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Relationship between subjective responses and physical parameters of air-conditioner noises in a car

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ABSTRACT

Sound pressure levels (SPL) of air-conditioner noise are decreasing due to the developments of noise control techniques. However, people can still feel uncomfortable by certain aspects of the sound quality, even when the actual SPL is low. Not only quantity aspects of the noise, such as SPL, but also quality aspects of the noise can affect the subjective evaluation of air-conditioner noises in a car. Therefore, both the SPL and the sound quality of an air-conditioner noise are important for the user's acoustic comfort. The aim of this paper is to clarify the characteristics of air-conditioner noises in a car and determine the factor that is most influential on the subjective responses caused by the noise. Sound quality can be characterized by factors obtained from autocorrelation function (ACF) and interaural cross correlation (IACF) of a sound. Subjective loudness and annoyance were evaluated using a paired comparison method. Multiple regression analyses were performed using linear and nonlinear combinations of SPL, the ACF, and IACF factors, and their standard deviations. The subjective loudness and annoyances were formulated by the ACF factors.

Keywords: Road noise, Air-conditioner noise, Sound quality

1. INTRODUCTION

Many people spend a lot of time in vehicles; thus, the comfort of a car has become important to passengers. Sound environments in cars are becoming quieter because of acoustic insulation and absorption, such as in the case of a rubberized road surface (1), and the prevalence of low-noise engines, such as hybrid and electric engines (2). Reduction of noise levels heightens awareness of sound quality. A bad car interior sound quality can negatively affect passenger psychology and physiology (3). Therefore, sound quality is becoming increasingly important as a part of vehicle designs.

Many research papers on booming sound quality in a car have been published (3-8). In addition to general interior noise, there are various other types of vehicle noise, such as suspension shock absorber rattling noise (3) and heating, ventilation and air conditioning noise (9). People use air conditioner most of the time when they drive. Previous studies investigated sound quality of air-conditioner noise when the car was idling or stopping (9-11). However, there is little study on sound quality of air-conditioner noise when the car was running.

The aim of this study is to determine the factor that is the most dominant in terms of the subjective assessment caused by air-conditioner noises in running cars. The effects of the road noise and air-conditioner noises were considered in this study.

2. METHODS

2.1 Measurements of noises in running cars

Two cars were chosen for the measurement. Car A was a sedan while car B was a small car. Noise in the running car cabins were recorded by a laptop computer at a sampling rate of 48 kHz and a sampling resolution of 24 bits via a head and torso simulator (HATS, Type 4128C, Brüel & Kjær) and an AD/DA converter (Fireface UCX, RME). The HATS was located on the passenger seat. The effect of the air conditioner was investigated by setting the air-conditioning mode to off, weak, and strong.

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The cars run on a general road at a speed from 0 to 60 kilometers-per-hour and an express way at a speed from 70 to 90 kilometers-per-hour. All windows were closed during the measurement. For the comparison, noise in an idling state was recorded. The background noise level was measured according to the A-weighted equivalent continuous sound pressure level (L_{Aeq}) and is summarized in Table 1.

Table 1 – Background noise level, L_{Aeq} [dB], for each setting

Setting	Air conditioner off	Air conditioner weak	Air conditioner strong
Car A	37.2	46.3	60.6
Car B	40.5	49.2	60.3

2.2 Analysis of noises in running cars

The autocorrelation function (ACF) and interaural cross-correlation function (IACF) factors for sound quality evaluation have been proposed (12, 13). To calculate the ACF factors, the normalized ACF of the signal recorded from microphones, $p(t)$, as a function of the running step, s, is defined by

$$\phi(\tau) = \phi(\tau; s, T) = \frac{\Phi(\tau; s, T)}{\sqrt{\Phi(0; s, T)\Phi(0; s+\tau, T)}}, \tag{1}$$

where

$$\Phi(\tau; s, T) = \frac{1}{2T}\int_{s-T}^{s+T} p'(t)p'(t+\tau)dt. \tag{2}$$

where, 2T is the integration interval and $p'(t) = p(t)*s_e(t)$, where $s_e(t)$ is the ear sensitivity. In this study, $p(t)$ is the signal that was measured using the HATS. $s_e(t)$ represents the impulse response of an A-weighted network, including the transfer functions of the human outer and middle ear, for convenience (12, 13). Normalization of the ACF is performed using the geometric mean of the energy at s and the energy at $s+\tau$; this ensures that the normalized ACF satisfies the condition $0 \leq \phi(\tau) \leq 1$.

