



# Effects of sound environment on perceived enclosure in urban street canyons

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## Abstract

This study aims to examine the influence of sound on the perception of the enclosure in urban street canyons with varying height-to-width ratios (H/W). Two typical urban streets, one narrow and one wide were modelled with street widths of 6 m and 27 m, respectively. The H/W ratio was varied from 0.5 to 6 in seven steps by changing the height of buildings on both sides of the street. The experiment was conducted in a virtual reality (VR) environment. For visual images, three-dimensional models of the streets were created using visualisation software (3D Max and Adobe Photoshop) and moving vehicles were generated using Unity. For sound stimuli, synthesized car pass-by sounds were cut into 301 pieces then convolved with 301 impulse responses extracted from acoustic software (Odeon). The experiments consisted of three sessions: 1) an audio-only condition, 2) a combined audio-visual condition, and 3) a visual-only condition. Participants were asked to rate their subjective responses to stimuli in terms of the perceived pleasantness and perceived source width for the audio-only condition, the perceived enclosure, perceived spaciousness, perceived pleasantness, and perceived source width for the audio-visual combined condition, the perceived enclosure, perceived spaciousness, perceived pleasantness for the visual-only condition. The results showed that the perceived enclosure, perceived spaciousness, perceived pleasantness and perceived source width decreased when the H/W ratio increased. The presentation of sound significantly influenced perceived spaciousness, perceived pleasantness and perceived source width, whereas perceived enclosure was not affected by sound.

**Keywords:** Enclosure; Street canyon; Height-to-width ratio; Audio-visual interaction; Virtual Reality.

## 1 Introduction

Street canyons are visually three-dimensional, consisting of horizontal and vertical surfaces so that the buildings on both sides create an enclosure. Many studies have examined the perception of enclosure in urban environments because it is closely associated with practical planning and design strategies. More specifically, the perceived degree of enclosure, perceived width, and perceived height have been introduced as a dependent variable of subjective impression of enclosure [1,2]. Additionally, perceived comfort and safety in urban environments have been evaluated because enclosure relates to the sense of comfort and safety in such environments [3-5]. However, few studies dealt with the perceived enclosure with a presence of sound.

Hence, in this paper, the impact of sound on the perception of the enclosure in urban street canyons is investigated with a range of H/W ratios. The purpose of this study is to explore whether enclosure is affected by the presentation of sound in narrow and wide urban streets. It was hypothesised that sounds in the street canyons would play a significant role in the perception of enclosure. It was also expected that the impacts of sound on enclosure might be difference across the H/W ratios. 3D visual images of various streets were created from three-dimensional models using a variation in H/W ratios. Sound stimuli were then made by using impulse responses extracted from the computer simulations convolved with the car passing by sound that cut into pieces. Virtual reality (VR) models were created by using 3D models, sound stimuli and 3D visual images. Laboratory experiments were performed in order to clarify the effect of sound stimuli on the perception of the enclosure in urban streets. Participants rated the 3D visual images and sound stimuli in terms of perceived enclosure, perceived spaciousness, perceived pleasantness, and acoustic source width.

## **2 Methodology**

### **2.1 Participants**

Although our target number of participants is 30-40 participants, as this is an ongoing experiment, we currently have data from 10 participants (8 males and 2 females) aged between 40 and 53 ( $M=48.2$ ,  $SD=3.9$ ). None of the participants reported any hearing disabilities.

### **2.2 Street canyons**

The street canyon model used in this study is identical to that of Lee and Kang (2015) [6]. The model employs a 400 m length of the street with continuous buildings along the sides at constant heights. Two street canyon widths of 6 m (2 lanes) and 27 m (6 lanes) were chosen to represent narrow and wide urban streets, respectively [5]. Nelessen (1994) [7] recommended different widths for urban streets; approximately 6 m for alleys and 26.2 m for boulevards. The heights of the buildings were changed at seven steps for each width; consequently, the height-to-width ratio (H/W) varied from 0.5 to 0.6. Similar to study of Lee and Kang (2015) [6], the minimum height of the buildings was 3 m corresponding to the standard height between floors, whereas the maximum heights were 36 m and 162 m for narrow and wide streets, respectively.

### **2.3 Stimuli**

The visual stimulus material consisted of 14 images of two typical urban streets, one narrow and one wide with street widths of 6 m and 27 m, respectively. The H/W ratio was varied from 0.5 to 6 in seven steps by changing the height of buildings on both sides of the street. Figures 1 and 2 show the three-dimensional street canyon models created by using 3DsMax.



