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# Role of sounds in perception of enclosure in urban street canyons

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ABSTRACT

This study aims to examine the influence of sound on the perceptions of enclosures in urban street canyons with varying height-to-width ratios (H/Ws). Two typical urban streets, one narrow and one wide, were modelled with street widths of 6 m and 27 m, respectively. The H/W was varied from 0.5 to 6 in seven steps by changing the heights of the buildings on both sides of the street. Three-dimensional visual images were created in a virtual reality (VR) environment, and a synthesised car pass-by sound was convolved with impulse responses extracted from acoustic computer simulations as the sound stimuli. Laboratory experiments were conducted with a total of 41 participants. The experiments consisted of three sessions: 1) a visual-only condition, 2) a combined audio-visual condition, and 3) an audio-only condition. The subjective responses to the stimuli were rated in terms of the perceived enclosure, perceived spaciousness, perceived pleasantness, and perceived source width. The results from the experiment revealed that the perceived enclosure, perceived spaciousness, and perceived pleasantness of the visual stimuli decreased as the H/W increased. The presentation of sound significantly influenced the perceived enclosure and perceived spaciousness, whereas the perceived pleasantness was less affected by sound. The effects of sound on the subjective responses were greater for narrow streets than for wide streets.

## 1. Introduction

A street canyon, i.e., a place where the street is flanked by continuous buildings on both sides of the road, is a basic geometric unit used to form large-scale urban structures affecting various environmental factors in urban spaces. A number of studies have investigated urban street canyons by focusing on environmental aspects such as daylight, thermal comfort, and air pollution (Ali-Toudert & Mayer, 2006; Memon et al., 2010; Chatzidimitriou & Yannas, 2017; Mei et al., 2019). In particular, the sound propagation in street canyons has been examined by considering the acoustical characteristics of the street boundaries (i.e., absorption and diffusion). In particular, the sound diffusion on building façades has been investigated based on variations of the scattering/diffusion coefficients (Kang, 1996; Onaga & Rindel, 2007) and the effects of sound diffusion on noise reduction in urban areas have also been reported (Picaut & Scouarnec, 2009; Kusuma et al., 2015). The majority of the studies have used image source and ray tracing methods to predict the sound fields of streets with perfectly smooth and geometrically reflective façades (Heutschi, 1995; Kang, 1996; 2005). Computer simulations have also been conducted to examine sound propagation in urban areas (Kang, 2005; Lee & Jeon, 2011; Lee & Kang, 2015). For instance, commercial software was employed to explore the sound fields of street canyons (Lee & Kang, 2015). In particular, Lee and Kang (2015) reported that the reflected sounds from building façades influenced the sound fields in urban streets with different geometries.

Street canyons are visually three-dimensional (3D), consisting of horizontal and vertical surfaces such that the buildings on both sides create an enclosure. The term enclosure indicates the degree to which the streets and other public spaces are visually defined by buildings, walls, trees, and other elements (Ewing & Handy, 2009). It also refers to the degree to which containment is perceived as a result of the surrounding solid surfaces (Alkhresheh, 2007). Many studies have examined the perception of enclosure in urban environments, as 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 dependent variables concerning the subjective impressions of enclosures (Stamps III & Smith, 2002; Stamps III, 2005a; Lindal & Hartig, 2013). Additionally, the perceived comfort and safety in urban environments have been evaluated, as the enclosure relates to the sense of comfort and safety in such

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environments (Stamps III, 2005a; b; Alkhresheh, 2007). The relationship between perceived safety and enclosure in urban spaces also can be explained with recent studies on peripersonal space and size of the reachable space. Coello et al. (2012) reported that the extent of a peripersonal space can be reduced owing to the threatening parts of dangerous objects. It was also found that a defensive peripersonal space is affected by individual levels of anxiety (Sambo & Iannetti, 2013) and morality (Iachini et al., 2015). Furthermore, the size of a room affects the sense of safety and pleasantness; however, the effect of the size on human perception of the space was found to be insignificant when a threatening sound source is added (Tajadura-Jiménez et al., 2010).

The literature has suggested that the perception of an enclosure is related to the physical environmental attributes of the urban spaces. Physical regions, as represented as proportions of an image covered by solid surfaces, have been introduced to understand the perceptions of enclosures. Stamps (2001) recommended considering the proportion of views covered by features which block vision or motion, and Stamps III and Smith (2002) subsequently discovered a strong relationship between the proportions of the scenes covered by walls or ground and the ratings of an enclosure. Based on a meta-analysis, Stamps III (2005b) also reported that the perception of an enclosure is highly influenced by the percentage of vertical solid surfaces. The ratios between the dimensions of the street canyons have long been thought to influence the perceptions of an enclosure. Im (1984) found that dimensional ratios such as the height ratio and opening ratio influence visual preferences regarding enclosed spaces. Ashihara (1983) also argued that the ratio of a block height to the street width (H/W) is related to the sense of enclosure. Similarly, several studies have explored the association between H/Ws and preferences regarding urban spaces (Christopher et al., 1977; Alkhresheh, 2007). Based on these findings, ideal H/Ws have been recommended by urban design studies (Ashihara, 1983; Nelessen, 1994; Carmona et al., 2010). For instance, 1:2 to 1:1 was proposed as the appropriate H/W for enhancing comfort and safety in street canyons (Nelessen, 1994). Nevertheless, the majority of studies on perceptions of enclosures have utilised images of streets without the presence of sound (mainly produced by traffic). As shown in previous studies (Carles et al., 1999; Pheasant et al., 2008; Rycharikova et al., 2013; Hong & Jeon, 2014; Lindquist et al., 2016), sound influences the perceptions of a landscape; as such, the presentation of sound could affect the sense of enclosure in street canyons.

Axelsson et al. (2010) proposed a theoretical model for assessing soundscape, which consists of intensity (i.e. eventful or uneventful) and emotional magnitudes (i.e. annoying or pleasant). This model was later introduced in ISO 12913-2 (ISO, 2018), and many studies have adopted this model in different contexts. For instance, Medvedev et al. (2015) investigated the perceived pleasantness of an acoustic environment along with physiological monitoring. The study found that pleasant sounds produced lower skin conductance levels than unpleasant sounds. Similarly, Zhao et al. (2021) assessed open public spaces in China in terms of arousal and valence: in other words, they evaluated eventfulness and pleasantness. One of their major findings involved the positive impact of urban management on the perception of pleasantness. The results indicate that traffic volume, crowd size, odour, and urban planning, which are related to sustainable cities, may affect the pleasantness of soundscapes,

Hence, in this study, the impacts of sound on enclosure in urban streets with a range of H/Ws are investigated. This study could provide information on issues concerning audio-visual interactions, particularly for enclosures in urban streets. Further, this study could be beneficial to urban planners and designers, it enhances the knowledge of the acoustic environment in the context of cityscapes and sustainability. The purpose of this study is to explore whether an enclosure is affected by the presentation of sound within narrow and wide urban streets. It was hypothesised that sounds in the street canyons would play a significant role in the perception of the enclosure. It was also expected that the impacts of sound on the enclosure might be different across the different H/Ws. Visual images of various streets were created from 3D models based on variations in the H/Ws and were presented in virtual reality (VR) environments. Sound stimuli (i.e. road traffic noise) were then made by using impulse responses extracted from the computer simulations. Laboratory experiments were performed to clarify the effects of sound stimuli on the perceptions of the urban streets. Participants rated the visual and sound stimuli in terms of the perceived enclosure, perceived spaciousness, perceived pleasantness, and acoustic source width.