L_{Aeq} is determined based on the A-weighted $p(t)$ signal as a function of s. L_{Aeq} is then calculated using

$$L_{Aeq}(s, T) = 10\log\Phi(0; s, T). \tag{3}$$

This means that the ACF includes L_{Aeq} as a factor.

The other ACF factors are calculated from the normalized ACF. τ_1 and ϕ_1 are defined as the time delay and the amplitude of the first maximum peak. τ_1 and ϕ_1 are related to the perceived pitch and the pitch strength of the complex sounds, respectively (12, 14). Higher values of τ_1 and ϕ_1 indicate that the sound has a lower pitch and a stronger pitch, respectively. The other ACF factor, $W_{\phi(0)}$, is defined using the delay time interval at a normalized ACF value of 0.5, and represents the width of the first decay. $W_{\phi(0)}$ is equivalent to the spectral centroid (13). Higher values of $W_{\phi(0)}$ indicate that the sound includes a higher proportion of low frequency components. From the IACF analysis, the interaural cross-correlation coefficient (IACC), which is defined as the maximum of the IACF, the delay time at the IACC, τ_{IACC}, and width of the IACC, W_{IACC}, were analyzed. We calculated the ACF and IACF factors for the noises as a function of time. The integration interval was $2T = 0.5$ s and the running step was $s = 0.1$ s in all calculations. The analyses were conducted using a MATLAB-based program.

2.3 Subjective assessments

Subjective loudness and annoyance caused by noises measured in car cabins was evaluated to clarify the effects of the ACF and IACF factors on loudness and annoyance. Nine participants took part in the experiments. All participants had normal hearing, no history of neurological disease, and ranged in age between 20 and 40 years. Informed consent was obtained from each participant after the nature of the study had been explained. The study was approved by the ethics committee of the National Institute of Advanced Industrial Science and Technology (AIST) of Japan.