Figure 1 – Narrow streets with the building heights of 3, 6, 12, 18, 24, 30 and 36 m.

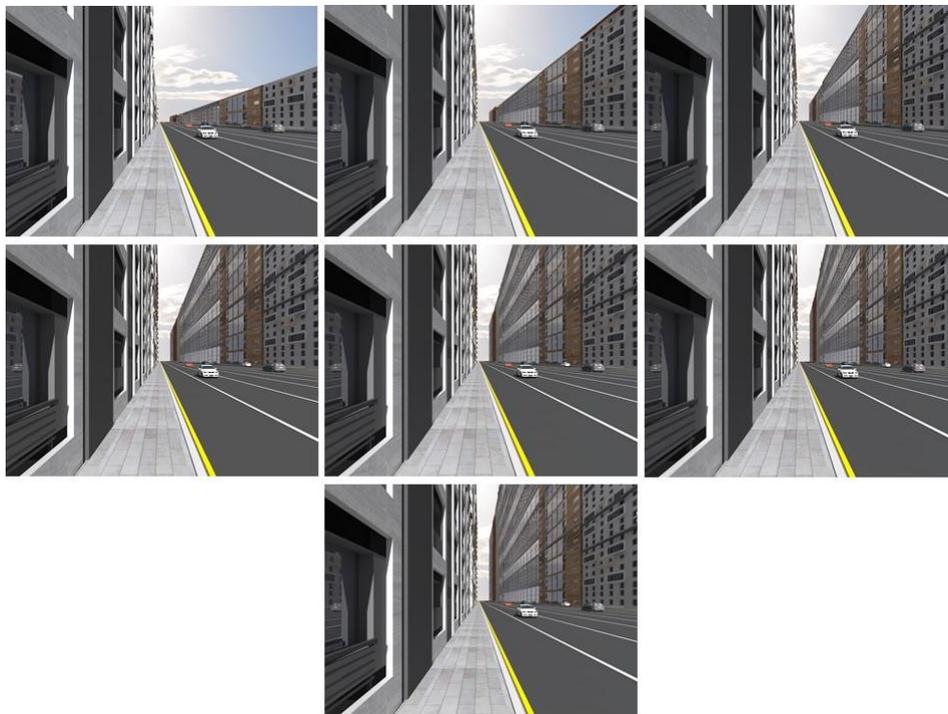


Figure 2 – Wide streets with the building heights of 13.5, 27, 54, 81, 108, 135 and 162 m.

For the VR experiment of street canyons, 3D models were prepared by using Sketch-up Software. Virtual Reality models were created by Unity Software by using 3D Sketch-up models (Figure 3). Visual edits on the roads and lighting were made in the Unity model to make VR environment more realistic. Moving vehicles were generated by using Unity and Oculus Rift. The vehicles were then combined with the convolved sound sources. Ten and 30 cars were used for the narrow and wide streets, respectively in the VR models. Due to the difference in the cars, sound pressure levels of the narrow streets (55 dB) were 5 dB greater than those in the wide streets (60 dB).



Figure 3 – Views from the Sketch-up models of the urban streets.

Lee and Kang (2015) [6] reported that the H/W ratios of the street canyons significantly affected the sound fields in terms of the sound pressure level and reverberation time. In order to adjust the acoustic characteristics of the street canyons across the H/W, the car pass-by sound was cut into pieces and then convolved with acoustic impulse responses obtained from acoustic simulations (Odeon). Firstly, the thirty seconds long car pass-by sound (50 km/h) was cut into 301 pieces (0.09 second each)[8]. While the receiver was fixed at one position, the 301 sound were located along the street in the Odeon. For the narrow streets, 301 impulses responses (301 sources (in the middle of two lanes)  $\times$  1 receiver) were extracted from each narrow street while 903 impulses responses (301 sources at 3 positions  $\times$  1 receiver) (Figure 4) were extracted for each of the wide streets for more realistic reflections. As shown in Figure 5, the original car pass-by sound was partitioned into 301 segments using Hamming window in Matlab for convolution. Then three different overlap settings (i.e. 0.33 overlap, 0.67 overlap and 0.5 overlap) for Hamming window were implemented for the convolution with 301 impulse responses to make the smoothest and the most realistic convolved car pass-by sound. Figure 6 shows the convolved sounds with different overlaps.



Figure 4 – Locations of the sources at 3 positions (1,2,3) for wide streets.