## 2. Methods

### 2.1. Participants

The participants were recruited after receiving ethical approval from the Central Ethics Committee of the University of Liverpool (approval reference: 8419). Overall, 41 participants (31 males and 10 females) aged between 30 and 56 ($M$ = 44.3, SD = 6.0) participated in the experiment. The number of participants was chosen to achieve a statistical power of 80% ($\alpha < 0.05$, two-tailed). None of the participants reported any hearing or visual disabilities. In addition, 31 participants held at least an undergraduate degree, whereas the remaining participants had a high school education.

### 2.2. Street canyons

The street canyon model used in this study was identical to that of Lee and Kang (2015). The model employed a 200-m length of the street with continuous buildings along the sides at constant heights. Two street canyon widths of 6 m and 27 m were chosen to represent narrow and wide urban streets, respectively (Lee & Kang, 2015). Nelessen (1994) recommended different widths for urban streets, i.e., approximately 6 m for alleys and 26.2 m for boulevards. Another study (Alkhresheh, 2007) also reported that the maximum widths of major urban streets in cities in the USA, Italy, and Iraq were approximately 26 m. The heights of the buildings were changed at seven steps for each width; consequently, the H/W varied from 0.5 to 6.0. Similarly to Lee and Kang (2015), 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 the narrow and wide streets, respectively.

### 2.3. Stimuli

The visual stimulus material consisted of 14 3D street canyon models with different H/W levels. The 3D models of the buildings were made using Sketchup and then were imported to Unity to create the VR models. Additional visual edits to the roads and lighting were made in Unity to make the VR models more realistic. Furthermore, 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 in the VR models for the narrow and wide streets, respectively. Examples of the 3D models used in this study are displayed in Fig. 1.

The sound stimuli used in the present study was road traffic noise produced by vehicles in an urban area, as this is the most common noise source in urban environments. Lee and Kang (2015) reported that the H/Ws of street canyons significantly affected the sound fields in terms of the sound pressure level (SPL) and reverberation time. To adjust the acoustic characteristics of the street canyons across the H/Ws, the road traffic noise was convolved with the impulse responses from the computer simulations conducted by Lee and Kang (2015). For the convolution, a synthesised car pass-by sound at a driving speed of 50 km/h was used (Forssén et al., 2018). First, a 20-second long car pass-by sound was cut into 301 pieces (0.09 second/piece). Secondly, impulse responses were generated from the acoustic simulations in which the receiver was fixed at one position and the 301 sound sources were located along the street. For the narrow streets, 301 impulse responses (301 sources × one

a)

b)

**Fig. 1.** Examples of visual images used in the present study: (a) streets with a width of 6 m at height-to-width (H/W) ratio = 0.5 and (b) streets with a width of 27 m at H/W = 0.5

receiver) were extracted from each narrow street, while a total of 903 impulses responses ((301 sources × three positions) × one receiver)) were extracted for each of the wide streets. Next, the 301 segments of the car pass-by sound were convolved with impulse responses using the Hamming window in MATLAB. Three different overlap settings (i.e., 0.33, 0.67, and 0.5 overlaps) were implemented for the Hamming window to generate the smoothest and most realistic convolved car pass-by sounds. The sound pressure levels were fixed at 55 dB and 65 dB at the lowest H/W level (H/W = 0.5) for narrow and wide streets, based on the assumption that an increased number of vehicles in wider streets leads to louder noise.

The acoustical characteristics of the sound fields are listed in Table 1 in terms of the SPL, reverberation time (RT), early decay time (EDT), and lateral energy fraction (LF). The SPL accounts for the subjective impression of loudness, and it is one of the most widely used acoustic indicators. The RT is defined as the time taken for a sound to decay by 60 dB after the cut-off of the source, whereas the EDT is based on the decay from 0 to -10 dB. The RT and EDT are both associated with reverberance, whereas the LF is linearly related to the subjectively perceived spatial impression (varying between 0 and 1). Higher values of the LF represent greater feelings of spaciousness. For the street canyons with a width of 6 m, all of the acoustic parameters increased as the H/W increased, except for the LF. For instance, the sound pressure level increased by 3.2 dB in the range of H/Ws = 0.5–6, whereas the LF values remained largely constant across the range of H/W levels. Similarly, the acoustic parameters increased across the H/W levels for streets with a width of 27

**Table 1**
Acoustical characteristics and proportion of wall of the street canyons ("Wall") across the height-to-width (H/W) ratio (SPL: sound pressure level, RT: reverberation time, EDT: early decay time, and LF: lateral fraction). SPL, RT, and EDT were values at 1 kHz, whereas LF was averaged over 125 Hz–1 kHz.

| | | H/W | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0.5 | 1 | 2 | 3 | 4 | 5 | 6 |
| 6 m | SPL [dB] | 55 | 57.8 | 57.8 | 58.1 | 58.2 | 58.2 | 58.2 |
| | RT [s] | 0.5 | 0.9 | 1.2 | 1.5 | 1.7 | 1.8 | 1.9 |
| | EDT [s] | 0.4 | 0.7 | 1.1 | 1.4 | 1.5 | 1.6 | 1.6 |
| | LF | 0.24 | 0.22 | 0.22 | 0.21 | 0.22 | 0.22 | 0.21 |
| | Wall [%] | 64.0 | 76.2 | 84.6 | 86.7 | 87.8 | 88.3 | 88.8 |
| 27 m | SPL [dB] | 65 | 65.2 | 65.2 | 65.3 | 65.3 | 65.2 | 65.3 |
| | RT [s] | 2.3 | 3.3 | 4.5 | 5.2 | 5.7 | 5.9 | 6.0 |
| | EDT [s] | 1.4 | 2.0 | 2.3 | 2.5 | 2.6 | 2.6 | 2.6 |
| | LF | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| | Wall [%] | 65.3 | 77.8 | 83.9 | 85.7 | 86.4 | 86.9 | 86.9 |

m; however, the change in the SPL was not significant, and there were no changes to the LF. Compared to the streets with a 6 m width, the streets with a width of 27 m had longer RTs and EDTs owing to the larger volume of the street. Nonetheless, the LFs of the streets with a width of 27 m were significantly shorter than those of the 6 m streets, owing to the lack of lateral reflections from the buildings.

### 2.4. Experimental design

Similar to studies on audio-visual interactions comparing sound perceptions in conditions with and without visual appearances (Jeon et al., 2012; Park et al., 2020), this experiment was designed to include sessions with and without the presence of sound stimuli. As illustrated in Fig. 2, three sessions were considered: 1) Session 1: a visual-only condition; 2) Session 2: a combined audio-visual condition, where images were provided along with the sound stimuli during the experiment; and 3) Session 3: an audio-only condition.

In Sessions 1 and 2, it was hypothesised that the presence of sound stimuli and varying acoustic conditions could have had an impact on the perception of the enclosure. Session 3, which only involved sound stimuli, was designed to investigate the perception of the acoustic environment. During Sessions 1 and 2 (with the presence of visual images), the participants were asked to rate their perception of the enclosure in terms of perceived enclosure, perceived spaciousness (Stamps III, 2005a; 2011), and perceived pleasantness. The participants rated perceived enclosure on an 11-point numerical scale ranging from 0 (*extremely closed*) to 10 (*extremely open*). The participants also rated the stimuli on an 11-point numerical scale of perceived spaciousness from 0 (*not spacious at all*) to 10 (*extremely spacious*), whereas the perceived pleasantness was assessed on an 11-point numerical scale from 0 (*not pleasant at all*) to 10 (*extremely pleasant*). During Sessions 2 and 3 with the presence of sound stimuli, participants rated the perceived source, which was introduced as the auditory width of the sound field in the street canyons by employing the concept of the apparent source width in room acoustics (Okano et al., 1998). For the rating of the perceived source width, an 11-point numerical scale (with 0 representing "not wide at all" and 10 "extremely wide") was also used. In Session 3, the perceived pleasantness of the sound stimuli was rated along with the perceived source width.

