Indoor Noise Annoyance Due to Transportation Noise

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Abstract

This study examined the relationship between noise annoyance and sound pressure levels in indoor environments due to various modes of transportation including road traffic, railways, and aircraft. The experiments were conducted in a laboratory environment, where the limited sense of presence was overcome by using an appropriate exposure duration. The degree of annoyance was surveyed and the average score was converted into percent of annoyance (%PA) and percent high annoyance (%HA) values among respondents for comparisons with the noise levels. As expected, the subjective response increased in proportion with the noise level and there was an extremely high correlation. Notably, the smallest deviation in responses was found for road traffic noise. Overall, the noise levels corresponding to a %PA of 50% were 41 dB(A), 48 dB(A), and 49 dB(A) for road traffic noise, railway noise, and aircraft noise, respectively. In addition, the levels corresponding to a %HA of 20% were 45 dB(A), 51 dB(A), and 53 dB(A), respectively. The %HA values coincided well with current regulations for indoor noise in Korea (45 dB(A)).

Keywords: transportation noise; exposure time; annoyance; indoor noise

1. Introduction

One of the most important aspects in assessing the subjective response of people to noise is how effectively variables can be controlled to reduce experimental errors and increase the accuracy of the assessment. For example, Fields and Walker (1982) argued that the season during which a subjective response study is conducted may influence its results. While windows are generally open during summer, they are often closed during winter and people also tend to spend more time indoors (Schultz, 1978), which limits the influence of external noise at this time. Residential conditions may also affect subjective responses to noise. For example, the indoor levels of external noise sources will differ according to the sound insulation level of windows and walls facing the source, thus resulting in different subjective responses. Moreover, the size of the region being studied and the degree of background noise are also significant factors. This is because awareness of noise may differ depending on the size of region, and environmental noise may be perceived more strongly in environments with low background noise. Furthermore, economic status and social customs can also influence awareness of noise and subjective responses.

Among the various types of environmental noise, transportation noise such as that from road traffic, railways, and aircraft is very relevant in the residential environment. It has been identified as the greatest source of dissatisfaction among different types of external noise (Park et al., 2012). However, transportation infrastructure is beneficial to human life, and thus, the convenience of living close to various modes of transportation must be weighed against the detrimental aspects of the associated noise. Accordingly, many studies have been conducted to measure, analyze, and establish standards for road traffic noise. In particular, studies have explored the differences between the effects of various sound sources such as road traffic noise, railway noise, and aircraft noise. For example, Kryter (1982) reported that annoyance from aircraft noise is greater than that from other transportation noises and that annoyance from road traffic noise is higher than that from railway noise (see also Fields and Walker, 1982; Schultz, 1982; Miedema, 2004). However, Yano et al. (1997) and Morihara et al. (2004) found no significant difference between road traffic noise and railway noise. It is speculated that these differences stem from differences among societies and nations. Overall, economic conditions and the social atmosphere of a nation can determine awareness of noise, and the characteristics of external noise and the physical conditions of residences have a direct influence on the perceived noise effects.
As discussed earlier, assessment of the subjective response to transportation noise involves many variables that are not easy to control. This is because most such variables such as attitude toward noise, living environments, and awareness are subjective themselves. However, these confounding factors can be mitigated by performing listening experiments in a laboratory. This method makes it easier to obtain direct results on the response to noise in contrast to a field study. However, one problem with laboratory experiments is that subjects may lack a feeling of presence in a real environment. The duration of noise is an important factor in the subjective feeling of presence. A preceding study (Kim et al., 2012) verified that the exposure time of transportation noise affects the subjective response and that 10 min of exposure is appropriate for obtaining stable subjective responses.

In South Korea, domestic standards on transportation noise currently follow noise measurement standards for apartment complexes that have been enforced by the Ministry of Land, Transport and Maritime Affairs since January 2008. The noise level must be less than 65 dB when measured at the outer wall of an apartment, and indoor noise should be less than 45 dB. However, there is no clear basis for such noise regulations, and the numbers need to be verified through a response experiment on transportation noise.

