Proceedings of the 2012 ICME
International Conference on Complex Medical Engineering
July 1 - 4, Kobe, Japan

The Alteration of Simultaneity Perception in the Cross-modal Integration under Motor Control

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***Abstract*—We investigated the effect of the efference copy and the proprioceptive feedback on auditory-tactile temporal order judgment, using Temporal Order Judgment (TOJ) task to measure the differences in Point of Subjective Simultaneity (PSS) and Just Noticeable Difference (JND). These parameters were measured under Voluntary condition, Involuntary condition, and No-movement condition. While both the Involuntary and Voluntary conditions contain proprioceptive feedback, only Voluntary condition contains efference copy. JND of Voluntary condition was smaller than that of No-movement condition. PSS was significantly different among the three conditions. Movement condition shifted PSS to the point where auditory stimulus presented prior to tactile stimulus compared to No-movement condition. Furthermore, the shift in PSS of Voluntary condition was larger than that of Involuntary condition. These results suggest that each proprioceptive information and efference copy accelerates tactile perception, and voluntary movement improves the resolution of TOJ for audio-tactile stimulus, while the proprioceptive information alone does not achieve significant effect of improvement on the judgment in involuntary motion.**

***Index Terms*—Temporal order judgment · Simultaneous perception · Efference copy · Proprioception · Voluntary movement.**

I. Introduction

The temporal coincidence provides a crucial clue in the integration of cross-modal sensory information from the environment [1], [2]. However, in the process temporal integration, a lot of delays are included: delays of sensory integration, sensory motor coordination, and interaction with the environment. It is important to understand the characteristics and the mechanism of temporal integration not only in cognitive psychology but also in the field of medicine where temporal processing deficit is the source of pathology such as dyslexia. The previous studies found that dyslexic patient showed lower performance in temporal order judgment of two stimuli presented at slightly different time than healthy people [3], [4]. This inability of simultaneity perception was also observed in autism [5] and schizophrenia [6]. These studies suggest that temporal integration such as simultaneous perception is related to some mental and learning disorders. The mechanism of temporal integration is, however, not clear yet.

We focused the simultaneity of an event as one of the simplest sensory integration. Several cognitive psychology and neuroscience researches have been focused the temporal integration (for reviews see [7]). Simultaneity Judgment (SJ) task [8] - [13] and Temporal Order Judgment (TOJ) task [14] - [22] were often used to investigate cross-modal simultaneity perception. These studies have shown that participants perceived pairs of visual and auditory stimuli and pairs of visual and tactile stimuli as simultaneous when the visual stimuli come earlier; additionally, participants perceived pairs of auditory and tactile stimuli as simultaneous when tactile stimuli preceded auditory stimuli [17], [19]. Such asymmetry in Point of Subjective Simultaneity (PSS) was reported to be affected by stimulus intensity and selective attention [11], [20], [22] in addition to spatial location [21], [22]. Furthermore, participants exposed to a fixed audiovisual time lag for several minutes exhibited PSS shifts toward the lag and Just Noticeable Difference (JND) increase [9].

Previous studies, however, have primarily focused on simultaneous perception in the situation where the participants received the stimuli passively. In daily life, people often per-

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ceive information from the environment. Furthermore, some information from the environment occurs by the movement of self. Simultaneous perception in the situation where participants obtained the stimuli voluntarily such as “active touch” [24], [25] or “active head movement” [26] were marginally investigated. In the field of virtual reality research [27], a TOJ task using visual and haptic stimuli revealed that the PSS decreased, and the JND was narrowed under conditions with active motor control. This finding suggests that active control influences simultaneity perception, although the nature and extent of this influence has yet to be resolved.

Motor-related factors that may affect synchrony perception include the efference copy of a motor command and the proprioceptive feedback which represents body orientation and movement. The efference copy signal is thought to influence activity in the sensory areas indirectly [28]. Libet and colleagues [12] have suggested that the efference copy signal for an active motor control occur around 250 msec before the movement. The efference copy may, therefore, be used to predict the consequences of the movement [29]. On the contrary, Winter et al. claimed that the efference copy does not affect simultaneity perception based on the result of simultaneity judgment of active/passive touch [30]. Information derived from proprioceptive sensation, on the other hand, has been suggested to be used to judge whether sensory stimulus provides feedback information of the body movement [13].