### 2.5. Procedure

The experiment took place at the Fire Insurers Laboratories of Korea. The participants were provided with a consent form and information sheet upon their arrival, and only those who gave their consent participated in the test. After answering demographic questions and short questionnaires, the participants were invited to familiarise themselves with the virtual interface on a head-mounted display (HMD) and controllers during a training session. The listening test was conducted in a listening booth with dimensions of 4 m (width) × 7.5 m (length) × 3 m (height). The background noise level was approximately 30 dBA, and the RT was between 0.71 seconds at 50 Hz and 0.40 seconds at 8 kHz. The audio and visual stimuli were presented by using a headphone (Sennheiser HD 518) and HMD (Oculus Rift) throughout the experiment, respectively.

Each participant was exposed to a total of 42 stimuli, including 14 visual stimuli (Session 1), 14 combinations of simultaneous sound and visual stimuli (Session 2), and 14 sound stimuli (Session 3). In each session, the sound and/or visual stimuli were presented for 10 seconds, and the participants were given seven seconds to rate the questions on the HMD. In Session 1 (i.e. visual-only condition), white noise at 40 dBA was presented, whereas a dark grey screen was presented to the participants in Session 3 (i.e. audio-only condition). In each session, stimuli were randomly presented to avoid the order effects. A training session was conducted before the sessions began to help the participants become acquainted with the experiment. The training session lasted approximately three minutes and consisted of street canyons with widths of 6 m and 27 m. During the training session, each participant evaluated the

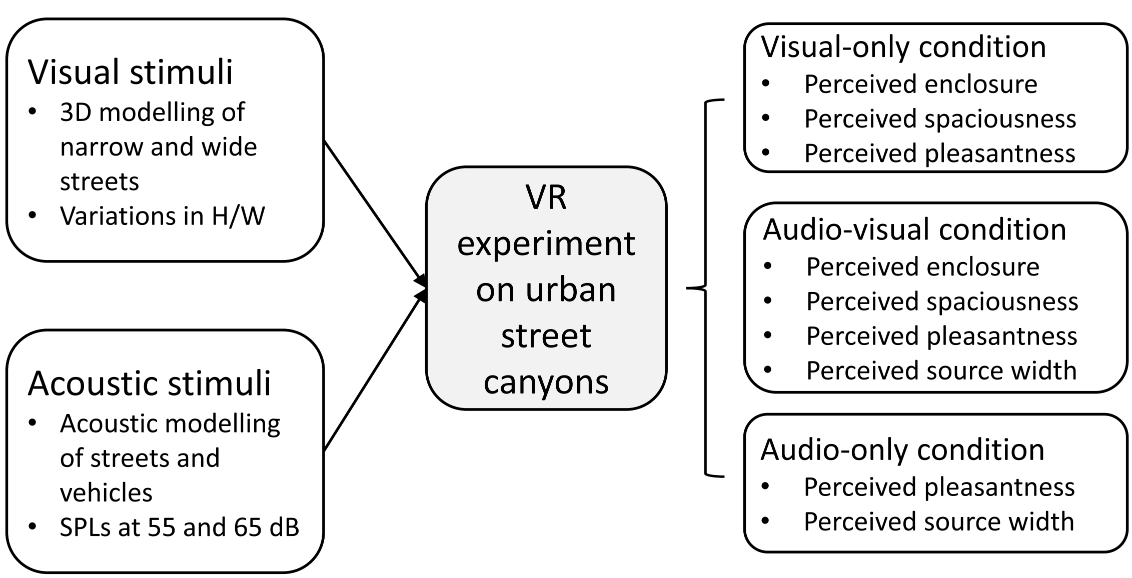


**Fig. 2.** Experiment outline.

visual and sound stimuli of the main sessions.

### 2.6. Data analysis

All statistical analyses were performed using the statistical software package SPSS for Windows (version 22.0, SPSS Inc., Chicago, IL). A repeated-measures analysis of variance (ANOVA) was performed to investigate the effects of the independent variables on the subjective responses. In the visual-only and combined audio-visual conditions, two-way repeated-measures ANOVAs were conducted to investigate 1) the impacts of the H/W and street width on the perceived enclosure and spaciousness and 2) the impacts of the H/W and presentation method (visual-only and audio-visual) on the perceived enclosure and spaciousness. Similarly, the impacts of the H/W and street width on perceived pleasantness and perceived source width were computed by using two-way repeated-measures ANOVAs in the audio-only condition. $\eta^2$ was used as an effect size measure. In cases where Mauchly's test revealed that the assumption of sphericity was violated ($p < 0.05$), the Greenhouse–Geisser procedure was applied to adjust the degrees of freedom for the tests of the within-subject effects. The normality of the