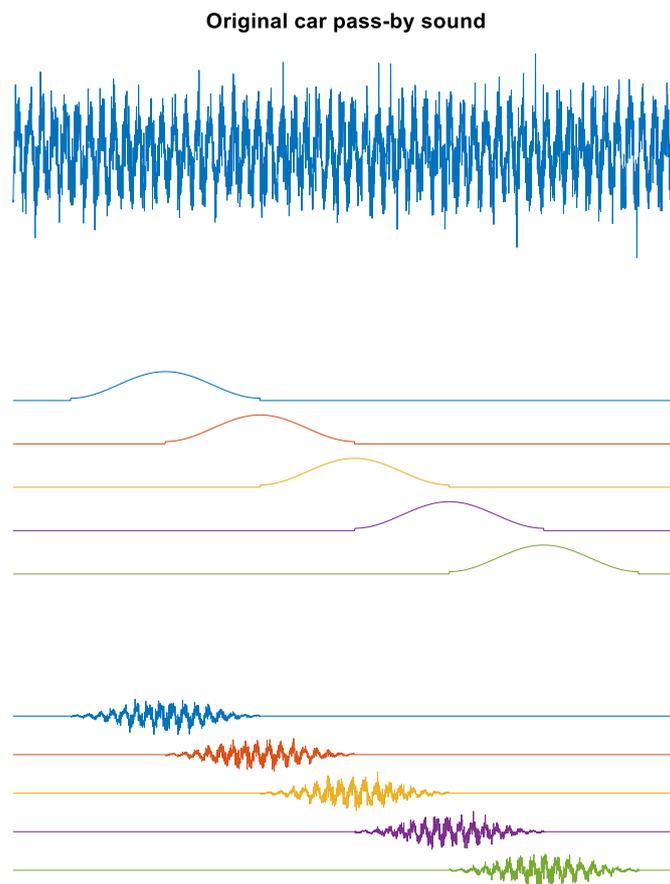


Figure 5 – The visual representation of half overlap of Hamming window on the original car pass-by sound.

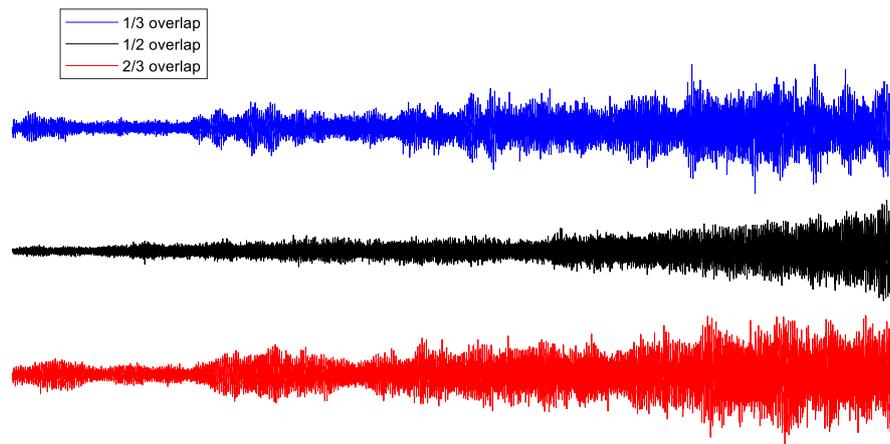


Figure 6 – The final convolved moving car sound with three different overlaps.

## 2.4 Procedure and design

This experiment was designed to include sessions with and without the presence of sound stimuli and visual stimuli similar to some previous studies that have compared the perception of sound stimuli in different conditions with and without visual stimuli [9,10]. In the experiments, three sessions were considered:

1) Session 1: an audio-only condition, 2) Session 2: a combined audio-visual condition, where visual models were provided with convolved car pass-by sounds, and 3) Session 3: a visual only condition, where only visual models were presented.

In sessions 2 and 3, it was hypothesised that the presence of visual stimuli and varying acoustic conditions could have had an impact on the perception of enclosure. Session 1, which only involved sound stimuli, was designed to investigate the perception of the acoustic environment. Each participant was exposed to a total of 42 stimuli, including 14 sound stimuli (Session 1), 14 combinations of sound and visual stimuli (Session 2), and 14 visual stimuli (Session 3). Sessions lasted for approximately 40 minutes in total, 10-12 minutes each which are 7 minutes of stimuli and then answering the questions. In each session, stimuli were randomly presented to avoid the order effects. A training session was carried out before the sessions began to help participants become acquainted with the experiment. The training session was lasted approximately four minutes and consisted of both street canyons with widths of 6m and 27m. During the training session, each participant evaluated audio, audio-visual and visual stimuli of the main sessions.