The effects of these motor-related factors on the perception of simultaneity should be analyzed in a differentiating manner (Fig. 1). This study examined whether the audio-tactile TOJ is influenced by voluntary finger movement or not. The present study investigated the effect of the efference copy and the proprioceptive information on the audio-tactile TOJ. We made choice of audio-tactile TOJ, because little is known about the effects of active motor control on audio-tactile synchrony detection. We have previously investigated TOJ task with active movement [25]. The present study elaborated the experimental condition and increased the number of participants.

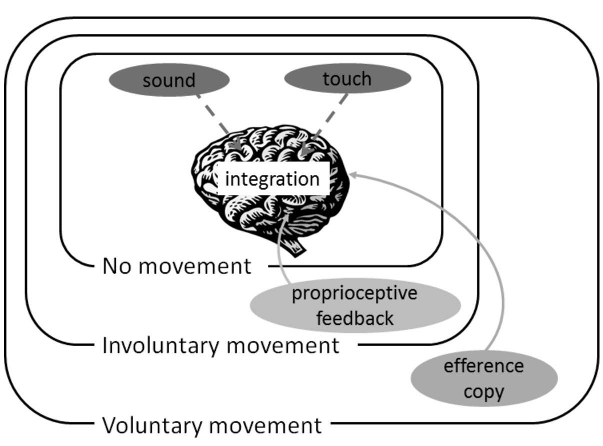

Fig. 1. Possible factors that affect simultaneous perception.

Fig. 2. Illustration of the haptic device. The participant’s right index finger was strapped into the haptic device.

II. Method

A. Participants

Twelve paid participants (males; mean age of 23.8) attended the experiment. They were all right handedness, had an appropriate auditory threshold and normal touch, and exhibited no problems in moving their right index finger. They all have not participate TOJ experiment before.

B. Stimuli

The participants were presented with sinusoidal wave sound (2000 Hz, 50 dB, 15 msec) in both ears through earphones (HP-RHF41, radius, Japan). The timing of the presentation was controlled to an error margin of 1 msec. The PHANToM® Desktop haptic device (SensAble Technologies, USA) was used to provide tactile stimuli (3N, 15 msec, rectangular pulse). The movement of the haptic device was also controlled within an error margin of 1 msec. These sensory stimulation systems were operated by computer programs installed on a PC workstation (HP xw4600/CT, Hewlett-Packard, USA), which were developed using the OpenHaptics software development toolkit (SensAble Technologies, USA) on the Microsoft® Visual C++ 2008 platform (Microsoft, USA). Tests were conducted in a sound-attenuated room free from noises that could possibly interfere with the auditory stimulation. The participants wore sound-insulating earmuffs over the earphones during the