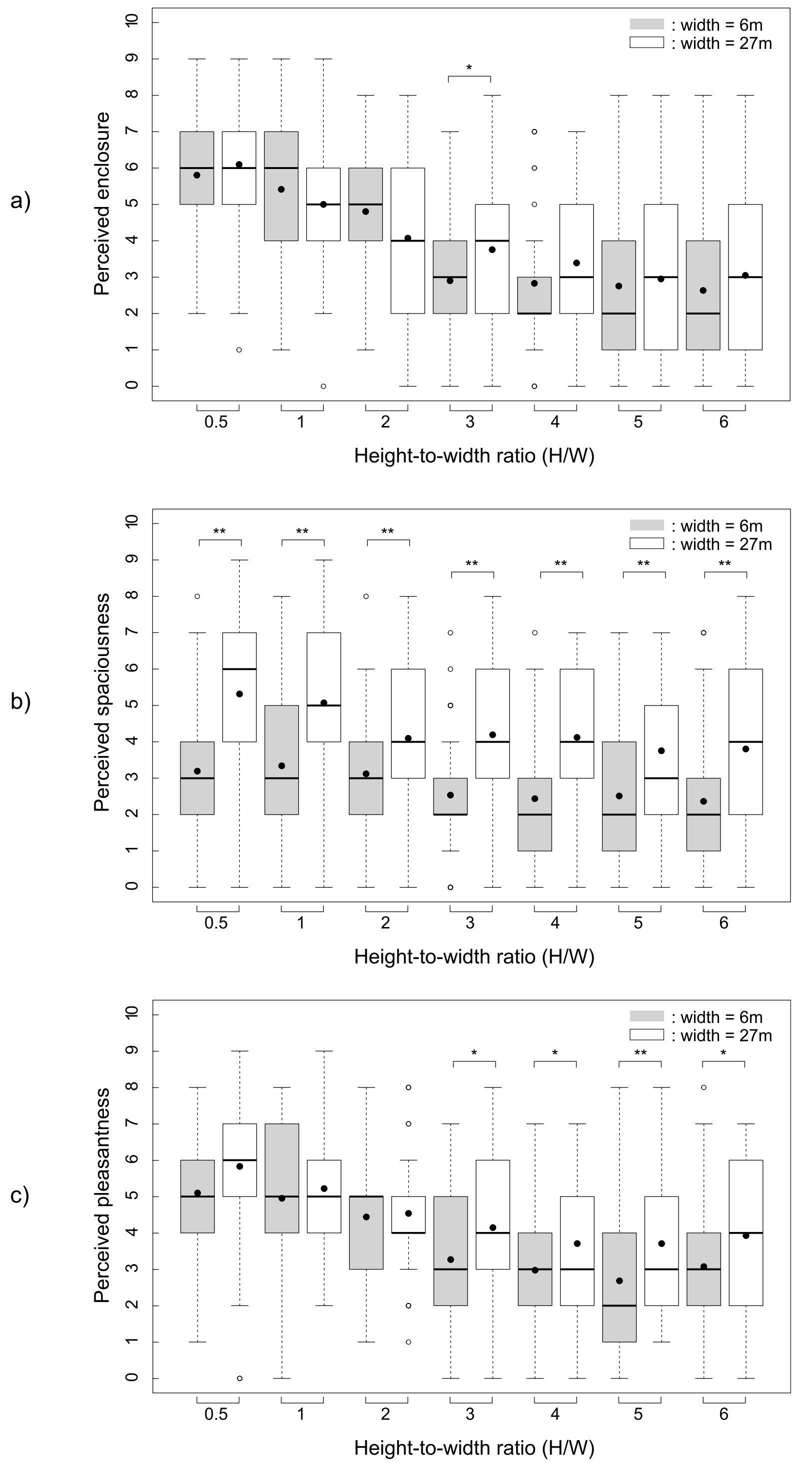


**Fig. 3.** Boxplots of perceived enclosure (a), perceived spaciousness (b), and perceived pleasantness (c) as a function of H/W in a visual-only condition (Session 1). *$p < 0.05$ and **$p < 0.01$.

distributions for the dependent variables was examined using Shapiro-Wilk's test, and the results showed that some of the datasets violated the normality assumption (e.g., data at each H/W). Thus, the differences in the mean values were evaluated with the Wilcoxon test to estimate the significance of the differences in the subjective responses between groups (6 m width vs. 27 m width and visual-only condition vs combined audio-visual condition). The results were considered significant at the level of $p < 0.05$.

## 3. Results

### 3.1. Effects of height-to-width (H/W) on subjective responses

Fig. 3(a), 3(b), and 3(c) show the boxplots for the perceived enclosure, perceived spaciousness, and perceived pleasantness as a function of the H/W in the visual-only condition (Session 1), respectively. The upper and lower boundaries of the boxes indicate the 75th and 25th percentiles, the bars in the middle of the boxes indicate the medians, and the filled circles represent the mean value. The whiskers show the minimum and maximum. Asterisks indicate significant differences between means according to the Wilcoxon test (*$p < 0.05$ and **$p < 0.01$). For the width of 6 m, all of the mean ratings decrease with an increase in the H/W. The decreases in the perceived enclosure and pleasantness are more significant than the change of the perceived spaciousness. For instance, as the H/W increases from 0.5 to 6, the perceived enclosure decreases significantly from 5.8 to 2.6 on the 11-point scale, whereas the perceived spaciousness varies between 3.2 and 2.4. Similar patterns are observed for the street with a width of 27 m, showing decreases in the perceived enclosure, perceived spaciousness, and perceived pleasantness with the varying H/Ws. Similar to the width of 6 m, the perceived spaciousness varies between 5.3 and 3.8, a significantly smaller range than those for the perceived enclosure and perceived pleasantness. In particular, the perceived spaciousness scores are almost constant in the range of H/W = 3–6.

Two-way repeated measures of ANOVA were used to estimate the significance of the differences in the mean ratings across the different H/Ws and road widths. The main effects from the H/W are statistically significant on the perceived enclosure [$F(6, 240) = 50.344$, $p < 0.01$)], perceived spaciousness [$F(6, 240) = 31.195$, $p < 0.01$)], and perceived pleasantness [$F(6, 240) = 11.593$, $p < 0.01$)]. The impact of the road width on the perceived enclosure is not significant [$F(1, 40) = 0.499$, $p > 0.05$)] but its effects on the perceived spaciousness [$F(1, 40) = 32.595$, $p < 0.01$)] and perceived pleasantness are significant [$F(1, 40) = 9.127$, $p < 0.01$)]. It is also observed that the interactions between H/W and width are not significant for all of the responses. To estimate and quantify the distinctiveness of the subjective responses, $\eta^2$ was calculated as a mean variability score for each width. A higher $\eta^2$ indicated a strong difference between the seven H/W levels, whereas a low $\eta^2$ indicated reduced subjective distinctiveness regarding the perceived enclosure and perceived spaciousness. The differences in the perceived enclosure and perceived pleasantness are more significant than those in the perceived spaciousness, as clearly revealed by the differences in the $\eta^2$ measures (0.56 for perceived enclosure, 0.44 for perceived pleasantness, and 0.22 for perceived spaciousness).

The paired Wilcoxon signed-rank test was conducted with the perceived enclosure, spaciousness, and pleasantness as the dependent variables, and the street width (6 m and 27 m) as the independent variable. The results showed that the differences in perceived enclosure ratings between the streets with 27 m and those with 6 m are not significant, except for at a H/W of 3. However, the wider streets generate greater perceived spaciousness ratings than the narrow streets at every H/W level ($p < 0.01$), whereas the perceived pleasantness ratings of the wider streets are greater than those of the narrow streets at H/W levels $\geq$ 3 ($p < 0.01$ for H/W = 5 and $p < 0.05$ for other levels).

The ratings for the perceived enclosure, perceived spaciousness, perceived pleasantness, and perceived source width as measured under the combined audio-visual condition (Session 2) are presented in Fig. 4(a), 4(b), 4(c), and 4(d), respectively. The two streets with different widths show similar tendencies across the range of H/Ws in the subjective ratings. As expected, the perceived enclosure sharply decreases with the increasing H/W. In other words, the participants perceive that the street canyons become more enclosed with a greater H/W. The decreases in the other ratings are less than those of the perceived enclosure. In particular, the perceived source width ratings do not change much across the H/W levels. A two-way repeated measures ANOVA reveals the significant main effects of the H/W on the subjective ratings (perceived enclosure: $F(6, 240) = 39.996$, $p < 0.01$, $\eta^2 = 0.50$; perceived spaciousness: $F(6, 240) = 11.593$, $p < 0.01$, $\eta^2 = 0.22$; perceived pleasantness: $F(6, 240) = 11.759$, $p < 0.01$, $\eta^2 = 0.23$; perceived source width: $F(6, 240) = 7.614$, $p < 0.01$, $\eta^2 = 0.16$), demonstrating a greater impact of the H/W on the perceived enclosure than on the others. The main impacts of the road width on the subjective ratings are also significant (perceived enclosure: $F(1, 40) = 74.117$, $p < 0.01$, $\eta^2 = 0.65$; perceived spaciousness: $F(1, 40) = 144.827$, $p < 0.01$, $\eta^2 = 0.78$; perceived pleasantness: $F(1, 40) = 12.807$, $p < 0.01$, $\eta^2 = 0.24$; perceived source width: $F(1, 40) = 21.918$, $p < 0.01$, $\eta^2 = 0.35$). The effect of the road width on the perceived spaciousness is the greatest, followed by the perceived enclosure, perceived source width, and perceived pleasantness. The paired Wilcoxon test results indicate that differences in the subjective responses between the streets with different widths are found at all H/W levels, except for the perceived spaciousness and perceived source width at H/W = 0.5 (perceived enclosure: $p < 0.01$ for all H/W levels; perceived spaciousness: $p < 0.01$ for H/W = 1, 2, and 5 and $p < 0.05$ for H/W = 3 and 6; perceived spaciousness: $p < 0.01$ for all H/W levels; perceived source width: $p < 0.01$ for all H/W levels).

