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# Influence of interaural cross-correlation coefficient and loudness level on auditory source width at different frequency

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# ABSTRACT

Auditory source width (ASW) is the perceived width of an auditory event of a stimulus, which has complicated relationships with the interaural cross-correlation coefficient, loudness level and frequency. In this paper, the virtual acoustics pointer method is used as the reference signals to investigate the relationship for headphone users. It is found that increasing the loudness level increases the ASW, but with different degrees at different frequencies. The minimum ASW increment appears around 1600 Hz and the maximum occurs around 200 Hz. The average of the ASW increment is approximately 5.4 degrees for 10 phons loudness increment. Decreasing IACC can broaden the ASW, the maximum of the increment of ASW occurs around 400 – 800 Hz and the average increment is approximately 4.8 degrees for the decrement in IACC of 0.2. A formula is developed by curve fitting to describe the relationship among the three factors and the ASW, which can be used to predict the auditory source width for stereo sound reproduction using headphones and help hearing impaired people perceive more accurate ASW of sound.

*Keywords:* Interaural cross-correlation coefficient; Loudness levels; Auditory source width.

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# 1. Introduction

Auditory source width (ASW) is a spatial perception that has been long studied in the field of room acoustics [1, 2]. It is a function of the binaural cues that humans use to localize and identify source width. Early studies focus on room environments, and many physical factors affecting the ASW perception have been found, which include the interaural cross correlation (IACC), the lateral fraction and the sound pressure level (SPL). It has been found that ASW increases monotonously as the IACC decreases from 1 to 0 and increases approximately 1.6 degrees with 1 dB SPL increase [3-5].

The influence of IACC on the ASW has been studied via headphones for some time, and the ASW at low centre frequency or with low interaural coherence is found to be wider in free field or headphone listening experiments [6]. The ASW variation is different at different frequency bands in low reverberation spaces [7]. However, the interaction of IACC and frequency on ASW needs more research.

The effect of loudness level on ASW has been discussed in details in room acoustics. The effect of loudness on the ASW was firstly noticed in concert halls in 2001 [8], which was further investigated in 2006 via loudspeakers in the frequency bands from 100 Hz to 12500 Hz [9]. The experimental results show that both the frequency and the loudness affect the ASW as separate factors, and the ASW increases approximately 4.8 degrees with 10 phons loudness level increase. The effect of loudness level on ASW with headphone users might be different, but there is no quantitative experiment report in literature.

The centre frequency of a stimulus also affects the ASW. It has been found that different frequency components play different roles in perceiving ASW [10]. The maximum of ASW occurs at the low frequency and the ASW decreases with frequency increase from 100 Hz to mid frequency, and increases slightly above 3200 Hz [11]. The reference signal used in these experiments is a stimulus with fixed centre frequency and varying IACC. The stimulus with different IACC was selected by the subjects to have the same perceived ASW as the fixed stimulus, and then the IACC value was used to represent the ASW of the fixed stimulus. The problem of the research is that the IACC value is not an angle value, so it is not directly related to an ASW value. It is desired that a reference signal with an angle value can be used in the tests to directly give an ASW value [12].

The ASW value depends on the IACC, loudness level and centre frequency of the stimuli; however, their quantitative relationship for headphone users is not clear. This is investigated in this paper in the frequency bands from 120 Hz to 12800 Hz by using a quantitative virtual acoustics pointer. The influence of the loudness on ASW during headphone playback is studied first, and then the influence of frequency and IACC on ASW and the interaction of IACC and frequency on ASW are investigated. Finally, a formula is developed based on variance analysis and curve fitting to describe the relationship among the ASW and the three factors, which can be used for calculating the ASW of a stimulus with fixed IACC, loudness level and frequency.

This formula is useful for providing a more accurate perception of ASW in sound field reconstruction by adjusting the IACC and loudness level between two ears [13]. For aged people or hearing impaired patients, who are insensitive to changes in ASW based on the IACC, the loudness adjustment can help them perceive more accurate ASW of sound [14-15]. This formula can also be used to represent areas, sizes and regions of spatially extended sound sources by generating multiple stimuli that carry specific ASW information in virtual auditory displays [16].

## 2. Methodology

### 2.1. Procedure

Many methods have been proposed for measuring the ASW via headphones, such as the Blauert's mapping method, the Johannes's scoring method and the Mason's adjustment method [6, 7, 11]. The virtual acoustics pointer method proposed by Becker is adopted in this paper to perform the quantitative experiments because the consistency and repeatability of this method are more reliable than most of the other methods [12, 17].