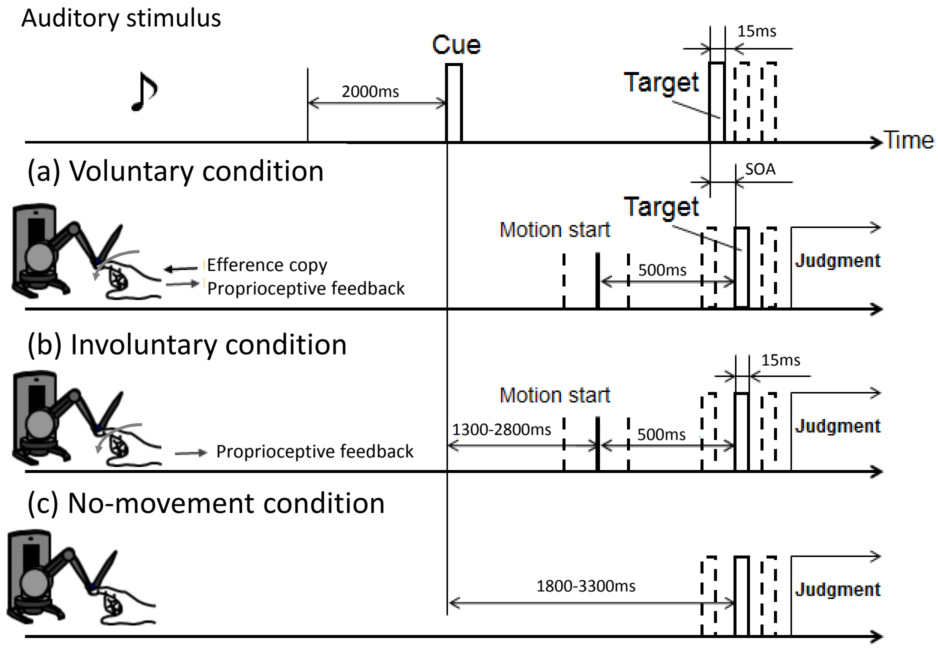

Fig. 3. Schematic illustration of the three conditions: Voluntary, Involuntary, and No-movement. Under Voluntary condition (a), the participants started to move their right index finger voluntarily at their own timing after single tone. Under Involuntary condition (b), the haptic test device started to move the participant's right index finger 1,300 to 2,800 msec after the tone. Audio-tactile stimulus was presented at 500 msec from the start of the finger movement under Voluntary/Involuntary conditions. Under No-movement condition (c), the audio-tactile stimulus was presented after 1,800 to 3,300 msec delay from the presentation of the tone. The SOA ranged from -200 msec to 200 msec.

experiments. In addition, right index finger was held in a brace, to control the hand movement.

C. Procedure

The audio-tactile TOJ tasks were performed under three conditions: Voluntary condition, Involuntary condition, and No-movement condition.

Voluntary condition (Fig. 3(a)):

The participants were seated in front of the stimulation systems with the palmar side of participant's right index finger touching the haptic test device (Fig. 2). For each run of trials, a single tone was generated to announce that the recording was ready. The participants started to move their right index finger voluntarily at their own timing. On a preliminary experiment, the temporal gap between the presentation of the single tone and the start of the hand movement was 1,300 to 2,800 msec. The start time of motion was defined as the time when the finger moves 10mm from the initial position. A tactile stimulus was presented at 500 msec from the start of the finger movement. Additionally, the high-pitched tone stimulus was presented in sync with the tactile stimulus. The participant was then given a two-alternative forced choice test to provide the temporal discrimination of the auditory and tactile stimulus pairs by answering which stimulus was presented first. The preceding time of the auditory stimulus onset relative to that of the paired tactile stimulus was selected from the following stimulus onset asynchrony (SOA) values: -200, -90, -60, -30, 0, +30, +60, +90, and +200 msec (where the negative values indicate that the tactile stimulus preceded the auditory stimulus).

Involuntary conditions (Fig. 3(b)):

Similar to the Voluntary conditions, a single tone was generated to indicate the start of the recording. The haptic test device started to move the participant's right index finger 1,300 to 2,800 msec after the tone. This temporal gap between the presentation of the single tone and the start of the device finger movement was determined to reproduce the variance in the onset timing of voluntary movement in a preliminary experiment. A tactile stimulus was presented at 500 msec from the start of the finger movement. The speed of the finger movement was chosen for each experimental run from 76, 88, 100, 112, and 124 mm/s, whose occurrence rates were calculated from the distribution of data collected under the voluntary conditions in preliminary experiments. The procedure for evaluating the temporal discrimination, and the SOA values were the same as those used for the Voluntary condition.

No-movement condition (Fig. 3(c)):

A single tone indicating the start of the recording was generated, and a tactile stimulus was presented after 1,800 to 3,300 msec (1,300+500 to 2,800+500 msec) delay from the presentation of the tone signal.

The experimental design was developed to make the following comparisons: 1) results of the No-movement condition and the Voluntary condition to reveal the effect of voluntary movement on the audio-tactile TOJ; 2) results of the Voluntary and Involuntary condition to clarify the effect of the efference copy; 3) results of the No-movement condition and the Involuntary condition to examine the effect of the proprioceptive sensation.

In this experiment, the participants completed five blocks each for the three conditions (each block consisting of 45 trials, that is 5 trials for each SOA). The sequential order of the blocks was chosen randomly. There was a 2,000 msec interval between trials. In order to learn to move participant's finger at a speed as close to 100 mm/s as possible, the participant underwent one block of practice sessions for the Voluntary condition before embarking on the formal test trials. In addition, they conducted practice runs of 5 trials just before each block under the Voluntary condition. During the practice sessions, only the tactile stimulus was presented, and no auditory stimulus was delivered for temporal judgment. In order to make the participants accustomed to TOJ task, they were also given practice sessions consisting of one block each for all test conditions before starting the formal data collection trials. It took approximately five minutes for them to complete one block of trials. They were given several minutes of rest between blocks. They completed a total of 880 runs (including practice runs), and the entire procedure took roughly three hours. In order to eliminate confounding effects by visual stimuli, they were instructed to close their eyes during the experiments. Additionally, we asked them to pay constant attention to the tactile stimuli during the trials in order to control for the 'prior entry' effect [11], [20], [23] on the test results under different testing conditions, which relatively facilitates the processing of an attended stimulus compared with an unattended stimulus.