Fig. 5 represents the boxplots of the perceived pleasantness and perceived source width as a function of the H/W in the audio-only condition (Session 3). The mean ratings of the perceived pleasantness do not change significantly across the range of H/W, and the ratings of the two streets are almost constant. This is because the variation in the SPLs is less than 3 dB, i.e., is a barely noticeable difference in loudness. The main effect of the H/W on the perceived pleasantness is not significant and the $\eta^2$ value is also very small (< 0.05), revealing that the H/W is not effective for understanding the perceived pleasantness in the audio-only condition. However, the main effect of the road width on the perceived pleasantness is significant [$F(1, 40) = 57.430$, $p < 0.01$] with a high $\eta^2$ value (0.59), and the interaction between the H/W and road width is not significant. The perceived source width ratings also remain relatively constant with the increase of the H/W, and the effects of the H/W on the perceived source width are significant [$F(6, 240) = 2.985$, $p < 0.01$]; however, the $\eta^2$ value is only 0.07. The road width also shows a significant impact on perceived source width [$F(1,40) = 26.537$, $p < 0.01$] with $\eta^2 = 0.4$, but the interaction between the H/W and road width is not significant.

Based on the results of the paired Wilcoxon tests, it was found that the perceived pleasantness ratings of the streets with a width of 27 m are significantly smaller than those of the streets with a width of 6 m at each H/W, owing to the 10 dB difference in the SPLs between the two streets. The perceived source width ratings for the narrow streets are greater than those for the wider streets. This can be explained by the differences in lateral reflections, which contribute to the sense of spaciousness. As listed in Table 1, the LF values of streets with a width of 6 m are greater than 0.2 across all H/Ws, whereas the LFs for the streets with a width of 27 m are 0.04 for all H/Ws.

### 3.2. Effects of sound on perception of enclosure

Fig. 6 shows comparisons of the ratings for the perceived enclosure for the streets with different road widths, both with and without the presence of sound stimuli. As shown in Fig. 6(a), for the streets with a width of 6 m, the mean ratings of the perceived enclosure are sharply reduced in the range of H/Ws between 0.5 and 3, and then become

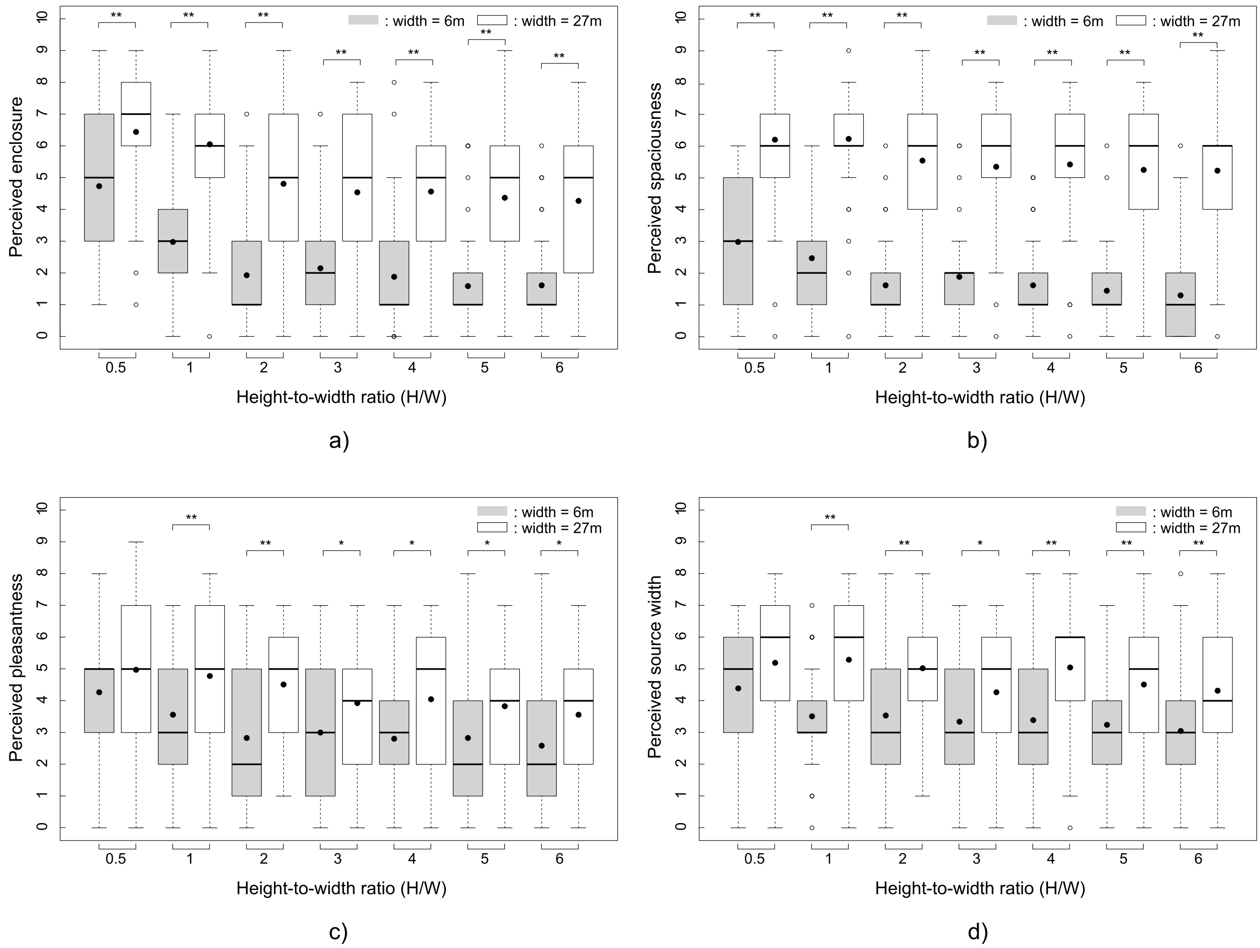


**Fig. 4.** Boxplots of perceived enclosure (a), perceived spaciousness (b), perceived pleasantness (c), and perceived source width (d) as a function of H/W in a combined audio-visual condition (Session 2). $^{*}p < 0.05$ and $^{**}p < 0.01$.

almost constant. The mean ratings under the combined audio-visual condition are lower than those in the visual-only condition, and the differences between them become smaller as the H/W increases. Different tendencies are found in the streets with a width of 27 m, demonstrating that the combined audio-visual condition results in a greater perceived enclosure relative to the visual-only condition, as presented in Fig. 6(b). The paired Wilcoxon tests reveal that the differences between the two conditions are statistically significant at all H/Ws for 6 m ($p < 0.01$) and at four H/Ws for 27 m ($p < 0.05$ for H/W = 3 and $p < 0.01$ for H/W = 1, 5, and 6).

The ratings of the perceived spaciousness ratings for the visual-only and combined audio-visual conditions are plotted across varying H/Ws in Fig. 7. For the street canyons with a width of 6 m, the presence of sound stimuli results in a lower perceived spaciousness compared to the visual-only condition, as depicted in Fig. 7(a). The paired Wilcoxon test reveals that the perceived spaciousness ratings from the combined audio-visual condition are significantly different from those in the visual-only condition, except for at H/W = 0.5. In contrast, the perceived spaciousness shows a different pattern in the streets with a width of 27 m. As shown in Fig. 7(b), adding sound stimuli leads to greater ratings than without. The paired Wilcoxon test also confirms that the differences between the visual-only and combined audio-visual conditions are statistically significant at every H/W level except for H/W = 0.5.