The measurements contain two stages as shown in Fig. 1. The first stage is for training so that the subjective participators get familiar with the procedures and form a stable memory for the spatial positioning of the reference signals. This training can help subjects to avoid the front-and-back confusion and up-and-down confusion of the reference signals and improve the spatial positioning accuracy of the reference signals

[18].

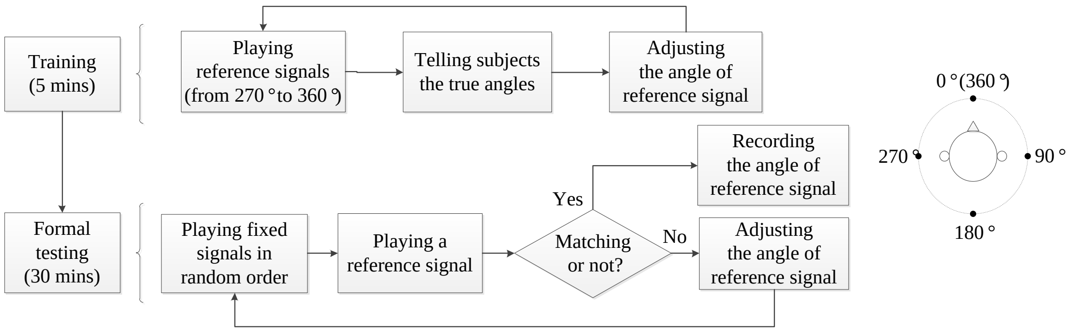


FIG. 1. The procedure of the listening tests

In the training stage, the reference signals from the 270°(left 90°) to the front 0° (360°) are played back with an interval of 5°. While the reference signal is being played, the real value of the space angle and the reference mark are given, so that the subjects can have an intuitive impression on the angle of different reference signals. The training lasts for 5 minutes and the consistency and accuracy of individual spatial localization can be improved after the training [19].

In the formal testing stage, a “method of adjustment” paradigm is used by asking the subjects to adjust a variable stimulus to be the same perceived ASW as a given fixed signal [20]. In the tests, only one stimulus is selected to compare with the reference signals at a time and each stimulus is presented for three times in random order. The fixed stimulus is presented firstly and then the variable stimulus. According to the feedback of the listeners, the spatial angle of the reference signal is adjusted until the subject ensures that the positions of reference signal is the same as the edge of the fixed signal. The subjects can compare two stimuli repeatedly until they find the closest angle of the reference signal. Then twice of the spatial angle of the reference signal is recorded as the width of the fixed signal.

In the tests, the fixed stimuli were adjusted to the sound loudness levels of 60 phons, 70 phons and 80 phons at each ears following the equal loudness contours in ISO 226 [21]. The sound loudness levels of the left and right channels in reference signals are different and the average sound loudness level of the left and right channels was adjusted to 70 phons.

All experiments were performed in a standard listening room with low background noise and suitable reverberation time. Fourteen normal-hearing volunteers (11 females, 3 males, aged between 20 and 25 years old) from Nanjing University participated in the listening tests. The listeners have normal hearing during the regular physical examination and the individual listening results are consistent. The subjects only need to judge the perceptual feeling whether the two signals match without any specific information of the fixed signal and the variable signal, so this method can be considered as a double blind test.

### 2.2. Stimuli

In order to conduct the experiments in a controlled manner, both fixed stimuli and variable stimuli were adopted in this research. The fixed stimuli are based on the suppressed carrier amplitude modulation with a time offset between channels [22]. The fixed stimuli are obtained by mixing signals $s_1$ and $s_2$ with

$$l = G\, s_1 + (1-G)\, s_2 \tag{1}$$

$$r = G\,s_1 - (1-G)\,s_2 \tag{2}$$

where $l$ is for the left channel, $r$ is for the right channel, and $s_1$ and $s_2$ are calculated with,

$$s_1 = \sin(2\pi f_c t)\sin(2\pi f_m t) \tag{3}$$

$$s_2 = \sin(2\pi f_c [t + t_m])\sin(2\pi f_m [t + t_m]) \tag{4}$$

where $f_c$ is the center frequency, $f_m$ is the modulation frequency and $t_m = 1/4f_m$ is the time offset. The IACC of the fixed stimuli changes with $G$. Adjusting $G$ from 0.5 to 1 changes IACC from 0 to 1. The values of $G$ were calculated before the experiments so that the IACC can be changed from 0 to 1 with an interval of 0.2 in the tests [22].