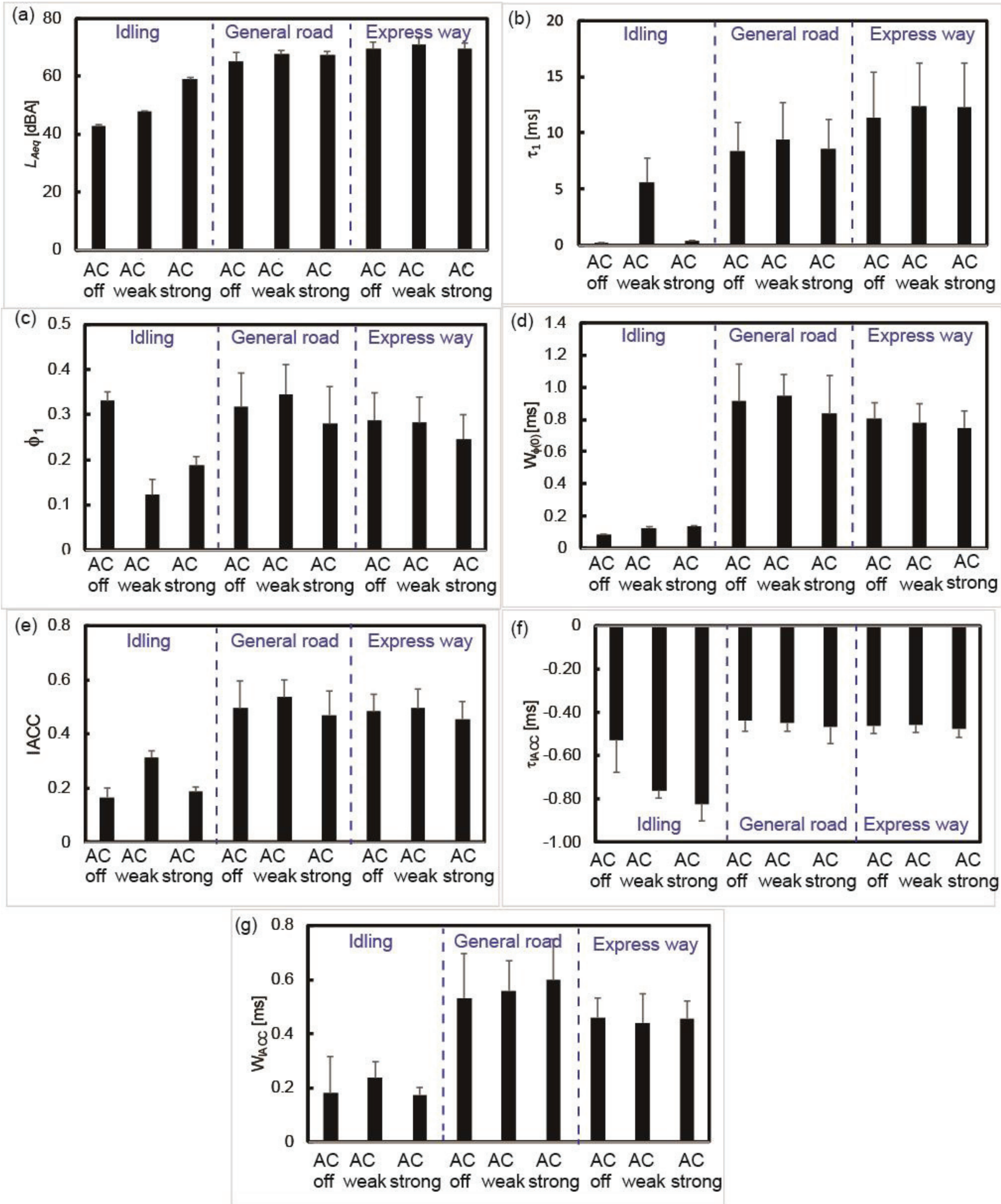

Figure 1 – Mean values of (a) L_{Aeq}, (b) τ_1, (c) ϕ_1, (d) $W_{\phi(0)}$, (e) IACC, (f) τ_{IACC}, and (f) W_{IACC} (± standard deviations) of noises generated by idling, general road, and express way conditions at air-conditioning mode of off, weak, and strong.

Twelve stimuli were selected from the measured noise recorded by the HATS in car cabins running on an express way to focus on the air-conditioner noises in running cars. The stimuli were presented binaurally through headphones (HD800, Sennheiser). The stimuli were presented binaurally at the same L_{Aeq} as the actual measured stimuli. L_{Aeq} was verified using a dummy head microphone (KU100, Neumann) and a sound calibrator (Type 4231, B&K).

Scheffe's paired comparison tests (15) were performed for all combinations of pairs of stimuli, by interchanging the order in which the stimuli in each pair were presented in each session and by presenting the pairs in random order. The duration of the stimuli was 2.0 s. The rise and fall times were 100 ms, and the silent interval between stimuli was 1.0 s. After the presentation of each pair of stimuli, the participants were required to compare the two stimuli in each case based on seven grades by considering the differences between the two stimuli.

The averaged scale values of loudness and annoyance according to each participant were calculated based on the modified Scheffe's method (16). To calculate the effects of each objective factor on participant loudness and annoyance, multiple regression analyses were conducted using a linear combination of the ACF, IACF factors and their standard deviations (SDs) as predictive variables by stepwise procedures. The analyses were carried out using SPSS statistical analysis software (SPSS version 22.0, IBM).