The comparisons of the ratings of perceived pleasantness with and without the presence of sound stimuli are plotted in Fig. 8. For the street canyons with a width of 6 m, the differences between the visual-only and audio-visual combined conditions are seen only in the region of H/W between 0.5 and 2. In contrast, there are no significant differences between the conditions for the street with a width of 27 m. The paired Wilcoxon tests reveal that the differences between the two conditions are statistically significant only for the streets with a width of 6 m at smaller H/Ws for 6 m ($p < 0.05$ for H/W = 0.5 and $p < 0.01$ for H/W = 1 and 2).

### 3.3. Relationships between geometry measures and enclosure

A correlation analysis was conducted to investigate the relationships between the subjective responses and the physical characteristics of the street canyons. A number of studies (Hayward & Franklin, 1974; Stamps III & Smith, 2002; Stamps III, 2005a; Ewing & Handy, 2009) have introduced physical attributes of urban sites (e.g., horizontal or vertical format and depth) for the purposes of understanding the perceptions of enclosures. In the present study, in addition to the H/W, the proportion of views covered by walls ("Wall") was added as a physical feature of the street canyons. Thus, the correlation coefficients between H/W and Wall and the perceptions were computed for the visual-only and combined audio-visual conditions. For the audio-only condition, acoustic parameters such as SPL and RT were introduced as physical measures. However, H/W and Wall were not considered because only acoustic stimuli were presented to the participants.

As listed in Table 2, the Wall as well as the H/W is significantly correlated with perceived enclosure, spaciousness, and pleasantness in the visual-only and combined audio-video conditions. Compared to the relationships between the physical features and enclosure, the perceived spaciousness and pleasantness show lower correlation coefficients. In

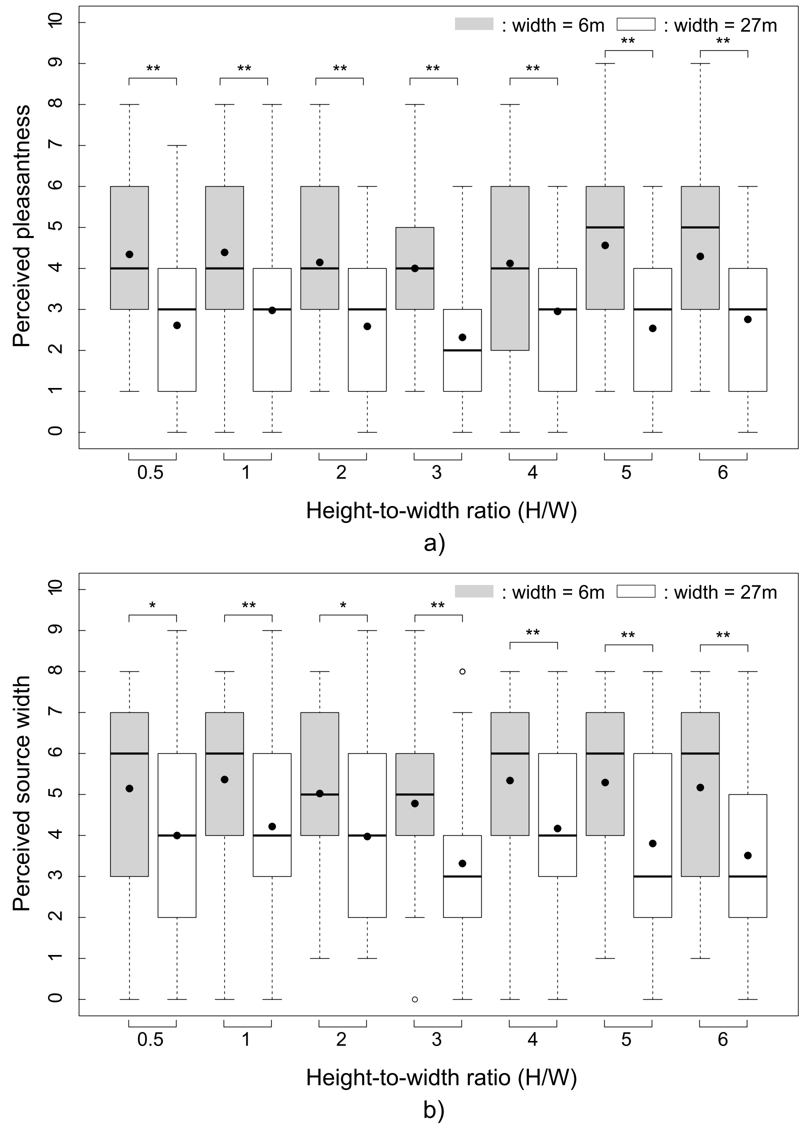


**Fig. 5.** Boxplots of perceived pleasantness (a) and perceived source width (b) as a function of H/W in an audio-only condition (Session 3). $*p < 0.05$ and $**p < 0.01$.

the condition with the presence of audio stimuli (Session 2), the subjective ratings are also significantly correlated with the acoustics measures. In particular, in both narrow and wide streets, the RT, EDT, and SPL show greater correlation coefficients than the other measures, owing to the larger variations than in the LF.

Differences between the narrow and wide streets are also found in terms of the size of correlation coefficients. Most correlation coefficients in the narrow streets are greater than those in the wide streets. For instance, the correlation coefficients between the perceived enclosure and physical measures are approximately 0.5 in the narrow streets in the visual-only condition, whereas those are approximately 0.4 in the wide streets. In addition, in the wide street, the LF is not correlated with subjective responses, whereas the subjective responses in the combined audio-visual condition are moderately related to the LF in the narrow streets.

## 4. Discussion

In the present study, it was revealed that the impact of the road width on the perceived enclosure was not significant, whereas the road width significantly affected the perceived spaciousness. This finding indicates that the effect of road width on the perceived spaciousness is greater than that on the perceived enclosure. This is because the horizontal area and road width are more directly related to the perceived spaciousness than to the enclosure (Alkhresheh, 2007; Stamps III, 2011). This study also found strong relationships between the H/W and enclosure. This result is consistent with the findings of previous studies (Hayward & Franklin, 1974; Alkhresheh, 2007), in which the perceived enclosure was significantly associated with the H/W based on a laboratory experiment using simulated visual images of urban streets. The current data indicate that the relationships between the H/W and enclosure are significant for both narrow and wide streets. This result also supports the findings of Hayward and Franklin (1974), who argued that the perceived enclosures are similar for spaces with similar H/Ws, regardless of scale.