D. Data analysis

The ratio of the answers indicating the earlier presentation of the auditory stimulus was calculated for each SOA. We conducted logistic regressions using a generalized linear model with the ratio data of each experiment [31]. The following equation was applied to the regression analysis:

$$y = \frac{1}{1 + e^{\frac{(\alpha - x)}{\beta}}} \quad (1)$$

where α represents the estimated PSS, x denotes SOA, and β is related to JND as shown in the following:

$$JND = \frac{x_{75} - x_{25}}{2} = \beta \log 3 \quad (2)$$

where x_p represents the SOA with p percent of 'auditory first' responses. MATLAB Statistics Toolbox® (MathWorks, USA) was used for the statistical regression calculation and graphic presentation of the results. Under the Voluntary condition, the data with 60 mm/s to 140 mm/s finger velocity were used for the analysis in accordance with the previous study [30].

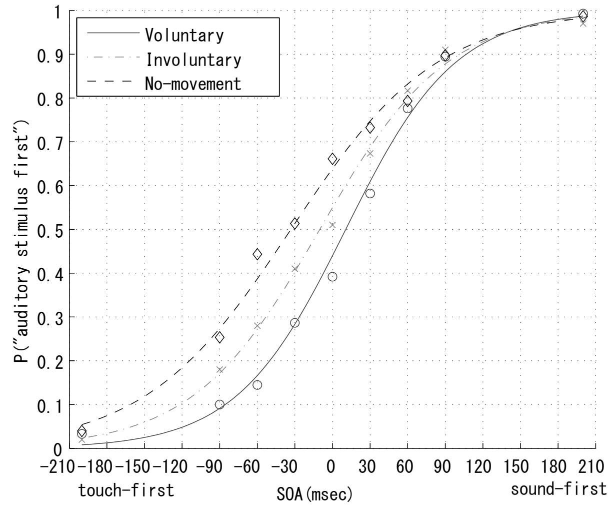

Fig. 4. Average psychometric functions across all participants under the three conditions.

III. Results

As illustrated in Figure 4, psychometric curves were fitted to the distribution of the mean TOJ data for the Voluntary, Involuntary, and No-movement condition. We determined the JND and PSS values for each participant using the regression analysis (Eq. (1) and (2)), and further processed the data statistically to obtain the mean and standard error values for each condition. As shown in Figure 5, The JND under the Voluntary condition was smaller than other two conditions. In addition, Figure 6 shows the mean PSS on the Voluntary/Involuntary condition were shifted to side in which sound presented first, compared to No-movement condition.

The results of JND and PSS were examined by a repeated-measures analysis of variance (ANOVA) with motor conditions as the within participants factor, and the difference of JND among the three conditions was significant ($p < 0.05$). In the PSS, a significant difference in conditions was also observed ($p < 0.001$). Tukey-Kramer post-hoc test evaluated the between-group differences in each of JND and PSS values. The results (Fig. 5) indicated that the JND value under Voluntary condition was smaller than the No-movement condition ($p < 0.05$). The results (Fig.6) showed that under Voluntary condition the PSS shifted more to the point where auditory stimulus was presented before tactile stimulus, compared with the Involuntary condition ($p < 0.05$), and the No-movement condition ($p < 0.001$).

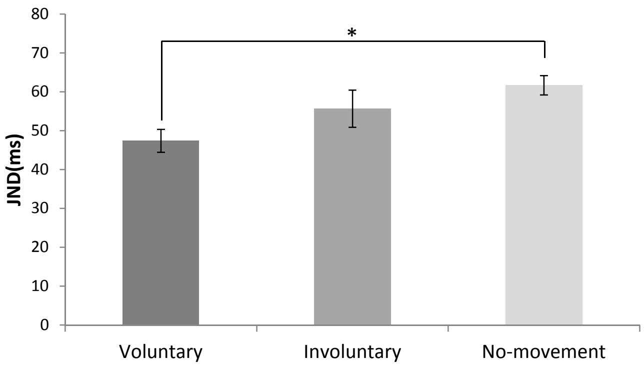

Fig. 5. The mean JNDs under the three conditions. Error bars represent the standard errors of means. $*p < 0.05$