The modulation frequency $f_m$ is set as 20 Hz, which is an optimal compromise to make the stimuli has an adequate narrow bandwidth at all test frequencies [22]. The center frequencies of the fixed stimuli are 120 Hz, 200 Hz, 400 Hz, 800 Hz, 1600 Hz, 3200 Hz, 6400 Hz, and 12800 Hz. 100 Hz is not used because the stimuli with the centre frequency being an odd multiple of $f_\mathrm{m}$ have different characteristics in perceived ASW [11].

The variable stimuli are the reference signals, which are obtained by convolving the broadband white noise with the HRTF filter coefficients. The broadband white noise is an appropriate choice for sound localization [23-24]. It can provide an accurate sense of spatial angle after being filtered by a bandpass filter with a pass band of 200 – 14000 Hz and convolved with the HRTF filter coefficients [25].

The HRTF data of the MIT with a vertical elevation angle of 0 ° and a horizontal opening angle of 270 ° to 360 ° is adopted to generate the reference signals with specific spatial angles [26]. Due to the usage of non-individualized HRTF data, most of the listeners have the best spatial resolution in front of the horizontal plane with a resolution of approximately 5 ° while the spatial positioning resolution on the left and right sides slightly decreases to approximately 10 – 15 ° [19, 24]. The spatial resolution of the MIT data is 5 °, so the spatial resolution in the experiments was set as 5 °. Because the minimum resolution of spatial hearing via headphones is approximately 4.1 °, it is accurate enough to distinguish different position between the fixed stimuli and the variable stimuli with an interval of 5 ° [19].

The SPL of the stimuli was calibrated by using a B&K Head and Torso Simulator (HATS, Type: 4128c), where the sound materials were played back via professional headphones (Type: AKG K702, sensitivity: 105 dB/V) on the HATS. The ISO 226 was adopt to calculate the real loudness of the fixed stimuli [21]. For the variable reference signals, the loudness level was calculated by using the Loudness_ANSI_S34_2007 program [27]. All the stimuli were equalized by an inverse frequency response filter of the headphones to minimize the effect of the frequency response on the results [28].

