Bayesian Explanation of the Effects of Tactile Feedback on the Affective Evaluation of Switch Sounds

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Abstract: In our previous study, the effects of tactile feedback on the affective evaluation of switch sounds were examined through auditory and tactile evaluation experiments using 15 switches, and it was shown that these effects could be modeled using multiple regression analyses. However, the reason why these effects can be modeled by multiple regression analyses remains unanswered. In this study, extended experiments were conducted using 25 switches. In the auditory evaluation experiment, using 26 adjective pairs on 7-point category scales, two groups consisting of 22 subjects each participated as operators and listeners, respectively. In the tactile evaluation experiment, using 16 adjective pairs, another group of 52 subjects participated. The results of both experiments were analyzed, separately, using factor analyses, with the three factors of potency, evaluation, and activity being extracted for both experiments. The factor scores of the operators were modeled using multiple regression analyses with the factor scores of listeners and tactile evaluations. Another modeling was conducted based on Bayes’ theorem, wherein the factor scores of listeners and operators were regarded as prior and posterior distributions, respectively, with the tactile factor scores being regarded as likelihood. The fact that these two models show almost the same estimation performance suggests that the effects of tactile feedback on the affective evaluation of switch sounds are modeled well by the multiple regression analysis because Bayesian multisensory integration is the origin of the cross-modal effects. This can be understood by the fact that the estimation equations of both models are essentially the same.

Keywords: Switch sound, Auditory evaluation, Tactile feedback, Bayesian explanation, Factor analysis

1. INTRODUCTION

Because people use many mechanical switches or electrical buttons in their daily lives, the sounds or clicks emitted by them are a matter of interest, not only for users, but also for manufacturers. Therefore, several studies have investigated these sounds [1–5].

Our first study [4] focused on the differences in affective evaluations between operators and listeners in a psychoacoustical experiment using 15 switches. Here, an operator was defined as a person who pushes a switch and listens to its sound and a listener as a person who listens to the sound of the switch by sitting in front of the operator. Our subsequent study [5] conducted a tactile evaluation experiment using the same switches and found that the differences in affective evaluations between the operators and listeners can be modeled by multiple regression analyses with the listeners’ auditory evaluations and tactile evaluations. However, the reason why these effects can be modeled by multiple regression analyses remains unanswered. Therefore, this study aimed to address this question.

In the current study, more extensive experiments, also using 25 switches, were conducted for auditory and tactile evaluations. Their results were then analyzed by factor analyses. Finally, the operators’ auditory evaluations were estimated based on the listeners’ auditory and tactile evaluations to answer the research question.

2. AUDITORY AND TACTILE EVALUATIONS

2.1 Experimental methods

Auditory and tactile evaluations were performed using the semantic differential (SD) method [6]. Because the experimental methods of these evaluations are similar to those used in our previous studies [4, 5], they are briefly described below.

Figure 1 shows 25 switches mounted on a circular board, with them each being covered with uniform caps to prevent any visual information effects. Based on their mechanical structures, these switches are categorized into four groups: A (A1 to A8), B (B1 to B5), C (C1 to C9),
and D (D1 to D3), where Groups A, B, and C each had their own specific structures, but the three switches in Group D were structured miscellaneous.

In the auditory experiment, an operator rotated the board so that a designated switch was located at the nearest position and then continuously pushed it for 5 s (approximately 15 times). The operator and listener each rated the sound using 26 pairs of adjectives [4] on 7-point scales arranged in a random order. Two groups, each consisting of 22 subjects, participated as operators and listeners.

The tactile evaluation experiment consisted of 52 subjects. The subjects continuously pushed a designated switch for 5 s in the same manner as in the auditory evaluation experiment. They then rated the tactile feeling on 7-point scales using 21 pairs of adjectives, of which eight pairs, such as “likable–dislikable” and “shallow–deep,” were used in the previous study [5] and a further 13 pairs, such as “mild–sharp” and “distinct–faint” then being newly included in the current research. During the experiment, white noise was continuously played from a pair of headphones (Sennheiser, HDA 200) to mask the switch sounds.

### 2.2 Factor analysis

The results for each subject were analyzed using factor analyses separately for the auditory and tactile experiments. Three factors, potency (F1), evaluation (F2), and activity (F3), were extracted for both experiments, which show strong similarity with previous studies [4, 5].

