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Towards a method for subjectively evaluating the impact of facade insulation interventions by acoustic virtual reality

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ABSTRACT

In order to support acoustic consultants in providing tailored solutions to clients regarding facade insulation against environmental noise, a subjective method has been designed to assess the effect of four types of facade solutions by using acoustic virtual reality. In this exploratory study, environmental traffic noise was recorded in first-order Ambisonics inside an apartment of which the facade is exposed to road traffic noise, and simultaneously a 360-degree picture was captured. For a listening experiment, the measured indoor audio stimuli were filtered according to spectral changes corresponding to four facade insulation intervention scenarios. To test the effect of environmental noise on noise annoyance and performance, a within-subject experiment with n=10 participants was designed containing ISO/TS 15666 questions and a Rey auditory verbal learning task (ReyT). Both tasks were carried out in a VR environment, which consisted of a head-mounted display and headphones. The subjective results showed a statistically significant linear effect between the amount of noise and the annoyance. However, the objective results were inconclusive. This paper gives insight in the method to experience facade insulation interventions prior to construction.

INTRODUCTION

According to the WHO Regional Office for Europe [1], sound can be perceived as pollution and can negatively influence people’s health, affecting cardiovascular health, sleep and quality of life. Ruotolo et al. [2] mention that cognitive performance can be affected by environmental noise. Environmental noise can be caused by infrastructure, such as road traffic, railway traffic and airplanes [1]. When sound affects activities such as sleep or daily activities, it can cause stress. In the long-term, these interruptions can cause chronic effects on people’s health [3].

Environmental traffic noise has been shown to be one of the most annoying types of sounds in everyday life [4]. If the sound pressure levels (SPL) caused by environmental noise, such as road traffic, exceed a certain level at the facade, acoustics consultants need find a solution to decrease the sound level. Three types of solutions are always considered: reducing the SPL at the source (e.g. changing road pavement), reducing the SPL from source to receiver (e.g. through noise barriers) and reducing the SPL at the receiver (e.g.

through building interventions) [5]. Building interventions aimed at reducing environmental noise can be planned in advance in order to comply with the regulations of the national Building Code. However, sometimes the regulations do not solve the problem of noise pollution inside the building for the following reasons: i) the measured or calculated sound is averaged over a period of time and the maximum sound level of loud vehicles that sporadically drive by are not considered by the regulations; ii) lack of sufficient sound insulation of dated buildings that were built with older building codes; iii) the residents or occupants of the buildings are more sensitive to the local environmental noise than the building codes capture.

Several studies have tested human noise perception with virtual reality (VR) technology in the built environment [2], [8], [7], [8]. VR is also a tool to test the personal preference of the resident or occupant of the building besides following the Building Code. Therefore, VR technology is considered a good instrument for this assessment of building interventions based on the following three arguments.

First, VR includes both audio and video, which is necessary for a better evaluation of human perception. Several studies have shown that the combination of audio and video in a method can give different results regarding sound perception, due to human’s perception being multisensory by nature [5], [7], [9], [10]. VR technology allows humans to incorporate multiple senses simultaneously, and is therefore more realistic than audio only.

Second, VR is immersive. Jeon and Jo [7] mention with three references in their paper that laboratory studies lack the real-world experience. Being immersed in VR, users feel as if they are part of the virtual environment [3]. Research has also shown that participants respond sensitively to audio and visual information in a virtual environment [9].

Third, VR technology could address the fact that noise and health effects are individual. It would provide the opportunity to test noise perception individually and use the results as input for construction adjustments.

This paper presents a VR technology approach, developed to measure the environmental noise perception of individuals in residential buildings. It is an attempt to bridge the gap between interventions based on the Building Code and people’s preferences. The goal is to develop a method that can used by acoustic consultants looking for tailored solutions. The paper is to present the development of a method, and demonstrate its usage. The adopted VR framework, based on (modified) measured audio and images, is described as well as the objective and subjective test designed to evaluate the interventions. Results of a preliminary study are shown, followed by a discussion.