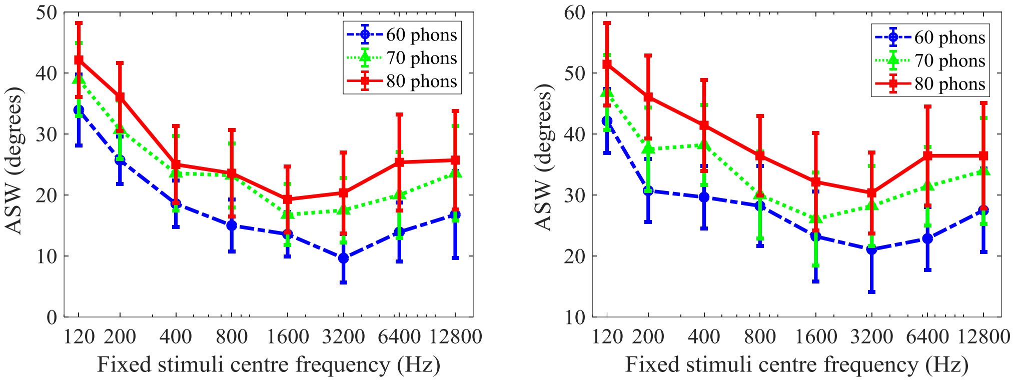
## 3. Data analysis and discussion

### 3.1. Data analysis

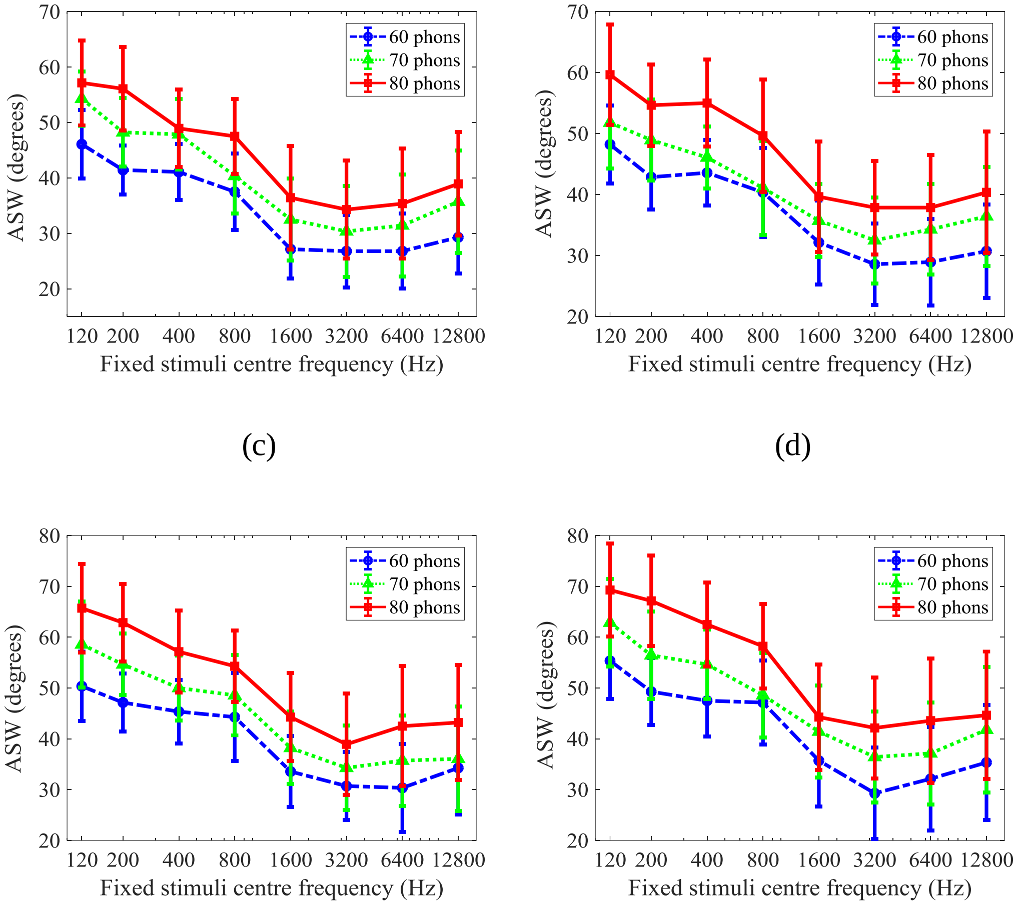
For each stimulus, all subjects judged the ASW for 3 times. The Cronbach's

Alpha of all the subjects were above 0.9 in the tests and the results were distributed within triple standard deviations of the means (Pauta criterion) so the results can be considered to be reliable [29]. An outlier analysis (Grubb's outlier test) was adopted and no subject was found, so no data was removed from the tests [28]. The results of twelve subjects were adopted to build the perceived model and the results of another two subjects were used in the verification tests.

The means and associated 95% confidence intervals of the ASW with 3 typical loudness levels are shown in Fig. 2 for 6 different IACCs from 1.0 to 0 with an interval of 0.2. The blue dash-dotted lines, the green dotted lines and the red solid lines represent the experiment results of fixed stimuli with 3 typical loudness levels, respectively.



(a) (b)



(c) (d)

(e) (f)

FIG. 2. Means and associated 95% confidence intervals of the ASW at different loudness levels as a function of the center frequency of the fixed stimuli from 120 Hz to 12800 Hz: (a) IACC = 1; (b) IACC = 0.8; (c) IACC = 0.6; (d) IACC = 0.4; (e) IACC = 0.2; (f) IACC = 0.

It can be observed from Fig. 2 that the ASW increases with loudness level increase at all frequency bands for different IACCs. The statistical analysis shows that the effect of the loudness level on ASW is significant with $p < 0.05$, where $p$ value is the product of the three-way analysis of variance, and a $p$ value lower than 0.05 is considered to be statistical significant [30]. The means of ASW achieves the minimum when the loudness level is 60 phons and the maximum of the ASW appears at 80 phons. The average of the increment of the ASW is approximate 5.4 degrees for 10 phons loudness increment. The maximum of the increment of ASW is 7.4 °around 200 Hz and the minimum is 4.1 °around 1600 Hz for 10 phons loudness increment. It can be inferred that the increment of the ASW with the loudness level increase is larger at the low frequency than that at the middle frequency. This is the first quantitative research on the effect of loudness levels on perceived ASW at different frequency bands via headphones.

Figure 3 shows the perceived ASW as a function of frequency with different loudness level. When the loudness level is 60 phons (solid line), the ASW decreases as the center frequency varying from 120 Hz to 3200 Hz and then increases slowly above 3200 Hz. The maximum occurs at 120 Hz and the minimum appears around 1600 – 3200 Hz. When the loudness is 70 phons (dotted line) and 80 phones (dashed line), the change trends of the ASW are the same as that of the 60 phons as the frequencies varying from 120 Hz to 12800 Hz. The relationship of ASW and frequency shown in Fig. 3 agree with that in Mason’s paper and an improvement is made in the reference signals [11]. A reference signal with an angle value has been used in our tests to provide an ASW value directly. This is the first time that this relationship has been obtained in full frequency bands with an angle value instead of the value of IACC or scores via headphones [7, 11]. It seems that the relationship between ASW and frequency holds for different loudness level.