The experiment has been conducting in the control room of the listening booth in the Fire Insurers Laboratories of Korea. The control room dimensions are 4 m (width) x 7.5 m (length) x 3 m (height). The background noise level was averagely 30 dBA and the reverberation time of the control room is between 0.71 seconds for 50 Hz and 0.40 seconds for 8000 Hz. All sessions of the experiment have been conducted by using VR headset (Oculus Rift Headset) and hand controllers.

## 2.5 Assessment

During Session 1, with the presence of sound stimuli, the participants were asked to rate their perception of enclosure in terms of perceived pleasantness and perceived source width. During Session 2, with the presence of visual and sound stimuli, the participants were asked to rate their perception in terms of perceived pleasantness, perceived spaciousness, perceived pleasantness and perceived source width. During Session 3, with only the presence of visual images, the participants were asked to rate their perception in terms of perceived enclosure, perceived spaciousness and perceived pleasantness. The participants rated perceived enclosure on an 11-point numerical scale ranging from 0 (closed, not wide at all, not comfortable

at all) to 10 (open, extremely wide, extremely comfortable). The participants also rated sound stimuli using an 11-point numerical scale (0: `not wide at all` and 10: `extremely wide`).

### 3 Results

Currently only 10 participants took part in the experiment, initial findings were presented here without statistical analyses.

#### 3.1 Effects of H/W on subjective responses

Figure 7 shows mean ratings of the perceived pleasantness, perceived enclosure, perceived spaciousness and perceived source width as a function of H/W in the combined audio-visual condition, respectively. Results show that in the wide street, participants feel more pleasant, open, spacious and wide for all H/W. For the width of 6 m, all perceived pleasantness, enclosure, spaciousness and source width decreased in the end as the H/W increased from 0.5 to 6, although there is some increase between H/W ratios of 2 to 5. The decrease of the perceived enclosure was significant between the H/W of 1 and 2, after H/W of 2, there are slight increases although the existence of some small fluctuations. There is big difference between narrow street and wide street in terms of perceived spaciousness. Although the perceived spaciousness in both narrow and wide streets decreased with the increase of H/W, the perceived spaciousness of the wide street was always much higher than the narrow street.

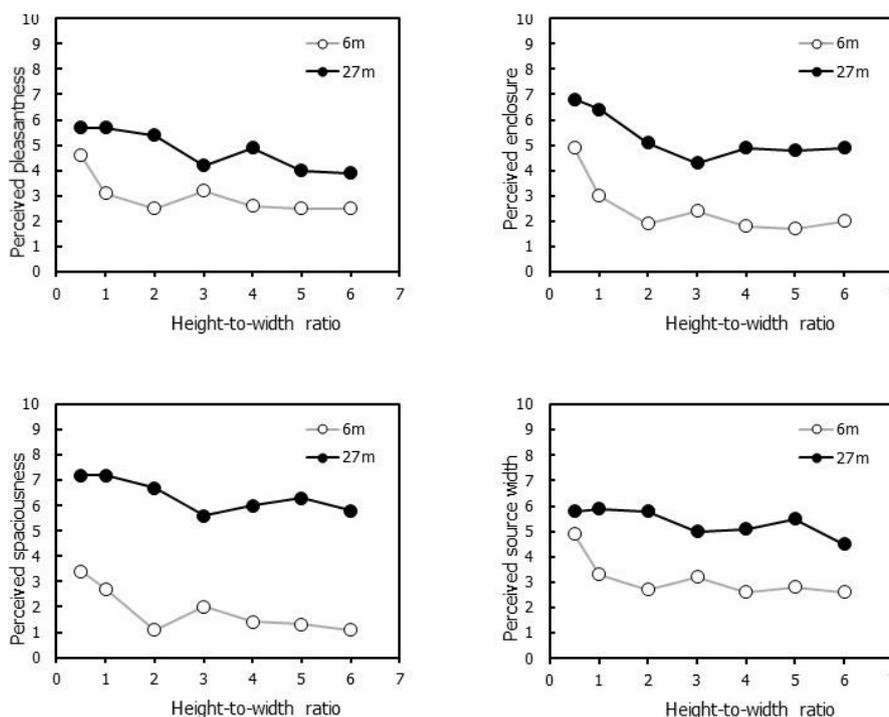


Figure 7 – The comparison between different H/W on perceived pleasantness, perceived enclosure, perceived spaciousness and perceived source width in the combined audio-visual condition.