METHOD

The laboratory experiment was a within-subject design conducted in a virtual environment with the use of VR. The auditory and visual environment were made for the experiment and explained in the second subchapter. During the experiment the participant performed two tasks multiple times in (acoustic) VR. This method can be applied to existing buildings to assess the interventions.

Setting and equipment of the VR

Since human perception is multisensory, VR technology was used to include both auditory and visual stimuli. The Head Mounted Display (HMD) that was used was the Oculus Rift and its Touch controller devices. This HMD was connected to the laptop of the experimenter (Lenovo ThinkPad P1). The Oculus Rift headphones were replaced by Sennheiser HD 265 linear. Unity was used as software to reproduce the virtual environment, characterized by the 360° image of the room, the experimental interface, and the audio stimuli. These included the first-order Ambisonics (FOA) recordings of the scene, filtered according to interventions, and the words to be remembered during the cognitive task. The resolution of the graphics of the VR headset were unchanged, therefore 1200 x 1080 px per eye with a refresh rate of 90 Hz and 110° field of view. In addition to the virtual environment, the Unity Experiment Framework was used to create the experiment.

Materials and setting

The experiment consisted of four different original audio files and four filters applied to each file, for a total of 16 different stimuli. For every condition the participant completed one cognitive task and two subjective questions, with a break after 8 conditions. An overview of the design of the experiment is shown in Figure 1. Eight ordered spoken word lists with randomized items were presented twice, each while listening to one of the 16 audio stimuli, presented in randomized order.

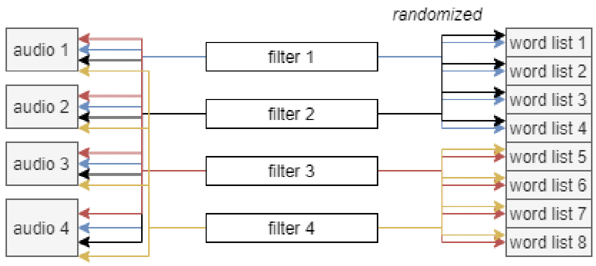

Figure 1: Overview of the experiment design

The room in which the recordings took place was part of an apartment building located at the 15th floor in Eindhoven, The Netherlands, visible in plan in Figure 2. The room was used for studying, which is a task consisting of reading and memorizing [11]. The recordings were made at the location of the black dots in Figure 2: the black dot with the red circle is where the recordings for the experiment took place, in front of the studying desk. The outdoor sound recording was used as the background sound for showing the experiment instructions while being immersed in VR in the 360 image of the balcony. At the same recording locations, with few cm of vertical displacement, the NTi Audio XL2-TA SPL meters were placed to measure the sound pressure levels during the recordings.

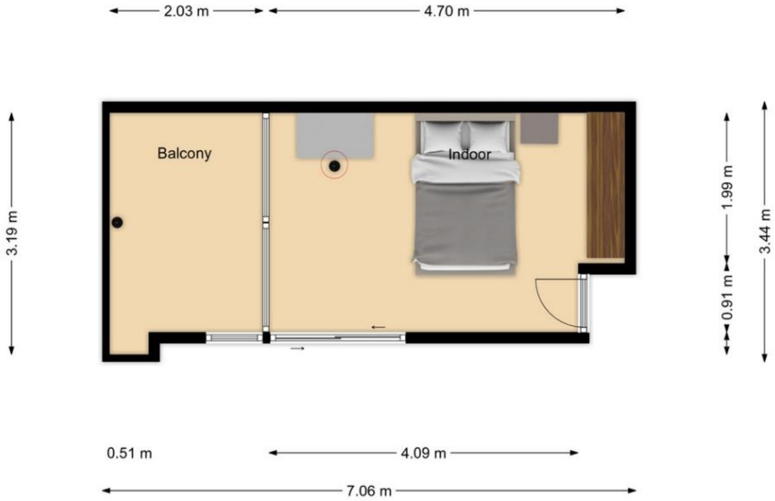

Figure 2: Map of the room and its measurement locations. Road traffic noise sources are left from this apartment

The visual scene was captured with use of an Insta360 One 4K UHD Action Camera, connected to a power bank. A 360° picture can be made via the app over Bluetooth, to ensure that there are no individuals in sight of the camera. The picture was made at the eye level of a sitting person (128 cm). In Figure 3, below, the 360° picture that was used in the experiment is shown.