The findings of this study reveal that the sound environments, reflected by the morphologies of the urban street canyons, significantly affect the perceptions of enclosures. More specifically, the presence of sound lowered the perception of the perceived enclosure in the narrow streets, whereas the perception of the perceived enclosure increased under the audio-visual condition in the wide streets. This implies that the presence of the sound influences the perceived enclosure across the different widths. The audio-visual combined conditions are more representative of real-life scenarios than the visual-only conditions. In this sense, this study demonstrates that the sound fields created by urban

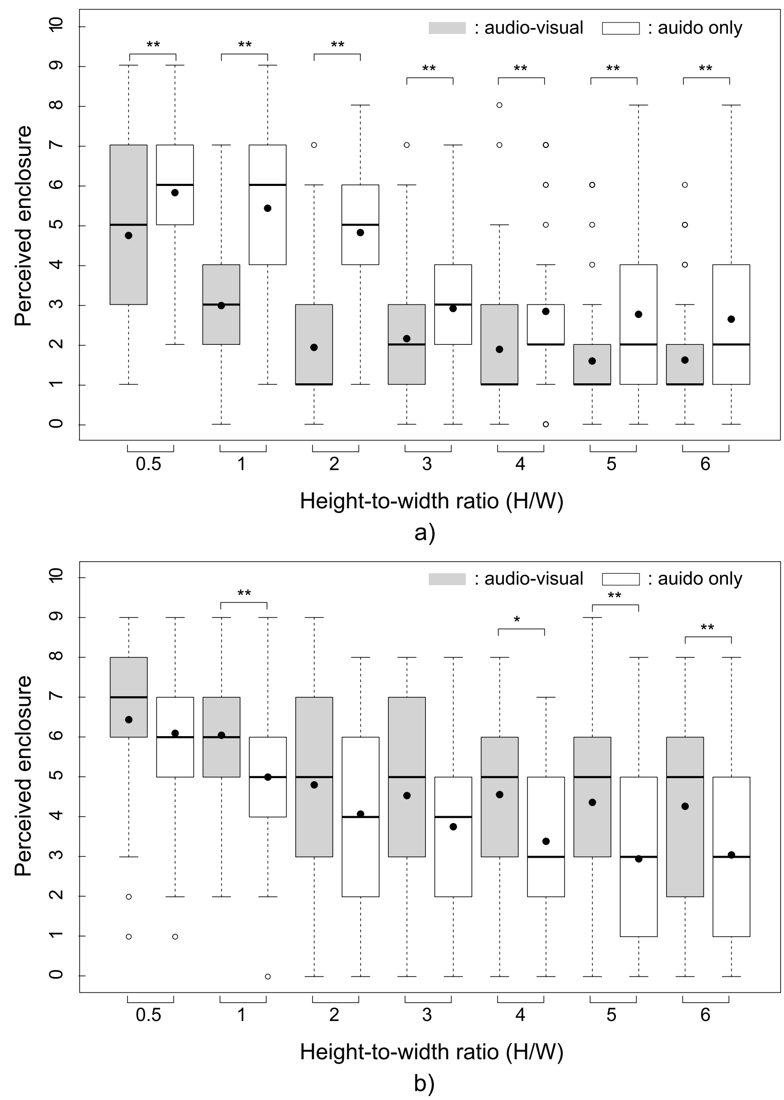


**Fig. 6.** Comparison of perceived enclosure in 6-m (a) and 27-m width streets (b) with and without presence of sound stimuli. $^{*}p < 0.05$ and $^{**}p < 0.01$.

forms should be considered one of the important environmental factors for urban design and planning. However, in the present study, only road traffic noise with a negative impression was reproduced to the participants; other sound sources with different impressions were not considered. Several studies (Jeon et al., 2010; Hong & Jeon, 2013) have previously reported that natural sound sources such as water sounds and bird songs might enhance the perception of the place and soundscape in urban environments. For example, water sounds were useful for minimising the negative impacts of road traffic noise on the subjective impressions of urban soundscapes (Jeon et al., 2010) and increasing the sustainability of the urban environments (Axelsson et al., 2014; Fahed et al., 2020). Thus, it is logical to expect that adding positive sound sources might enhance the sense of safety and enclosure in urban environments. In addition, the impacts of natural sound sources might be different across different road widths due to the level differences between road traffic noise and natural sounds. These hypotheses could be investigated in the future in relation to the sustainability of urban environments.

The correlation analysis showed that perception of the enclosure is associated with the physical features of street canyons, confirming the findings of previous studies (Stamps III & Smith, 2002; Ewing et al., 2005; Stamps III, 2005a; Ewing & Handy, 2009). The visual assessment survey developed an enclosure model (Ewing et al., 2005; Ewing & Handy, 2009) in which the proportion of the street wall on the opposite side showed the greatest regression coefficient, followed by the proportion of street wall on the same side, proportion of the sky, and long sight lines. According to this model, a more continuous street wall of building façades leads to a greater perception of the enclosure. Similarly, the proportion of views covered by physical features (e.g., walls) is strongly related to the enclosure (Stamps III & Smith, 2002; Stamps III, 2005a).

The relationship between the LF and enclosure was meaningful in the narrow street, confirming the results of other studies (Okano et al., 1998; Barron, 2000) on auditoriums that reported that auditory spaciousness depends on the LF. This indicates that strong reflected sounds from the building façades contributed to the auditory spaciousness in the narrow streets. However, this was not the case for the wide streets with a lack of lateral sound energy. Lee and Kang (2015) also previously reported that an increase in building height does not significantly affect the acoustic measures in streets with a large width, in which the direct sounds from the source are dominant. In the present study, the LF calculated from the impulse response was adopted to explain the auditory spaciousness. In the future, other special measures such as the interaural cross-correlation coefficient (IACC) between the two signals of a headphone could be used to represent the acoustic environment more explicitly.

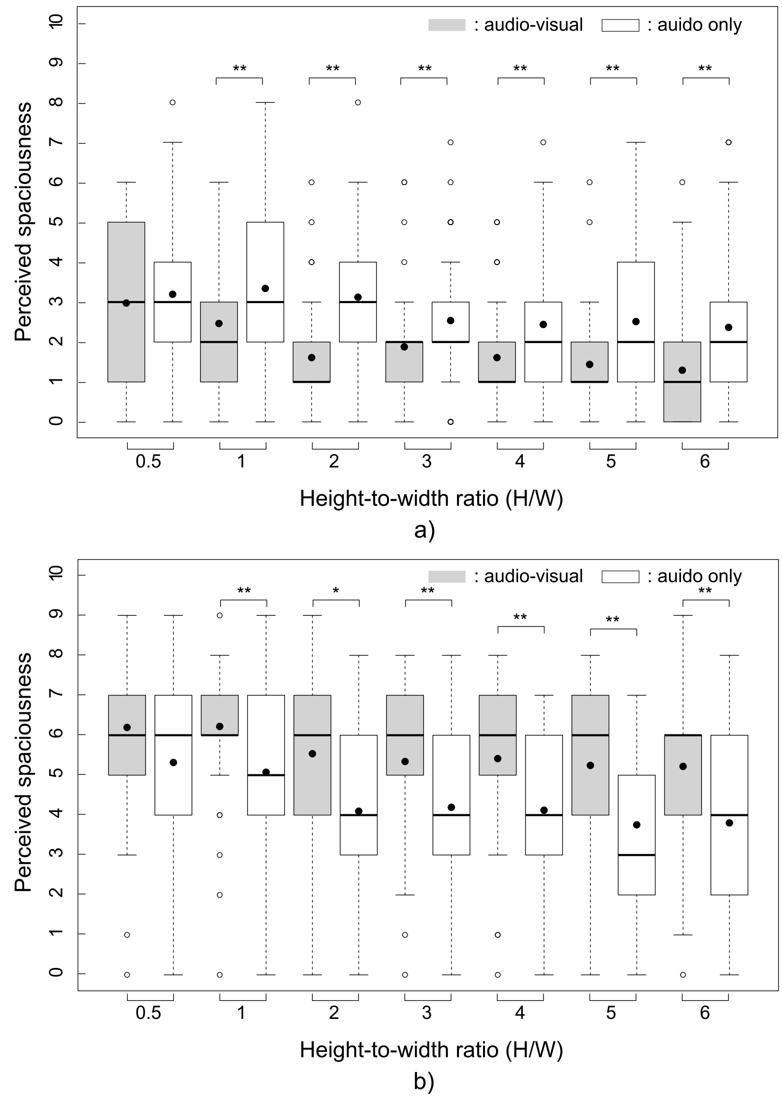


**Fig. 7.** Comparison of perceived spaciousness in 6-m (a) and 27-m width streets (b) with and without presence of sound stimuli. *$p < 0.05$ and **$p < 0.01$.