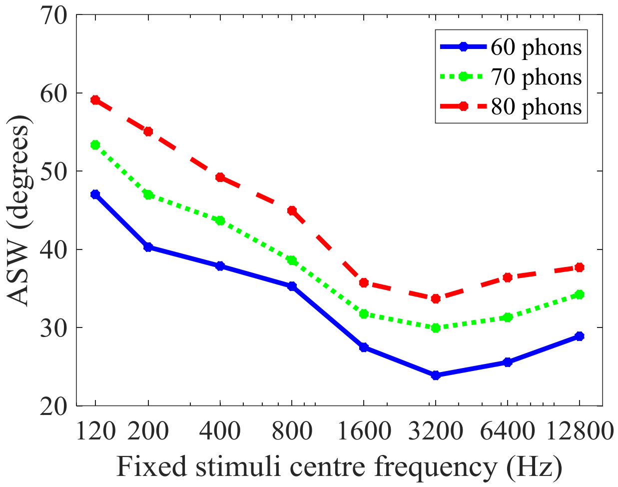


FIG. 3. Means of the ASW at different loudness levels as a function of the center frequency of the fixed stimuli from 120 Hz to 12800 Hz.

When the IACC decreases from 1 to 0, the perceived ASW increases from approximately 20 degrees to 50 degrees as shown in Fig. 4. The increment of the ASW decreases significantly as the IACC varying from 1 to 0.4, but changes little when the IACC changes from 0.4 to 0. The maximum of the increment of ASW occurs when the IACC changes from 1 to 0.8 and the less increment of ASW is observed for IACCs less than 0.4. The results shown in Fig. 4 agree with that in Blauert's paper [6], the new observation is that the quantitative results of increment of ASW has been obtained at different loudness levels as IACC varying from 1 to 0 via headphones. It can be inferred that changing IACC from 1 to 0.6 is more efficient for broadening ASW and the relationship between ASW and IACC holds for different loudness levels.

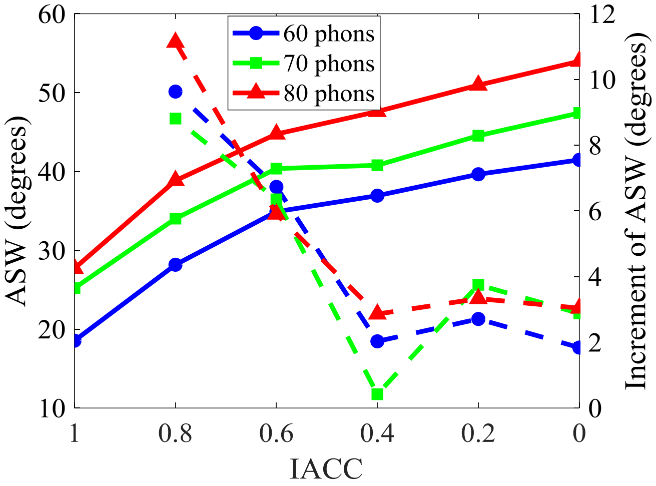


FIG. 4. Means of ASW (solid lines) and the increment of ASW (dash lines) of the three types of loudness levels as a function of IACC from 1 to 0.

For the IACC changes with an interval of 0.2, the averaged increment of ASW as a function of frequency is shown in Fig. 5. The averaged increment of ASW increases firstly and then decreases with the frequency. The maximum of the averaged increment appears around 400 – 800 Hz while the minimum of the increment appears above 6400 Hz. It seems that the ASW of a stimulus at low frequency bands around 400 – 800 Hz can be broaden more significantly by decreasing the IACC of the stimulus. The influence of IACC on ASW is different at different frequency and the ASW can be broaden more effectively at low frequency bands by changing the IACC.