3. RESULTS AND DISCUSSION

3.1 Analysis of noises in running cars

Figures 1 (a) to (d) show the ACF factors (L_{Aeq}, τ_1, ϕ_1, and $W_{\phi(0)}$) of the noise that was measured in the car cabins in an idling state, during running on general road and express way. The setting of the air-conditioning mode was off, weak, or strong. L_{Aeq} became larger in the running car. The effect of the air-conditioning mode was small in the running car. The τ_1 value increased with increasing running speed, suggesting the effects of engine sounds. The ϕ_1 value decreased in the idling state except when the air-conditioning mode was off. This indicates the masking effects of the air-conditioner noise on the idling sounds. The $W_{\phi(0)}$ value also decreased in the idling state. When the car run on the express way, the ϕ_1 and $W_{\phi(0)}$ values decreased in comparison to those when the car run on the general road. This suggests the effect of the road noise.

Figures 1 (e) to (g) show the IACF factors (IACC, τ_{IACC}, and W_{IACC}) of the noise measured in the car cabins. IACC became larger in the running car, suggesting the effects of sound sources other than the engine and air conditioner. The τ_{IACC} value show the effects of air-conditioner mode clearly in the idling states. However, effects of the air-conditioner noise on the τ_{IACC} value was little in the running car. The W_{IACC} value decreased in the idling state. The W_{IACC} value measured on the general road was greater than that measured on the express way.

3.2 Subjective assessments

The relationships between the averaged scale value of the loudness, annoyance and each factor are presented in Figures 2 and 3. Loudness was found to increase slightly with increasing L_{Aeq} and decreasing ϕ_1. Annoyance was found to increase slightly with decreasing ϕ_1.

A multiple linear regression analysis was performed with the scale values of loudness for all participants as the outcome variable. The final version indicated that ϕ_1, ϕ_1_SD, and L_{Aeq} were significant factors:

$$SV_{loudness} \approx a_1 * \phi_1 + a_2 * \phi_1\_SD + a_3 * L_{Aeq} + c. \quad (4)$$

The model was statistically significant ($p < 0.01$) and the modified determination coefficient was 0.76. The standardized partial regression coefficients of the variables a_1, a_2, and a_3 in Eq. (4) were −1.42, −0.96, and 0.38, respectively. The negative coefficients of ϕ_1, and ϕ_1_SD indicates that the weaker and unvaried pitch cause greater loudness. The negative coefficients of ϕ_1 is consistent with the previous finding of annoyance (10), however, the negative coefficients of ϕ_1_SD is inconsistent with the previous finding of annoyance (10). The positive coefficient of L_{Aeq} indicates that the larger L_{Aeq} causes greater loudness.

A multiple linear regression analysis was performed with the scale values of annoyance for all participants as the outcome variable. The final version indicated that L_{Aeq}, L_{Aeq}_SD, and $W_{\phi(0)}$ were significant factors:

$$SV_{annoyance} \approx b_1 * L_{Aeq} + b_2 * L_{Aeq}\_SD + b_3 * W_{\phi(0)} + c. \quad (5)$$

The model was statistically significant ($p < 0.01$) and the modified determination coefficient was 0.56. The standardized partial regression coefficients of the variables b_1, b_2, and b_3 in Eq. (5) were 0.50, 0.48, and −0.22, respectively. The positive coefficients of L_{Aeq} and L_{Aeq}_SD indicates that the larger and larger variation of L_{Aeq} cause greater annoyance. The negative coefficient of $W_{\phi(0)}$

indicates that the lower frequency components of the noises cause greater annoyance. This is consistent with the previous finding (10, 11).

4. SUMMARY

This study investigated the dominant factors for the subjective assessments caused by air-conditioner noises in running cars. Pitch strength, ϕ_1, the variation of the pitch strength, ϕ_1, and L_{Aeq} are dominant factors for subjective loudness. L_{Aeq}, the variation of L_{Aeq} and spectral centroid, which corresponds to $W_{\phi(0)}$, are dominant factors for subjective annoyance.