Thus, the purpose of this study was to analyze the relationship between transportation noise and the subjective response in a laboratory and to analyze the subjective response more accurately by considering the exposure time. The appropriateness of current regulations was also tested by deducing appropriate noise levels through experiments.

2. Experiment

2.1 Sound Sources

The sound sources used in this study were road traffic noise, railway noise, and aircraft noise, as shown in Fig.1. and described in Table 1. Sound sources were measured and recorded on site simultaneously for use in the experiment. The recorded sound sources were edited to simulate sound levels indoors by considering the sound insulation performance of windows. It was considered 16-mm-thick insulating double glass windows comprised of two 5-mm-thick panes separated by a 6-mm-thick intermediate air space (Fig.2.). The sound transmission class (STC) ratings are 30 for single windows, 39 for double windows with an expanded balcony, and 41 for double windows without an expanded balcony. The appropriate exposure time was set to 10 min based on a preceding study (Kim et al., 2012).

2.2 Subjects

Undergraduates and graduates attending J University were recruited as subjects. Their ages were between 20 and 30 years, and all subjects were verified to have normal hearing abilities. A total of 12 subjects (9 males and 3 females) with a mean age of 24.7 years participated in the experiment. Subjects were allowed to read books during the experiment to prevent them from responding too sensitively to noise. Allowing subjects to work on a task during an experiment is expected to better reflect actual life, where individuals perform daily chores without solely concentrating on noises.

In order to exclude effects from the sequence of presentation of sounds, the sources were randomly sequenced for three different sets. In order to maximize the sense of presence, subjects were made to feel
that the noises occurred while they were resting in a residential space. They were allowed to assume postures that they felt most comfortable in. That is, a comfortable atmosphere resembling daily life was created so that subjects participating in the experiment were relaxed. Sound sources were played once before the subject was asked to select a response. As shown in Fig.3., the duration of the sound was 20 s and there was a signal sound to distinguish one sound source from another. Subjects with no past experience in listening experiments were allowed to practice and become familiar with the experiment. Psychological pressure was reduced with frequent conversations and rest breaks during the experiment. Several breaks were allowed to make participants feel less bored.

During the listening experiments, subjects evaluated the degree of annoyance created by sound sources they listened to from point 7 extremely annoyed to point 1 not at all annoyed (Table 2.).

Table 2. Evaluation Sheet

| Adjective | Extremely | Not at all |
|-----------|-----------|-----------|
| Annoyance | 7 – 6 – 5 – 4 – 3 – 2 – 1 |

2.3 Laboratory

As shown in Fig.4., the experiment was conducted in a laboratory that was 4.96 m in length, 3.85 m in width, and 2.7 m in ceiling height, similar to a living room in a conventional apartment. Speakers were installed on the front wall and hidden behind a screen. Walls on both sides were furnished with sound absorption materials to suppress unnecessary reflections. The control room was placed in an acoustically separated space behind the laboratory. A fixed window installed between the laboratory and control room allowed for observations of the subject.

2.4 Analysis Method

Subjects were given a sufficient explanation about the purpose of the experiment prior to their participation in the listening sessions. Subjective evaluation of noise is often done through measurement of the attitude of people exposed to noise. In general, the Likert scale is used to measure this attitude. According to Yano et al. (1997), the degree of annoyance from transportation noise is not influenced by the number of steps in the scale. Hence, the seven-step response scale used in many preceding studies was also used here, as shown in Table 2. In accordance with this scale, strong annoyance was scored closer toward "7" and mild annoyance was scored closer toward "1." Since it may be difficult to differentiate between steps of the scale during the experiment, subjects received a sufficient explanation in advance and understood the contents of the experiment based on a preliminary experiment.