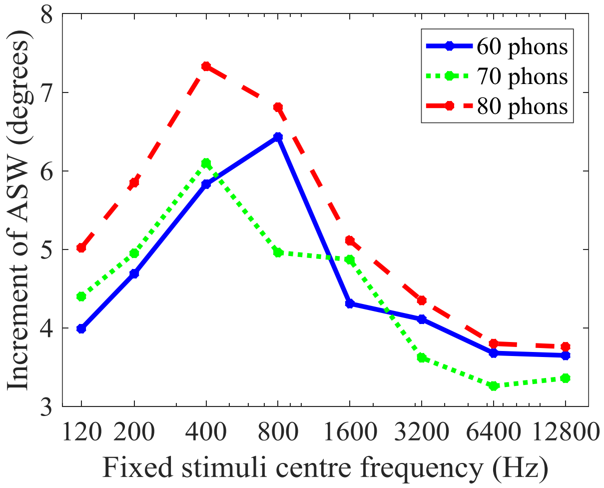


FIG. 5. Means of the increment in ASW at different frequencies as the IACCs varying from 0 to 1 with an interval of 0.2 at three loudness levels.

The influence of IACC on ASW has been investigated in Blauert's paper via headphones as IACC varying from 0.25 to 0.75 below 4000 Hz and the effect of IACC on ASW at the low frequency bands was found to be more significant [6]. Mason also noticed that the IACC in the low frequency band affects the perceived ASW and he studied the perceived ASW with IACC = 0 as frequency varying from 100 Hz to 960 Hz [11]. But there is no quantitative results of the increment of ASW for the IACC varying from 1 to 0 with an interval of 0.2 at full frequency bands. This is the first time that the results of the effect of different IACC on the increment of perceived ASW at different frequency bands via headphones are obtained.

### 3.2. Discussion and curve fitting

Table 2 shows the results of the analysis of the variance of the test data for the three factors, i.e., the loudness level, IACC and frequency [30].

Table 2 Analysis of Variance

| Factor | F-value | Significance $p$ | Partial $\eta^2$ |
|---|---|---|---|
| Frequency | 96.596 | 0.000 | 26.5% |
| Loudness level | 106.691 | 0.000 | 10.2% |
| IACC | 151.275 | 0.000 | 28.8% |
| Interaction (Frequency * Loudness) | 0.521 | 0.923 | 0.4% |
| Interaction (Frequency * IACC) | 1.481 | 0.035 | 2.7% |
| Interaction (Loudness * IACC) | 0.583 | 0.829 | 0.3% |
| Interaction (Frequency * IACC * Loudness) | 0.147 | 1.000 | 0.5% |

All of the three factors play an important roles in the perception of ASW. For the frequency and IACC, $p < 0.05$, the partial $\eta^2$ are 26.5% and 28.8%, respectively, so frequency and IACC are strong factors for the perception of ASW. For the factor of loudness level, $p < 0.05$, the partial $\eta^2$ is 10.2%, so loudness level is a significant factor for the perception of ASW.

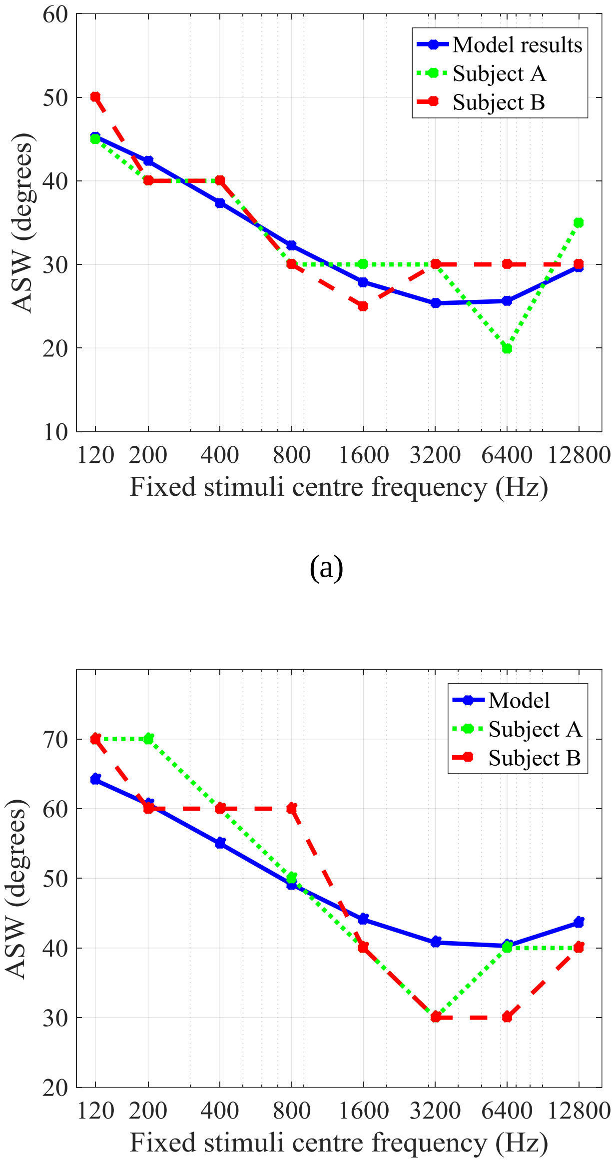
For the interaction of the three factors, most of them do not have significant influences on the perception of ASW ($p > 0.05$), except the interaction of frequency and IACC ($p < 0.05$). It's worth noting that the partial $\eta^2$ of interaction of frequency and IACC is 2.7%, so the interaction of frequency and IACC need to be considerred as one factor in the perception model. Figures 4 and 5 show that the relationship of the IACC and the increment of ASW is dependent on frequency and changing IACC at low frequency bands increases ASW significantly, so the interaction of frequency and IACC should be an important factor in the prediction model [11].