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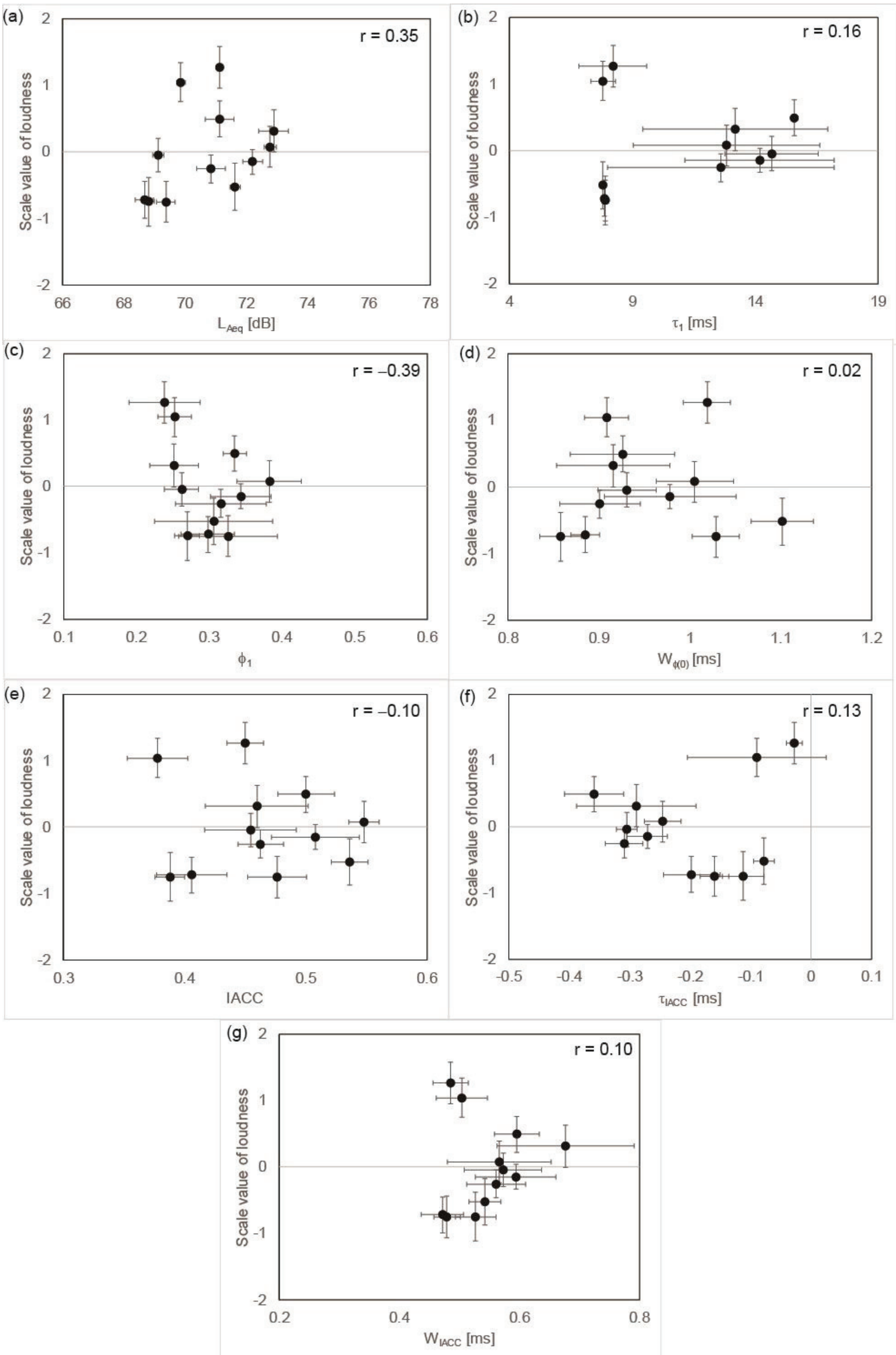

Figure 2 – Relationships between the scale value of loudness and (a) L_{Aeq}, (b) τ_1, (c) ϕ_1, (d) $W_{\phi(0)}$, (e) IACC, (f) τ_{IACC}, and (f) W_{IACC}. Error bars indicate standard deviations.