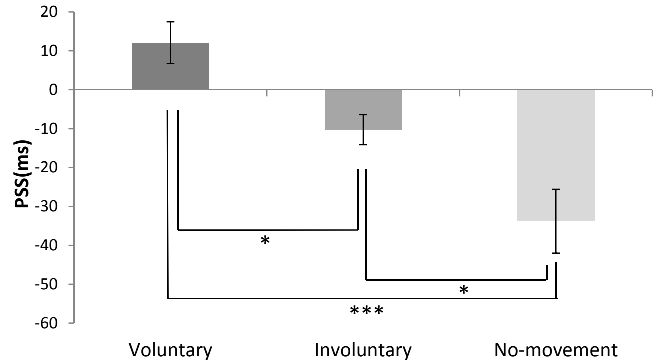

Fig. 6. The mean PSSs under the three conditions. Error bars represent the standard errors of means. Positive values mean that auditory stimulus was presented prior to tactile stimulus and vice versa. $*p < 0.05$, $***p < 0.001$

Furthermore, under Involuntary condition the PSS shifted to the point where auditory stimulus was presented first, compared with the No-movement condition ($p < 0.05$).

IV. Discussion

Our results on the JND corroborate the results of a preceding study by Shi et al., [27] between the Voluntary and No-movement conditions despite the difference of modality combination. Shi et al., examined the influence of visuomotor interaction on visual-haptic simultaneous perception, where participants could make predictions about the timing of stimuli by the combination of visual information, proprioceptive information, and motor efference copy. In our study, on the other hand, participants predicted the timing based only on proprioceptive information and efference copy. As illustrated in Fig. 5, the JNDs under the Involuntary and No-movement conditions were not significantly different. We assume that the proprioceptive sensation alone does not affect prediction of the time of arrival of the stimuli, and therefore, not improve a resolution of the JND. Thus, in the present study, the predictive performance improved with both proprioceptive information and efference copy.

We did not observed statistically significant difference at PSS among the three conditions in previous study [25]. The present study increased the number of participants and found significantly different among the three conditions. The PSS under the No-movement condition was in correspondence with the most studies which investigated audio-tactile TOJ without hand movement. Previous studies [17], [18] showed that in audio-tactile TOJ, the tactile stimulus had to be presented prior to auditory stimulus to percept simultaneity. On the other hand, as illustrated in Fig. 6, the PSS under the Voluntary condition shifted to the point where auditory stimulus was presented prior to tactile stimulus. This result denoted the same tendency of the previous TOJ study with movement [27]. Shi et al., conducted TOJ under four conditions: active motor control with additional visual feedback, active motor control and no additional visual feedback, no movement with additional visual feedback, and no movement and no additional visual feedback. In the situation of no visual feedback, PSS under active motor control condition was not different from under no movement condition. On visual feedback conditions, on the other hand, PSS decreased under active motor control condition. From this comparison, they suggested that the motor information was not enough to change PSS. The present study, however, showed that feedback information from active/passive motor control changed PSS. And we also found the difference between involuntary movement with only proprioceptive feedback, and voluntary movement with efferece copy and proprioceptive feedback. Although our experimental design is closer to that under no visual feedback condition of the previous study, the present results is more corresponding to that under visual feedback condition of them. This incongruous results was caused by difference of the combination of modality. That is, for the effect of voluntary movement on TOJ including visual information, the visual feedback corresponding to the voluntary movement is necessity while for that on TOJ including auditory information, the auditory feedback is not essential.

The present study suggests that the efference copy is one essential factor in TOJ with voluntary movement. However, based on the result of simultaneity judgment of active/passive touch, Winter et al. concluded that the efference copy did not affect simultaneity perception [30]. The disagreement between our view and Winter et al.'s view possibly stems from the difference of the experimental tasks. In their experiment, the SJ task was direct comparison of active and passive touch, always involving active motor control. Therefore, they mainly focused on PSS, and did not study the difference of JND between active and passive motor conditions. Besides, they reported that the difference between PSS and physical zero point was not significant, suggesting that the information processing speed of active touch differs little from that of passive touch. This result confirms our result on PSS. Although the mechanism of PSS on TOJ was considered to need further study [32], the present study suggests that the prediction in consequences of motion from the voluntary/involuntary movement change the simultaneous perception, and efference copy and proprioceptive feedback contribute to accelerate processing of tactile perception respectively.

In conclusion, our findings demonstrate that each the predictive function of proprioceptive information and efference copy accelerates tactile perception, and the resolution of TOJ for audio-tactile stimuli was improved by voluntary movement, while the proprioceptive information alone does not have significant effect of improvement on the judgment in involuntary motion.

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