On the contrary to the combined audio-visual condition, in the audio-only condition, ratings of the perceived pleasantness and ratings of the perceived source width were higher in narrow streets than the wide streets in all H/W ratios. In the narrow street (6 m width), there were some fluctuations in the ratings of perceived

pleasantness and the perceived source width while the H/W increases from 1 to 7 and the perceived pleasantness reduced by around 0.4 on the 11-point scale while the perceived source width also reduced by 0.3. In the wide street (27 m width), although there were some variabilities in the ratings of perceived pleasantness and perceived source width with the increase of H/W, both ratings decreased in the end (Figure 8).

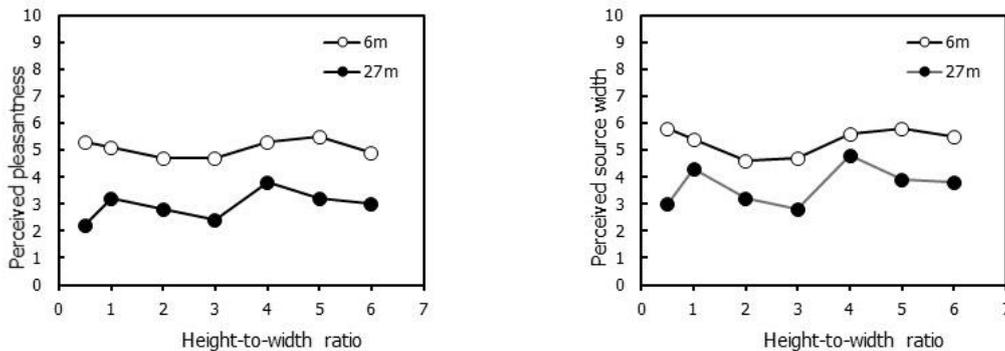


Figure 8– The comparison between different H/W on perceived pleasantness and perceived source width in the audio-only condition.

### 3.2 Effects of sound on subjective responses

The comparisons of mean ratings of the perceived enclosure, perceived pleasantness, perceived spaciousness and perceived source width for narrow streets, both with and without the presence of sound stimuli can be found in Figure 9. Both the perceived enclosure and the perceived spaciousness ratings were higher for the visual-only condition than the combined audio-visual condition. Although both ratings of visual-only conditions decreased for perceived enclosure and perceived spaciousness, the ratings were fluctuated for perceived enclosure while there was a slight decrease in the perceived spaciousness. It can be seen from the perceived pleasantness in Figure 9 that the ratings of perceived pleasantness were higher for the audio-only condition, followed by visual-only condition and combined audio-visual condition.