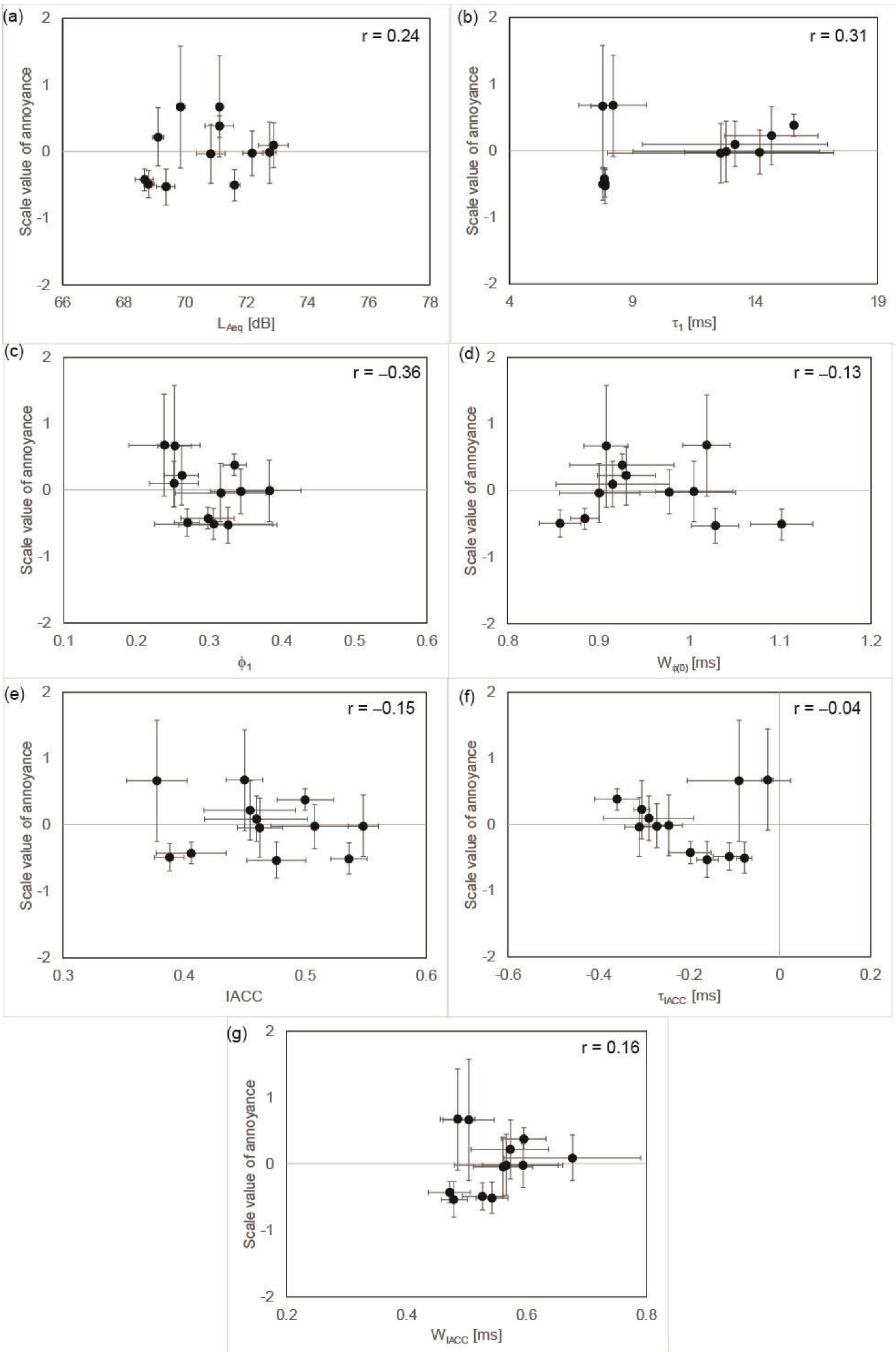

Figure 3 – Relationships between the scale value of annoyance and (a) L_{Aeq}, (b) τ_1, (c) ϕ_1, (d) $W_{\phi(0)}$, (e) IACC, (f) τ_{IACC}, and (f) W_{IACC}. Error bars indicate standard deviations.