Based on the research of Morimoto, Okano and Mason [3, 4, 11], a formula is developed by curve fitting the data obtained in this paper for the relationship between the three factors, frequency, loudness level and IACC, as shown in Eq. (5),

$$\begin{aligned}\mathrm{ASW} = &-49.90 + 109.42\log_{10} f + 0.653L - 18.58I_{\mathrm{ACC}} + 5.84I_{\mathrm{ACC}}\log_{10} f - \ldots \\ &48.92(\log_{10} f)^2 - 0.00089L^2 - 21.82{I_{\mathrm{ACC}}}^2 + 6.12(\log_{10} f)^3\end{aligned} \tag{5}$$

where ASW is the auditory source width in degrees, $f$, $L$ and $I_{\mathrm{ACC}}$ are frequency, loudness level, and IACC respectively. The formula holds for the frequency from 120 Hz to 12800 Hz and the loudness level between 60 phones and 80 phones.

The data from two subjects who participated in the verification tests but not the formal tests is used to test the validity of the proposed prediction model. Their perceived ASW and the predicted ASW with Eq. (5) as a function of frequency with different IACC and loudness levels are shown in Fig. 6. The proposed model can give reasonably good prediction of the ASW. The averaged errors between the model and subjects A and B are 5.4 ° and 4.9 °, respectively. The correlation coefficients between the perceived model and subjects A and B are 0.93 and 0.91 in Fig. 6(a), and are 0.97 and 0.93 respectively in Fig. (b).

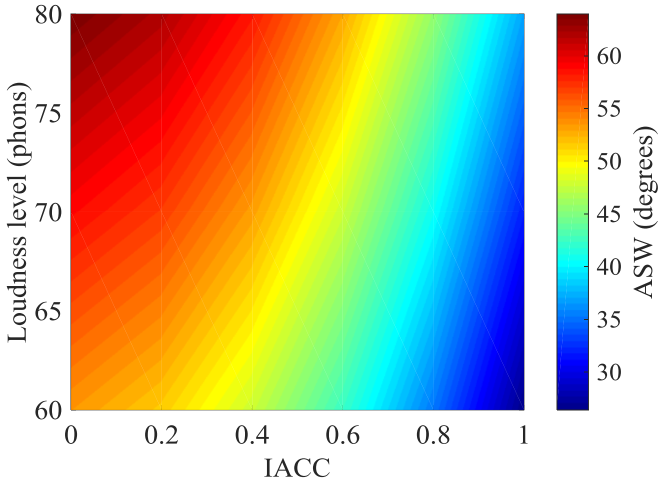


(a)

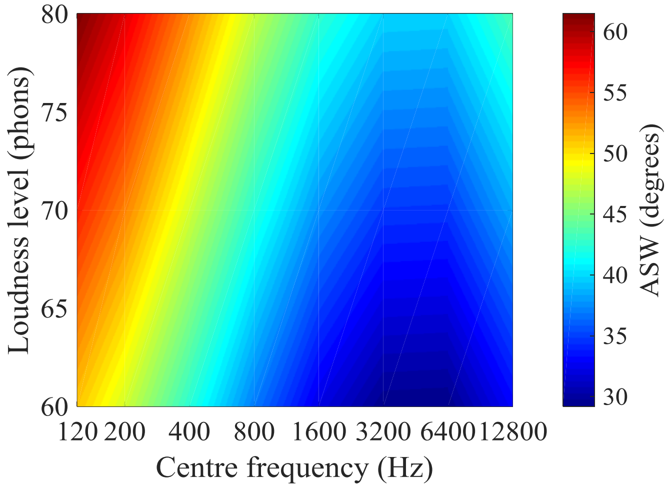
(b)

FIG. 6. The ASW of the perceived model and two subjects in the verification tests (a) IACC = 0.6, and loudness level is 60 phons; (b) IACC = 0.2 and loudness level is 80 phons.