Figure 3: The 360° picture of the room

The audio materials used in the experiment are recorded samples at the specific locations. This recording was done with a Rode NT-SF1 sound-field microphone connected with four channels to a TASCAM DR-680MK II recorder, set to a recording rate of 48000 Hz. The gain for all channels was set uniformly and it was ensured that no clipping would occur for the current conditions. The audio scenes used in the experiment were recorded with the sound field microphone in four different conditions, as shown in Table 1, while logging data with the two SPL meters. The recordings took place on the 23rd and 24th of October 2020 between 9 am and 12:00 pm.

Table 1. Audio recording conditions and locations

Condition	Where	Window	Height [m] (from floor level)	Distance from facade [m]
1	Outside (balcony)	Closed	1.50	2.0
2	Inside (bedroom)	Open	1.28	0.6
3	Inside	10 cm open	1.28	0.6
4	Inside	Closed	1.28	0.6

For each recording excerpt, four channels (A-Format) were imported into Reaper v6.13 and transformed into one FOA track. This was done through the plug-in VST: SoundField by RODE converting its native format to B-Format (AmbiX). The HRTF was managed in Unity by the Oculus Ambisonics decoder.

The volume of the room was 30 m^3 with a glass facade of 7 m^2. The reverberation time was assumed to be 0.5 seconds. The facade consisted of a full-height sliding window door consisting of two symmetrical frames, made of single paned glass with a thickness of 4 mm ($R_{Av,glass}$ = 26.8 dB(A)). A single sealing of the window with the window frame and the window frame with the stone construction was assumed. The natural ventilation present in the room was an air vent with sliders, located in the immobile sliding door, without thermal or acoustical insulation.

The existing facade sound reduction index was calculated according NEN-EN 12345-3 and NEN 5077 for traffic noise at $G_{A,k}$[1] = 19.4 dB(A), while the sound reduction index was also measured according to the difference in sound levels between traffic noise measurements and was 17.5 dB(A). This could mean that in theory the facade is slightly overestimated. Both values show that the facade does not meet the requirements according to the Dutch Building Code [12], namely 28 dB(A).

The first facade improvement was made by substituting the window with a double paned glass construction filled with air (glass 4 mm – cavity 12 mm – glass 6 mm) and a small air vent with sound insulation ($G_{A,k}$ = 22.4 dB(A)). The second solution was made of double paned glass construction filled with air (4-16-8) and a better sound insulated air vent ($G_{A,k}$ = 24.0 dB(A)). The third solution was calculated with a double paned glass construction filled with air (4-6-8) and an air vent with a high sound insulation (*Suskast Alusta Alumien 100*; $G_{A,k}$ = 24.8 dB(A)). The final solution was calculated with a laminated double window (8-160-12.2) and with the same insulated air vent (*Suskast Alusta Alumien 100*; $G_{A,k}$ = 30.9 dB(A)).

The filter gains were obtained as per theoretical calculations for the frequency bands ranging from 125 Hz to 2000 Hz according to the Dutch standard NEN 5077. The transmission losses beyond these frequency bands were assumed to be the same as the transmission loss value of 125 Hz (when lower) or 2000 Hz (when higher). The transmission losses were converted to (negative) gains for the four filters over the frequency spectrum, and are shown in Table 2. The filters were applied to the original sound recording in MATLAB with use of a graphic equalizer function, with 2nd order cascade structure, with a bandwidth of one octave.