While focusing on the relationship between values deduced from the subjective response evaluation and equivalent sound levels (Leq dB(A)), the relationship between the ratio of normal annoyance and ratio of extreme annoyance was analyzed. A polynomial function curve, which is often used for regression analysis, can result in errors corresponding to the maximum limit value (if the stimulation or noise level is extremely small or extremely large). Therefore, the Boltzmann equation, which accurately expresses the relationship between the stimulation and response, was used to deduce the regression equation and predict the relation between the noise level and the degree of annoyance (Origin, 1997).

\[
y = \frac{A_1 - A_2}{1 + e^{\left(\frac{x - x_0}{dx}\right)}} + A_2
\]

Here, \(x\) is the noise level, \(y\) is the degree of annoyance (%), \(A_1\) is the \(y\) value when \(x = -\infty\) (0% or 100%), \(A_2\) is the \(y\) value when \(x = +\infty\) (0% or 100%), \(x_0\) is the value of \(x\) at the mean value of \(y\) (that is, when \(y = 50\%\)), and \(dx\) is the slope in the middle of the regression line. In this study, the seven-step scale was expressed as a percentage. Values corresponding to each limit value, \(A_1\) and \(A_2\), were respectively fixed to 0% and 100% for the analysis.

3. Results and Discussion
3.1 Comparison of Subjective Responses to Each Type of Sound Source

(1) Road traffic noise. The mean value and standard error (SE) of reported annoyance was compared against the sound level, as shown in Fig.5. The lowest level of annoyance (1) was at 30 dB(A), and the
The highest level of annoyance (7) occurred at values of 55 dB(A) or larger. The change in annoyance between 40 dB(A) and 45 dB(A) was larger than that for the other intervals.

(2) Railway noise. Railway noise ranged between 30 dB(A) and 65 dB(A), as shown in Fig.6. Annoyance from railway noise showed a slight difference from that for road traffic noise. Though the overall trend for both was a gradual increase in annoyance with increasing noise levels, it was observed a smaller slope and larger standard error (mean standard error of 0.27) for railway noise compared to road traffic noise (mean standard error of 0.18). This suggests that there was more diversity in the responses of individuals to railway noise at identical noise levels.

(3) Aircraft noise. As shown in Fig.7, the response to aircraft noise was extremely similar to that for railway noise; additionally, the mean standard error was similar (0.28), but it was larger than that for road traffic noise.

### 3.2 Analysis According to Percent of Annoyance

The relationship between the stimulation (transportation noise) and response (annoyance level) was deduced by using the Boltzmann equation. To promote easier understanding of the seven-step scale values used for the analysis, the responses were converted into percentages, as shown in Fig.8. These percentages were classified into the mean percent of annoyance (called %PA hereafter; the data represent the percent of people annoyed) and percent high annoyance (called %HA hereafter; the data represent the percent of people highly annoyed). The %PA shows the mean annoyance of subjects as a percentage, and %HA shows the percentage of subjects who responded to a given sound source level with annoyance values of 6 or 7. Schultz used %HA to exclude the effects of non-acoustic variables and found an extremely high correlation with the subjective response (Schultz, 1978). However, Kryter (1982) criticized this approach stating that there is no basis for supporting %HA and argued that there was a higher correlation between %PA and the subjective response compared to %HA. It was compared the relationship between the transportation noise level and annoyance by using both %PA and %HA values, as shown in Fig.8. The graphs for the three types of transportation noise were similar. By comparing the graphs of %PA and %HA, the difference was especially salient at the middle levels. Moreover, the slope of %PA was more gradual than that of %HA; the slope %HA remained relatively flat from 0 until 40 dB(A), which means that no subject responded with an annoyance score of 6 or 7 up to 40 dB(A). Subsequently, the %HA values increased relatively rapidly, whereby they changed from 0% to 100% within an interval of 15 dB(A). For railway and aircraft noises, the change from 0% to 100% occurred from 50 dB(A) to 65 dB(A).

In a study on the relationship between the subjective response to road traffic noise and %HA, Rindel (1998) discovered a difference of 14 dB between subjective...
responses of 20% and 80%, which corresponds to a difference in the subjective response of 4.29% per dB. Unlike the results of Rindel (1998), it was found a difference of 4.0% per dB(A) with a 15 dB(A) change for a 60% change in %PA for road traffic noise. An extremely high slope of about 10% per dB(A) was seen in the %HA results. For railway noise, the slope was 3% per dB(A) for %PA and 7.5% for %HA. The slope for aircraft noise was 2.6% for %PA and 6% for %HA, which represent values lower than those for road traffic noise.