The proposed model can be used to plot equal ASW contours. In Fig. 7(a), the stimuli have a fixed center frequency (200 Hz in the example), and the ASW are shown as functions of IACC and loudness level. It can be observed that the ASW decreases when IACC increases and their values are different at different loudness level. The increment of ASW is approximately 8.8 degrees as the IACC varying from 1 to 0.8 and the increment decreases to 2.0 degrees as the IACC varying from 0.2 to 0, which are consistent with Fig. 4. It can be concluded that the change from 1 to 0.6 of IACC is more efficient to broaden ASW.



(a)



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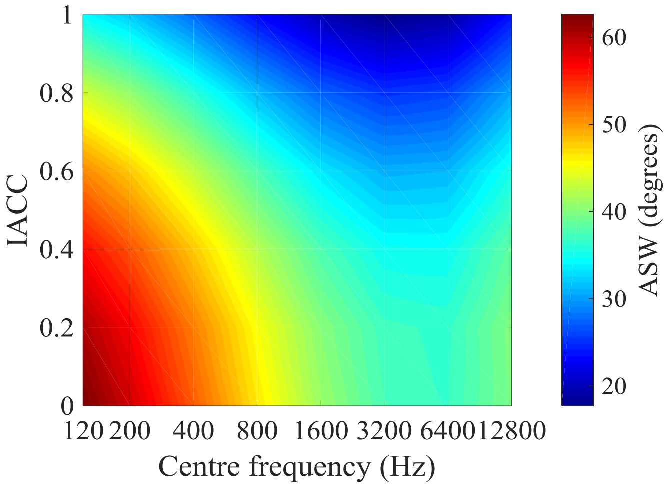

(c)

FIG. 7. Equal-ASW contours: (a) the center frequency of stimuli is fixed at 200 Hz; (b) the IACC of stimuli is fixed at 0.4; (c) the loudness level of stimuli is fixed at 70 phons.

If the stimuli have a fixed IACC (for example, 0.4), the ASW can be calculated as a function of the centre frequency and the loudness level, as shown in Fig. 7(b). The ASW decreases as the frequency varying from 120 Hz to 3200 Hz and rises as the frequency increasing above 6400 Hz. If the stimuli have a fixed loudness level (for example, 70 phons), Fig. 7(c) shows the calculated ASW as a function of the centre frequency and IACC.

In summary, a quantitative reference signal has been applied in the tests and the quantitative results of the relationship between ASW and the three factors have been obtained. Regarding the factor of loudness level, this is the first quantitative research on the effect of loudness levels on perceived ASW at different frequency bands via headphones. Regarding the factor of frequency, the relationship of the frequency and ASW has been obtained in full frequency bands with an angle value to directly give an ASW value. Regarding the factor of IACC, the quantitative results of ASW increment at different frequency bands as IACC varying from 1 to 0 have been obtained. The interaction of IACC and frequency on ASW has been investigated by variance analysis and all the findings has been combined into a new perceived ASW model, which can be used to predict the auditory source width of a stimulus with fixed loudness level, fixed IACC and fixed center frequency or provide equal-ASW contours for engineering applications.

## 4. Conclusions

Two sets of listening tests have been conducted with 14 subjects to investigate the realtionship between ASW and the three factors (frequency, IACC and loudness level) via headphones by using the virtual acoustics pointer method. It is found that increasing the loudness level increases the ASW, but with different degrees at different frequencies. The minimum ASW increment appears around 1600 Hz and the maximum occurs around 200 Hz. The average of the ASW increment is approximately 5.4 degrees for 10 phons loudness increment. Decreasing IACC can broaden the ASW, the maximum of the increment of ASW occurs around 400 – 800 Hz and the average increment is approximately 4.8 degrees for the decrement in IACC of 0.2. A formula is developed by curve fitting to describe the relationship among the three factors and the ASW, which can be used to predict the auditory source width for stereo sound reproduction using headphones and help hearing impaired people perceive more accurate ASW of sound. Future work includes investigating the perceived ASW of complex stimuli at more detailed frequency bands and applying this model to improve the ASW prediction accuracy of normal sound in hearing-impaired patients.

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