Figure 2 shows the auditory factor scores, which were averaged across all of the subjects. In the figure, each switch is represented by an arrow with the initial and terminal points corresponding to the factor scores of the operators and listeners, respectively. The three groups, A, B, and C, are clearly divided, especially on the F1–F2 score plane; this means that intrinsic auditory feelings were evoked by different mechanical structures.

The length of each arrow indicates the magnitude of the tactile feedback effect. As seen in Figure 2, the effects are relatively large for F3. The directions of the arrows appear different among the groups, suggesting that the effects of tactile feedback depend on the switch’s mechanical structure.

### 3. CONSIDERATION OF CROSS-MODALITY

Figure 3 shows the relationship between the observed factor scores of the operators and listeners. Deviations from the diagonal line denote the effects of tactile feedback. As shown in Figure 2, these effects are larger for F3, such that the correlation coefficient (r) is smaller and the mean squared error (MSE) is larger, for F3.
Figure 3: Relationship between the observed factor scores of the operators and listeners. $r$ is the correlation coefficient and MSE denotes the mean squared error.

Figure 4: Relationship between the observed and estimated factor scores of the operators. Circles and crosses show the results of the Bayes estimation and multiple regression analyses, respectively. $r$ and MSE are for the Bayes estimation.
Our aim was to estimate the factor scores of the operators (y) based on the factor scores of the listeners (x₁) and the tactile factor scores (x₂).

First, multiple regression analyses using the two factor scores were conducted, similar to a previous study [5]. The estimated value \( \hat{y} \) is given by the following regression equation:

\[
\hat{y} = a_1 x_1 + a_2 x_2
\]

where \( a_1 \) and \( a_2 \) are the partial regression coefficients. Prior to conducting the multiple regression analyses, the space of the tactile factor space was rotated [5] to minimize the least squared error between “the operator’s auditory factor scores” and “the tactile scores.”

This regression was performed separately for each of the three auditory factors. The estimated values are shown in Figure 4 with crosses. The correlation coefficients are 0.96, 0.89, and 0.81, and MSEs are 0.20, 0.22, and 0.41 from F1 to F3, respectively. Because the effects of tactile feedback are incorporated into the second term in Eq. (1), the estimated scores were similar to the observed ones. These results suggest that the cross-modal effect of the tactile feedback is modeled by a simple equation. However, the reason why it can be modeled in this manner remains unanswered.

Then, we tried an estimation based on Bayes’ theorem [8, 9]. If a prior distribution and likelihood follow a normal distribution, the optimal estimate of the posterior \( \hat{y} \) distribution is calculated by the following equation:

\[
\hat{y} = \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2} x_1 + \frac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2} x_2
\]

wherein the factor scores of the listeners and operators are regarded as prior and posterior distributions, respectively, and the tactile factor scores are then regarded as the likelihood. The variances of the prior distribution and likelihood are denoted as \( \sigma_1^2 \) and \( \sigma_2^2 \), respectively.

The estimated values are shown in Figure 4 with circles. As seen in the figure, the estimation performances are almost the same as those of the multiple regressions for the three factors. This can be understood by comparing Eqs. (1) and (2), if \( a_1 = \sigma_2^2/(\sigma_1^2 + \sigma_2^2) \) and \( a_2 = \sigma_1^2/(\sigma_1^2 + \sigma_2^2) \), the equations are the same. However, there is a difference between the two equations: \( a_1 \) and \( a_2 \) are common for all switches, but \( \sigma_1^2/(\sigma_1^2 + \sigma_2^2) \) and \( \sigma_2^2/(\sigma_1^2 + \sigma_2^2) \) are different among the switches. Thus, it is difficult to directly compare these coefficients.

In this section, we have outlined that the performances of the two estimation methods are comparable, with the structures of the estimation equations being the same. This suggests that the reason a multiple regression model works so well is due to the fact that the origin of tactile feedback is due to the Bayesian integration of multiple senses.

4. CONCLUSION

This study reveals that the differences between the auditory evaluations of both operators and listeners are explained by the cross-modal effects of tactile feedback. These effects can be explained similarly by two models: a multiple regression and a Bayesian estimation. By comparing the two estimation equations, these two estimation methods are similar, suggesting that the cross-modal effect can be explained by the Bayesian integration of multiple senses.

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