As summarized in Table 3., the coefficient of determination ($R^2$) for all sound sources was extremely high at 0.98 or higher. The value of $x_0$, which represents 50% of the subjective response, was 41.1 dB(A) for road traffic noise, 47.7 dB(A) for railway noise (6.6 dB(A) higher), and 49.2 dB(A) for aircraft noise (8.1 dB(A) higher). This shows that subjects were most sensitive to road traffic noise. The value of $dx$, which represents the slope of the curve, was the largest for road traffic noise, followed by railway noise and aircraft noise.

Table 3. Parameters of the Boltzmann Curves Used for Predictions of Annoyance

| Sound source | Annoyance | $R^2$ | $x_0$ | $dx$ |
|--------------|-----------|-------|-------|------|
| RTC %PA     | 0.98      | 41.1  | 5.4   |      |
| %HA         | 0.99      | 48.0  | 2.4   |      |
| RWK-L %PA   | 0.98      | 47.7  | 7.9   |      |
| %HA         | 0.99      | 55.3  | 2.9   |      |
| ACM-T %PA   | 0.98      | 49.2  | 9.2   |      |
| %HA         | 0.99      | 57.8  | 3.7   |      |

3.3 Comparison of the Relationship between the Sound Source and Annoyance

Many studies on annoyance caused by different transportation noises mention a so-called "railway noise bonus" (Fastl et al., 1996). That is, since subjects are commonly less sensitive to railway noise in comparison to road traffic noise, the evaluation should be done after moderating the noise level. However,
this approach has been criticized because different results can be obtained in different studies since subjective evaluations on noise can differ according to the frequency and temporal characteristics of the noise and the subjective attitude (Hall, 1984). In this study, a larger slope was found for road traffic noise compared to railway noise, as shown in Fig.9. Although annoyance values were similar at 30 dB(A), the difference in annoyance gradually increased with the increasing noise level. While railway noise and aircraft noise showed slight differences in noise levels above 50 dB(A), they had similar overall trends.

As such, the degree of annoyance caused by each type of transportation noise differed either slightly or greatly. A paired sample t-test was carried out in order to statistically test the difference in the mean values of responses to the noises. As listed in Table 4., the mean annoyance difference between road traffic noise and railway noise was 15.51, which was statistically significant at the 0.05 level. Similarly, the mean annoyance difference between road traffic noise and aircraft noise was also statistically significant. However, the mean difference between railway noise and aircraft noise was only 2.56, which was not significant. Note that the difference between road traffic noise and railway noise was consistent with the usual railway noise bonus. However, while such a bonus is usually about 5 dB, a slightly larger difference of about 6–7 dB(A) was found here (median value of %PA or %HA to set standards for indoor noise levels. As expected, clear proportional relationships with extremely high correlations were found between the subjective responses and transportation noise levels. The responses to road traffic had the smallest deviations among the subjects. This suggests that the subjective response to road traffic noise is more consistent compared to railway noise and aircraft noise. In addition, the slope between the noise level and subjective response was very different according to the type of noise. In the relation between %HA and noise, a larger slope was found compared to that reported by Rindel (1998) (4% per dB). Moreover, a larger railway bonus of 6 dB was found compared to the value generally reported (5 dB). Finally, the differences in mean values for aircraft noise and railway noise were found to be statistically insignificant.

Overall, the noise level at which 50% of subjects felt annoyed (%PA) was found to be 41 dB(A), 48 dB(A), and 49 dB(A) for road traffic noise, railway noise, and aircraft noise, respectively. In addition, the noise level

| Paired sample       | Paired difference | SE of Paired mean | 95% CI of difference | t value | df | Sig. (both) |
|---------------------|-------------------|-------------------|----------------------|---------|----|-------------|
| RTC vs. RWK-L       | 15.51             | 8.96              | 3.17                 | 8.02    | 23.00 | 4.90        | 7 | 0.02         |
| RTC vs. ACM-T       | 18.07             | 10.91             | 3.86                 | 8.95    | 27.19 | 4.69        | 7 | 0.02         |
| RWK-L vs. ACM-T     | 2.56              | 3.13              | 1.11                 | -0.06   | 5.18  | 2.31        | 7 | 0.054        |

df: degree of freedom  
sig: significance level  
sdev: standard deviation  
SE: standard error  
CI: confidence interval  
dif: difference  
LL: lower limit  
UL: upper limit