Table 2: The negative filter gains [dB] for the four solutions/filters in the frequency spectrum 31.5 to 16000 Hz

f [Hz]	31.5	63	125	250	500	1000	2000	4000	8000	16000
Filter 1	-2.9	-2.9	-2.9	-1.4	-1.3	-2.6	-3.5	-3.5	-3.5	-3.5
Filter 2	-4.0	-4.0	-4.0	-2.7	-3.9	-6.6	-6.6	-6.6	-6.6	-6.6
Filter 3	-7.9	-7.9	-7.9	-7.3	-7.0	-5.6	-6.2	-6.2	-6.2	-6.2
Filter 4	-17.0	-17.0	-17.0	-16.8	-17.0	14.1	-15.3	-15.3	-15.3	-15.3

Due to limited time constraints the sound level of the headphones could not be calibrated to accurately match the real environment. Therefore, the volume of the sound was approximated to perceptually resemble the real environment from experience. As a result, the audio settings of the laptop (Lenovo ThinkPad P1) were set to equal (volume 100) for all participants.

Tasks

The cognitive task that was used was the Auditory Verbal Learning Test, based on [2] and [13]. The three Dutch lists with fifteen words each from the study of Van Den Burg and Kingma [13] were used in the experiment. Seven additional lists were made that were similar in word frequency [14] and number of monosyllabic and disyllabic words. The meaning of the words was non-ambiguous and not abstract.

The words were transformed to audio files by using a Text to Speech Software converter (https://wideo.co/text-to-speech/). The voice that was used was Amanda Rose and the speed was set to 0.75 in increase perceived clarity of the words. The location of the voice was centered inside the head in Unity, as if it were thoughts instead of an additional external

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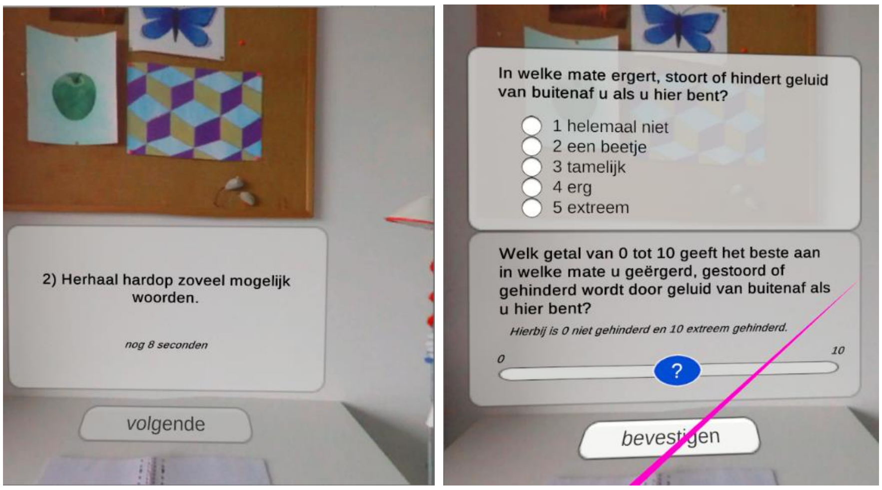
[1] $G_{A,k}$ is the sound insulation according to the Dutch calculation method called: "*Rekenmethode Geluidwering Grote Gemeenten.*"

sound source. The loudness of these thoughts was adjusted to a perceptual acceptable level that would not dominate the background noise. Every second a different spoken word was played back, for a total of fifteen words. The participant had 15 seconds after this to say the memorized words from that list out loud. The appearance of the countdown and the subjective question in VR are shown in Figure 4a-b.



2) Herhaal hardop zoveel mogelijk woorden.

nog 8 seconden

In welke mate ergert, stoort of hindert geluid van buitenaf u als u hier bent?

○ 1 helemaal niet
○ 2 een beetje
○ 3 tamelijk
○ 4 erg
○ 5 extreem

Welk getal van 0 tot 10 geeft het beste aan in welke mate u geërgerd, gestoord of gehinderd wordt door geluid van buitenaf als u hier bent?