The present study systematically investigated the influences of the H/Ws on enclosures and spaciousness with a wide range of H/Ws. As other physical features such as the visible depth and lightness were not changed, it was not feasible to examine the effectiveness of such other variables on understanding enclosures and spaciousness. Thus, future studies could focus on testing various physical and geometric measures in making predictions for enclosures, following previous research (Stamps III & Smith, 2002; Ewing & Handy, 2009). In the present study, the visual images of the street canyons consisted of buildings, traffic roads, and vehicles without any vegetation. Green features such as trees and flowers affect psychological restoration, as well as the perceived enclosure (Tabrizian et al., 2018; Liu & Schroth, 2019); thus, vegetation could be added to the street canyons. Furthermore, additional physiological measurements would be beneficial to understanding people's reactions to sound and visual stimuli in urban street canyons (Park et al., 2020; Frescura & Lee, 2022). Lastly, only road traffic noises were used as sound stimuli, but there are different types of sounds such as footsteps and honking, in urban street canyons. Thus, diverse sounds can be investigated to simulate more realistic situations.

## 5. Conclusion

The role of the sound in perception of urban street canyons has been investigated through laboratory experiments. The H/Ws varied from 0.5 to 6 for street widths of 6 m and 27 m representing narrow and wide urban streets, respectively. The judgements of the perceived enclosure under the audio-visual conditions were significantly different from those in the visual-only conditions for both the narrow and wide streets. In particular, significant differences in the perceived enclosure were found at all H/Ws for the narrow street, whereas the differences in the perceived enclosure were significant at higher H/Ws for the wide streets (H/W = 5–6). The perceived spaciousness was affected by the sound environment in both the narrow and wide streets, whereas the sound had little effect on the perceived pleasantness. Furthermore, the perceived enclosure, perceived spaciousness, and perceived pleasantness showed significant relationships with the H/Ws in both the visual-only and audio-visual conditions, whereas the judgements of the perceived source width were less influenced by changing the H/Ws.

The findings of this study could be implemented in urban and landscape designs by considering the relationships between the degree of enclosure and H/Ws with the presence of sound. For instance, design guidelines and policies can be recommended to ensure a feeling of belonging and control over urban environment. Furthermore, a proper height corresponding to each street width could be introduced into urban morphology dimensions in consideration of the sustainability of urban environments.

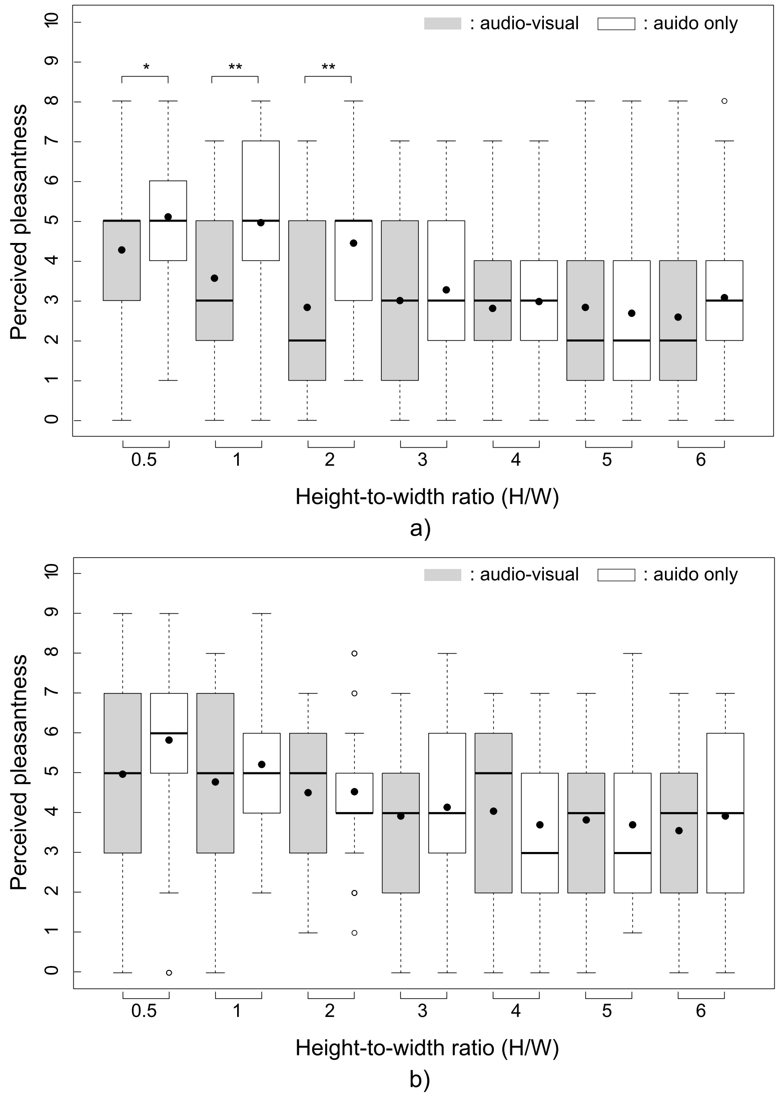


**Fig. 8.** Comparison of perceived pleasantness in 6-m (a) and 27-m width streets (b) with and without presence of sound. *$p < 0.05$ and **$p < 0.01$.

**Table 2**
Correlation coefficients between perception and physical measures ("Wall" is the proportion of views covered by walls, **$p < 0.01$ and *$p < 0.05$).

| Widths | Sessions | Perception | H/W | Wall | SPL | RT | EDT | LF |
|---|---|---|---|---|---|---|---|---|
| 6 m | Visual-only condition | Enclosure | -.523** | -.494** | - | - | - | - |
| | (Session 1) | Spaciousness | -.187** | -.160** | - | - | - | - |
| | | Pleasantness | -.422** | -.391** | - | - | - | - |
| | Combined audio-visual condition | Enclosure | -.412** | -.488** | -.466** | -.452** | -.455** | .417** |
| | (Session 2) | Spaciousness | -.319** | -.341** | -.297** | -.333** | -.334** | .270** |
| | | Pleasantness | -.230** | -.264** | -.241** | -.248** | -.250** | .224** |
| | | Source width | -.189** | -.208** | -.213** | -.200** | -.196** | .207** |
| | Audio-only condition | Pleasantness | - | - | -0.014 | -0.006 | -0.012 | 0.029 |
| | (Session 3) | Source width | - | - | 0.004 | 0.002 | -0.007 | 0.027 |
| 27 m | Visual-only condition | Enclosure | -.434** | -.443** | - | - | - | - |
| | (Session 1) | Spaciousness | -.250** | -.254** | - | - | - | - |
| | | Pleasantness | -.330** | -.344** | - | - | - | - |
| | Combined audio-visual condition | Enclosure | -.322** | -.338** | -0.063 | -.352** | -.344** | - |
| | (Session 2) | Spaciousness | -.184** | -.180** | -0.007 | -.197** | -.186** | - |
| | | Pleasantness | -.222** | -.195** | -0.048 | -.220** | -.206** | - |
| | | Source width | -.150* | -.126* | -0.006 | -.146* | -.133* | - |
| | Audio-only condition | Pleasantness | - | - | 0.059 | -0.013 | -0.007 | - |
| | (Session 3) | Source width | - | - | 0.011 | -0.067 | -0.059 | - |

## Declaration of Competing Interest

None.

## Data availability

Data will be made available on request.

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