2.57[a,1]	2.09[a,1]	2.20[a,1]	2.29[1]
	(0.67)	(0.69)	(0.67)	(0.68)
Post operam	2.85[a,1]	2.77[a,2]	3.54[b,2]	3.05[2]
	(0.75)	(0.79)	(1.08)	(0.87)

Equal letters or equal numbers indicate equal means ($p>.05$); ^PI = 370 m from the projected motorway, PII = 152 m; and PIII = 16.5 m.

Table 4
Mean (SD) noise annoyance ratings.

Condition	Distance			Total
	PI	PII	PIII	
Ante operam	6.10[a,1]	3.65[b,1]	4.20[b,1]	4.65[1]
	(2.83)	(2.59)	(2.44)	(2.62)
Post operam	6.40[a,1]	4.95[b,2]	7.40[a,2]	6.25[2]
	(2.82)	(2.62)	(2.30)	(2.58)
Total	6.25[a]	4.30[b]	5.80[a]	–
	(2.82)	(2.61)	(2.37)	

Equal letters or equal numbers indicate equal means ($p>.05$); ^PI = 370 m from the projected motorway, PII = 152 m; and PIII = 16.5 m.

Table 5
Correlation of scenarios' acoustic parameters with cognitive tasks and subjective evaluations of annoyance.

Measures	Acoustic parameters[a]				
	SPL	N	S	F	R
Cognitive tasks					
Rey test	−.360	−.177	.618	−.073	−.205
Backward counting task	.390	.172	−.678	.003	.183
Go–no-go task	.186	.313	.056	.422	.317
Subjective annoyance					
Visual	.850*	.846*	−.765*	.883*	.889**
Noise	.888**	.749*	−.938**	.597	.748*

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

exposed to noisy environments could often fail in tasks such as reading, sentence comprehension and so on. For all these reasons, cognitive measures should be taken into account when an environmental impact assessment of a new motorway has to be carried out.

As regards subjective evaluations, data showed a similar pattern in visual and auditory annoyance. In both cases, post operam scenarios were rated as more annoying than ante operam ones, particularly when the scenario closest to the noise source (position PIII) was considered. Instead, no difference was found between ante operam and post operam scenarios when participants visually and auditorily rated the scenario farthest from the new motorways (i.e. PI). From a theoretical perspective, the similarity between auditory and visual annoyance seems to confirm that auditory information and visual information are processed in close interaction, thus supporting the idea that humans perceive the environment holistically (Cassidy, 1997; Meyer et al., 2010).

From an applied perspective, it reinforces the idea that a method that takes into account the audio–visual way in which sounds are processed in real life is necessary for a valid noise assessment procedure (Iachini et al., 2012; Maffei et al., 2010; Ruotolo et al., 2012).

Although this research does not allow the exploration of the differences between the multisensory method and the traditional unimodal (e.g. audio-only or video-only) presentations, it is important to highlight that the methodology used in this study is based on the results of two previous researches. In particular, in a study about the acoustic comfort aboard metros, Iachini et al. (2012) explored the effects of metro noise on people's cognitive abilities and noise annoyance by comparing a unimodal auditory condition and a bi-modal audio–video presentation. Results showed that participants in the unimodal condition reported higher level of noise annoyance and had a better cognitive performance with respect to participants who experienced the multimodal presentation. A similar pattern of results was found by Ruotolo et al. (2012) by comparing the effects of a Wind Farm on individuals in three different conditions, with both auditory and visual components, with auditory features only, and with visual features only. Overall, the results from the above mentioned studies suggest that the impact of the auditory and visual characteristics of an infrastructure on people's annoyance and cognitive performances can vary according to the kind of methodology used. Since a huge number of studies have shown that human perception is multisensory by its very nature (Stein and Meredith, 1993), then a biologically plausible assessment method should be based on the multisensory way in which people experience their environment and not on a unimodal/mono-sensory presentation of the stimuli. Immersive virtual reality may help to reach this aim by simulating multisensory stimuli and the individual-environment interaction in a controlled way. Furthermore, there are an increasing number of studies showing that people show a sort of “behavioural realism” when they experience immersive virtual simulations, that is they behave as if they were in a natural environment (Jallouli and Moreau, 2009; Meyer et al., 2012; Slater, 2009). However, caution is needed and more studies are necessary to fully validate this methodology.

Finally, correlation analyses showed that perceived annoyance increased with higher levels of sound pressure levels, loudness, roughness and fluctuation, and decreased with higher levels of sharpness. On the one hand, these data seem to confirm the existence of a positive relationship between noise and annoyance largely reported in open-field and laboratory studies (Miedema, 2007; Miedema and Vos, 1998, 1999), on the other hand they suggest that different psychoacoustic parameters can determine different patterns of perceived annoyance. As regards the relationship between sharpness and annoyance, the literature shows contrasting evidence. According to the psychoacoustic annoyance (PA) model (Fastl and Zwicker, 2007), a sharpness increase leads to an increase in the PA index. However this is true only for sharpness values greater than 1.75 acum. In another study (Wang et al., 2012), where the sharpness values were lower (ranging from 0.5 to 0.8 acum), a negative correlation was found. In the current case study, when the low frequency contribution of the motorway is added to the natural background noise (post operam scenarios) the sharpness values became slightly lower, even though still higher than the just noticeable difference in sharpness (Pedrielli et al., 2008). This unexpected situation could be responsible for the reverse pattern between sharpness and annoyance. For this reason, environmental noise assessment procedures should always take into account the psychoacoustic parameters along with the analysis of the sound pressure levels (Fastl and Zwicker, 2007). Instead, as regards cognitive tasks, the results from correlation analyses are less conclusive, although a tendency emerged for sharpness affecting positively short term verbal memory and negatively backward counting task (the effect only approached significance). However, considering the few levels inserted in the analysis (only three positions and two conditions) these results should be taken with caution.

5. Conclusions

Overall, the results show that the introduction of a projected motorway in the environment can have detrimental effects on people's well-being depending on the distance from the noise source. In particular, noise due to the new infrastructure seems to exert a negative influence on people's short term verbal memory and to increase visual and noise annoyance. These effects increased with proximity to the noise source.

The fact that our results were in line with previous evidence about the effects of noise on people, would suggest that participants' responses to stimuli within the immersive virtual environment tended to approximate those that they would exhibit in response to the same but natural environment (Freeman et al., 2000; IJsselsteijn et al., 2000). Therefore immersive virtual reality could be considered a valid tool to simulate the multisensory way in which the environment, with embedded sounds, is perceived in everyday life and can offer innovative applications. Indeed, it may allow designers and consultants to understand in advance the possible negative effects of new infrastructure and to propose the best noise mitigation measures at the initial stage of motorway planning (see also Isaacs et al., 2011; Lange, 2011). However, more studies are needed to understand the limits and potentialities of this approach based on audio–visual immersive virtual reality (de Kort et al., 2003).

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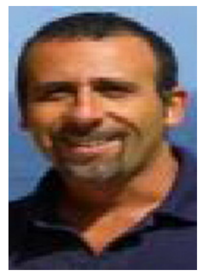

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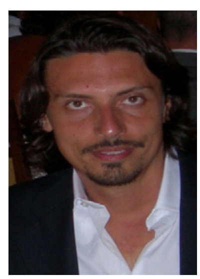
Affiliation: Built Environment Control Laboratory, Second University of Naples.



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