Hierbij is 0 niet gehinderd en 10 extreem gehinderd.

Figure 4a-b: The experiment interface in VR: (a) countdown for the cognitive task; (b) subjective noise annoyance question

The two subjective questions asked after the cognitive task were based on the ISO/TS 15666:2003 standard and asked in Dutch. The translated version is: “How much does noise from outside bother, disturb or annoy you?” The same question was asked twice per condition, but with a different answering scale: either five-point (“not at all” (1) to “extremely” (5)) or 11-point scale with only numbers (“not at all annoyed” (0) to “extremely annoyed” (10)).

Procedure

The experiment took place in the Virtual Reality lab of Human-Technology Interaction in the Atlas Building of the Eindhoven University of Technology to ensure a conditioned environment. The experimenter made sure the COVID-19 safety protocol of the HTI-lab was followed as indicated in Figure 5. Prior to the experiment, the participant registered him/herself, read and signed the informed consent form and read the instructions of the experiment. The participant was then asked to put on the VR headset and was instructed with guidance of the experimenter to stay with the head within a virtual mannequin, corresponding to the correct listening position in the scene. However, the participants was still able to move his or her head. After this the right oculus Touch controller was given to the participant and the headphones were put on the participants head. The experiment started with two recordings (recordings from window completely open and 10 cm open) that functioned as a training session for the interface. When the participant had no questions left, the experiment started. The first condition was a silent condition to track baseline performance of the cognitive task, followed by eight filtered FOA audio randomized in order, a break, and again, eight other conditions in randomized order as shown below in the figure.

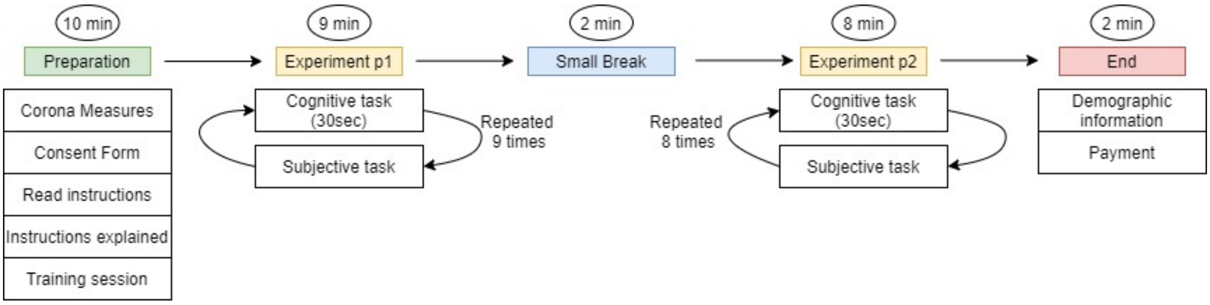


Figure 5: Procedure of the experiment

Overall, all the participant encountered a total of sixteen computed conditions in random order made of four audio recordings in combination with four filters. The experimenter then instructed the participant that the experiment was over and asked the participant to take off the headphones and headset. After a short debriefing, the participants were asked to send a payment request, which was immediately payed after receiving it.

Participants

The participants (n = 10) were recruited via the JSF database from the Human-Technology Interaction group. They all spoke Dutch, had no impaired hearing (self-reported) and had normal or corrected vision. The age of the participant ranged from 20 to 58, where the average age was 27, SD = 11.225, M = 23. Four males participated in the study and six females.

Data analyses

The data was checked for outliers and the relevant assumptions for the two main effects was checked: first the effect of the traffic noise level on cognitive performance and then the effect of the traffic noise on the subjective score. The first main effect was tested with a two-way ANOVA repeated measures to include the repetition of the audio and the filters per participant. Secondly, a correlation between the filter and the outcome of the subjective questions was tested with a Spearman’s test. An effect of the filter on the subjective questions was tested with a two-way repeated measures ANOVA, where the audio and the filters were repeated, again.