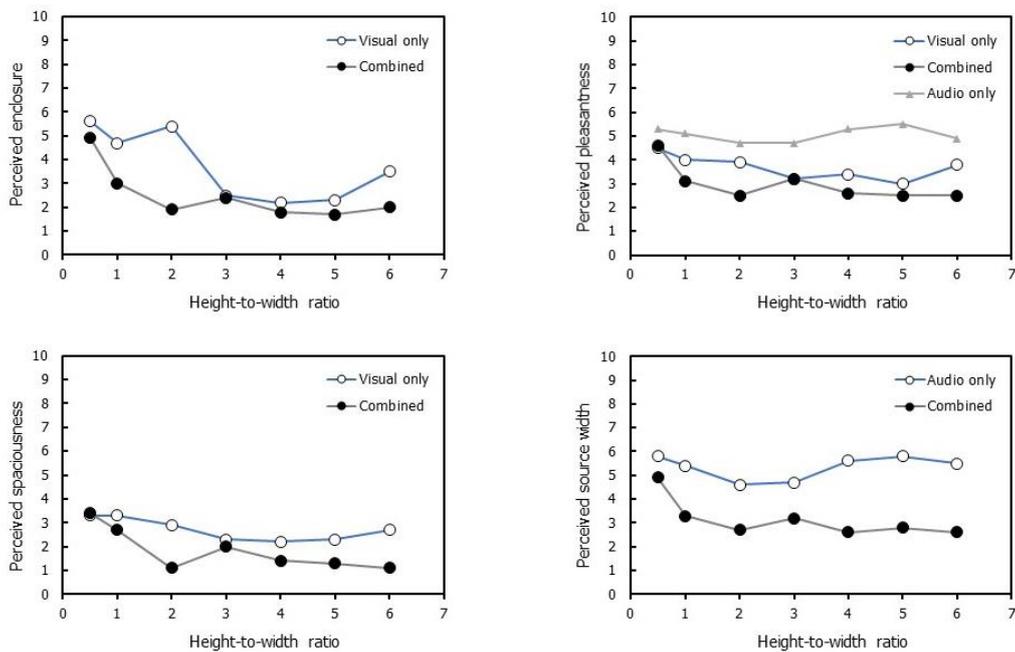


Figure 9– The comparison between visual-only, combined audio-visual and audio-only conditions on perceived enclosure, perceived pleasantness, perceived spaciousness and perceived source width in the narrow streets (6 m width).

For the streets with a width of 27 m, the perceived enclosure ratings of combined audio-visual condition were relatively less attenuated than the ratings of visual-only condition. When the perceived spaciousness in visual-only condition and combined audio-visual condition, it can be stated that the perceived spaciousness ratings were higher for the visual-only condition than the combined audio-visual condition for the lowest and highest H/W ratios although the ratings of perceived spaciousness decreased for the combined audio-visual condition while the rates increased for the visual condition between the H/W of 1-3. According to the perceived pleasantness in Figure 10, the ratings were lower for the audio-only condition than the visual-only condition and combined audio-visual condition.

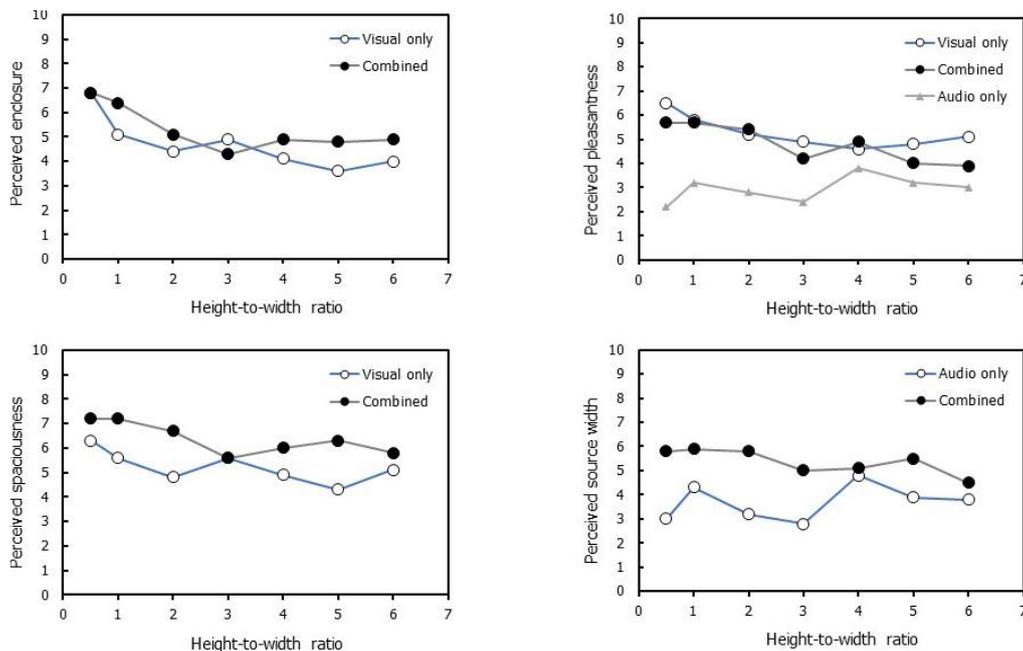


Figure 10– The comparison between visual-only, combined audio-visual and audio-only conditions on perceived enclosure, perceived pleasantness, perceived spaciousness and perceived source width in the wide streets (27 m width).

## 4 Summary

The effect of the sound environment on the perceived enclosure, perceived spaciousness, perceived pleasantness and perceived source width in urban street canyons has been investigated through laboratory experiments. The height-to-width ratio (H/W) varied from 0.5 to 6 for street widths of 6 m and 27 m, representing narrow and wide urban streets. The initial results showed that the impact of road width significantly affected perceived enclosure whereas the impact of road width on perceived pleasantness was not significant in the presence of sound stimuli. In addition, the results of the audio-only condition and visual-only condition showed big differences in the subjective rating. However, this is an ongoing study so further analyses will be conducted with 40 participants.

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