3.4 Review of Indoor Noise Level Standards

Much discussion is still required on the suitability of using %PA or %HA to set standards for indoor noise levels, as stated in section 3.2. In addition, instead of setting indoor noise level standards by fixing the percent of annoyance, it may be preferable to limit the ratio of people being affected by noise (Finegold et al., 2002). Table 5. lists the noise levels corresponding to the middle level (20%–80%) subjective response mentioned by Rindel (1998), where the regression line can be assumed to be linear. The parameters used in this calculation are from Table 3., and different values were obtained for %PA and %HA. For example, for a %PA of 50%, the corresponding road traffic noise level was 41 dB(A), that for railway noise was 48 dB(A), and that for aircraft noise was 49 dB(A). However, the noise level at which %HA was 20% was 45 dB(A) for road traffic noise, 51 dB(A) for railway noise, and 53 dB(A) for aircraft noise.

### Table 5. Predicted Sound Level Corresponding to Annoyance (%)

| Annoyance (%) | RTC dB(A) | RWK-L dB(A) | ACM-T dB(A) |
|---------------|-----------|-------------|-------------|
| %PA           | 20        | 34          | 37          | 36          |
|               | 30        | 37          | 41          | 41          |
|               | 40        | 39          | 44          | 45          |
|               | 50        | 41          | 48          | 49          |
|               | 60        | 43          | 51          | 53          |
|               | 70        | 46          | 54          | 57          |
|               | 80        | 49          | 59          | 62          |
| %HA           | 20        | 45          | 51          | 53          |
|               | 30        | 46          | 53          | 55          |
|               | 40        | 47          | 54          | 56          |
|               | 50        | 48          | 55          | 58          |
|               | 60        | 49          | 56          | 59          |
|               | 70        | 50          | 58          | 61          |
|               | 80        | 51          | 59          | 63          |

4. Conclusion

The purpose of this study was to examine the relationship between noise levels and subjective responses through a subjective response experiment on road traffic noise, railway noise, and aircraft noise. During the listening experiments, which were conducted in a laboratory, the exposure time to noise was taken into consideration in order to overcome the limitations of a laboratory experiment. After surveying the degree of annoyance, the mean subjective responses were compared to the noise levels. The responses were converted into percent of annoyance (%PA) and percent high annoyance (%HA) values, as suggested by Schultz (1978), for the analysis.

As expected, clear proportional relationships with extremely high correlations were found between the subjective responses and transportation noise levels. The responses to road traffic had the smallest deviations among the subjects. This suggests that the subjective response to road traffic noise is more consistent compared to railway noise and aircraft noise. In addition, the slope between the noise level and subjective response was very different according to the type of noise. In the relation between %HA and noise, a larger slope was found compared to that reported by Rindel (1998) (4% per dB). Moreover, a larger railway bonus of 6 dB was found compared to the value generally reported (5 dB). Finally, the differences in mean values for aircraft noise and railway noise were found to be statistically insignificant.

Overall, the noise level at which 50% of subjects felt annoyed (%PA) was found to be 41 dB(A), 48 dB(A), and 49 dB(A) for road traffic noise, railway noise, and aircraft noise, respectively. In addition, the noise level...
at which 20% of subjects felt highly annoyed (%HA) was found to be 45 dB(A), 51 dB(A), and 53 dB(A) for road traffic noise, railway noise, and aircraft noise, respectively. The results based on %HA coincide well with the current limit for indoor noise in Korea (45 dB(A)). However, since subjects are less sensitive to railway and aircraft noise, the limits for these types of noise can be somewhat moderated if they are measured using an equivalent noise level with an identical physical index.

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