RESULTS

Effect of filter on cognitive task

Normality was rejected for cognitive values in filter 1 and 4 conditions and no transformations were logical. Therefore, no repeated measures ANOVA could be run with reliable outcomes. However, a Kruskal-Wallis test was possible and showed no difference in effect between the four filters on the score of the cognitive task, $\chi^2 = 0.992$, $p = 0.803$. These results should be interpreted with caution, since the individual effect of the participants is not considered. The results are in line with the results from Figure 6 below: there is no clear effect of the filter on the score for the cognitive task visible.

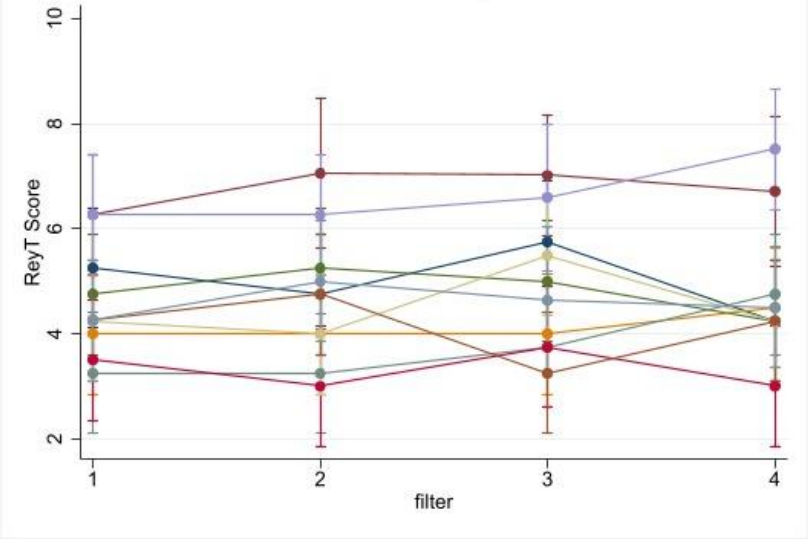


Figure 6: Margin's plot of cognitive task score for the four filters per participant

Correlation of subjective questions and the filter

The correlation between the values of the two subjective questions was statistically significant (r = 0.855, p < 0.005). The correlation between the first subjective question (5-point scale) and the filter gives r = -0.168, p = 0.030. Also, the correlation between the second subjective question and the filter gives a statistically significant and negative value (r = -0.156, p = 0.044). Although the correlations are very small, the effect is statistically significant and negative, as expected. This means that people indeed felt that they were more distracted/disturbed by the sound if the filter reduced the sound level to a lower amount. The same effect is shown in Figure 7, below: a better filter shows a lower score on the subjective questions.

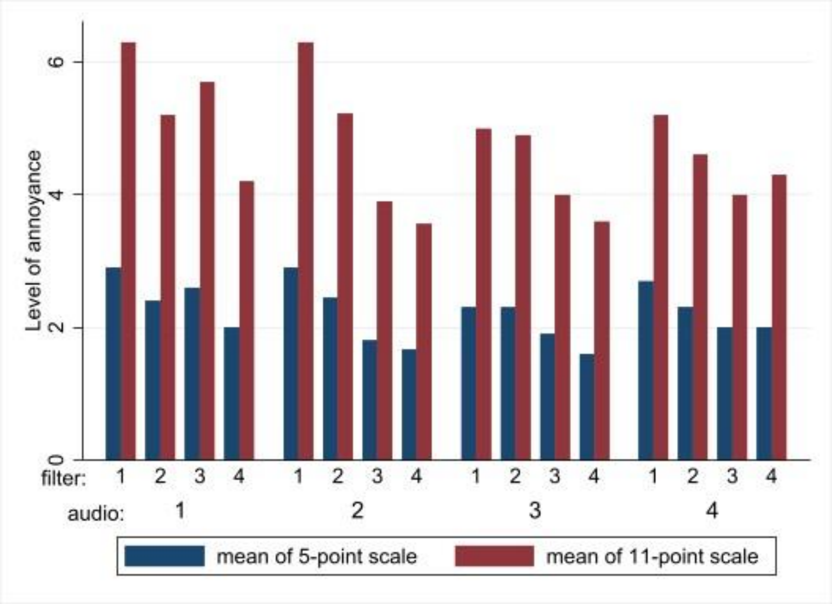


Figure 7: Bar graph with subjective scores per filter and audio condition. The broadband reduction values are for filter 1 = 3.1 dB(A), filter 2 = 4.6 dB(A), filter 3 = 5.4 dB(A) and filter 4 = 11.5 dB(A)

To give more insight in the relation between the filters and the subjective scores, two two-way repeated measures ANOVA were run. One with the 5-point scale and one with the 11-point scale as dependent variable. Not all the 5-point scale variables were normally distributed, therefore no strong conclusions can be made. However, the two-way repeated measures ANOVA shows that there is a statistically significant effect of the filters on the subjective score, $F(3, 141) = 12.40$, $p < 0.001$, $\eta^2_{partial} = 0.219$. This effect is larger than the effect of the audio samples on the subjective score, $F(3, 141) = 3.07$, $p = 0.030$, $\eta^2_{partial} = 0.065$. Nevertheless, the most significant contributor to the difference in the subjective scores are the participants, $F(9, 141) = 19.90$, $p < 0.001$, $\eta^2_{partial} = 0.058$.

The two-way repeated measures ANOVA with the 11-point scale lacked normality in two filter categories. However, an outlier was excluded by being 1.5 times the interquartile range added to the 75% of the variable and looking inconsistent according to eyeballing. After this exclusion, only the data in filter 4 was not normally distributed, as was the case in the previous ANOVA. The results from this repeated measures ANOVA were similar to the previous ANOVA. The effect of the participants on the subjective score was the largest, $F(9, 131) = 18.97$, $p < 0.001$, $\eta^2_{partial} = 0.438$. Then, the effect of the filter followed, $F(3, 131) = 10.23$, $p < 0.001$, $\eta^2_{partial} = 0.123$. And finally, the just statistically significant effect of the audio on the subjective score, $F(3, 131) = 2.85$, $p = 0.040$, $\eta^2_{partial} = 0.038$. The interaction between filter and audio was not statistically significant, $F(9. 131) = 0.98$, $p = 0.457$. Since some variables are not normally distributed, the results need to be interpreted with caution.

DISCUSSION

Evaluation of the results

The main effect of the filters on the score of the cognitive task has been analyzed. Nevertheless, the results should be interpreted with caution, since some variables were not normally distributed. Besides the lack of normality, the effect of the filters on the cognitive task has not been proved. The Kruskal-Wallis test showed no difference in the effect of filters on the cognitive performance. The effect can be explained by the fact that the equivalent sound pressure level of the audio between filter 1 and 2 and filter 2 and 3 does not differ much as shown in Table 3. The effect of the filter shows to be smaller than the effect of the audio file in some cases.

Table 3: L_{eqW} [dB(A)] per filter and audio recorded at desk with closed window

L_{eqW} **[dB(A)]**	**Filter 1**	**Filter 2**	**Filter 3**	**Filter 4**
Audio 1	30.6	29.3	27.0	18.5
Audio 2	28.7	27.4	25.2	17.0
Audio 3	26.6	25.3	23.1	14.7
Audio 4	31.4	30.3	27.3	18.7

The fact that the Kruskal-Wallis test over all the filters showed no difference in the cognitive score, could be explained by the fact that the difference between the audio tracks was not large enough. Nevertheless, the lack of effect on performance has been found in earlier research as well [15]. Moreover, the participants mentioned that the task is very difficult, which could encourage participants to shield from the noise [15].

The results show that the effect on the cognitive task score is mostly caused by the participants themselves. The effect of the participants on the score is likely not explained by the difference in gender, despite a slightly higher mean score of females. Other demographic information might explain the large effect of participants on the cognitive score [16].

Participants that have a history with the specific location might react differently to the experiment, since the effect of the long-term noise exposure has been shown to have a different impact than the short-term noise exposure [2], [3]. In this experiment the participants had never been in the specific location and could therefore have rated the noise differently than with a long-term history.

The subjective part of the experiment shows that there is a small, but statistically significant correlation between the noise annoyance and the filters. This shows that the participants slightly notice the difference between the filters and experience the sound that is less loud as less disturbing. Nevertheless, participants mentioned during the experiment that they were mostly bothered by the sounds that were unexpected: varying from clicking a pen, to a large truck driving by, which is in line with [15], [17]. This shows that equivalent sound levels are not enough to relate to annoyance, but that the variation in the sound may have a larger influence.

Method evaluation

In order to replicate the method, the template of the experiment in Unity can be used on request. The sound and visuals can be applied to any environment. The use of VR has given the opportunity to assess noise in a multisensory environment. The usefulness of a break in VR technology experiment has shown to be necessary in some cases. Fortunately, the option for a break in between did not seem to make difference on the results.

In the process of making the method, several assumptions were made. The first assumption was made for the sound pressure level of the sound in the headphones due to time constraints. To improve this study, this calibration step needs to be added to the method. The second assumption that was made was the location and level of the speech of the words to be recalled. Since there was no explanation of having an externally located sound source without being able to see it, the sound source was placed inside the participant’s head. It is unknown how this affects the experience. Moreover, the level of the voice relative to the background noise could have affected the difficulty of the task. Another assumption was made during the calculations of the sound insulation. The calculated values in theory might differ in practice. The study could be improved by using measurements to determine the sound insulation. This information could be used to have a better approximation of the room in theory and base the filters on this new approximated value.

Future research

Future research could improve five aspects of the study. First, the effect of the sound source location of the words on the participant should be investigated. There might be possible perceptual effects if this location is altered, which should be included in the research as well. One participant mentioned that the articulation of the words is a little muffled, making the words less pervasive, according to the participant. The second aspect is the effect of the location of the traffic noise with respect to the listener. In this experiment the sound field presented more energy on the left side of the participant. However, the participants were free to turn their head during the experiment. Since, this aspect was not controlled, further research might provide more insight in possible effects. Another aspect for future research is the cognitive task that was used in the experiment. There was a trade-off between visually presented words that would be less realistic or auditory presented words. In the experiment of [2] and [18], visually presented words were used for the cognitive task. Only in the former, the analysis of the performance showed statistically significant results. To increase the ecological validity, during the task no words were visually presented. However, the impact of visually presented versus auditory presented words in a cognitive task needs to be researched, due to inconclusive results [18]. The fourth aspect is the fact that the least noise was perceived as the best condition. However, future research is necessary to include the costs aspect of the possible constructions. Participants will, presumably, choose the option with the least noise, which is likely the most expensive facade solution. Therefore, further research should give insight in the acceptable facade solution, that is also perceived as comfortable. Finally, this study only focused on the assessment of sound in the facade interventions on existing buildings. Future research could give insight on the assessment of acoustic environments for new construction based on sound simulations, instead of recordings.

CONCLUSION

In this study a method has been designed to measure the environmental noise perception of individuals. In order to bridge the gap between designing facade interventions following a national Building Code and people's preferences, multiple sound insulation solutions were evaluated with use of subjective questions and cognitive tasks. Altogether, the results show that more research on cognitive tasks in audio assessment should be done. However, the subjective results show that this method can be used to assess noise annoyance of participants and determine the right construction solution. The experiment showed that noise is perceived differently across the participants and, therefore, this assessment is a good way to test noise annoyance individually. Several aspects can be improved, but this study has shown that VR technology is an appropriate tool for environmental noise assessment, also applicable in a consultancy company. The method is generalizable over multiple projects, since all information is available to replicate the study for different situations. This might be the beginning of handling facade interventions for each project in a tailored way, since the scenery, sound insulation, and audio recordings can all be changed.

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