Toward a subjective synchronous communication in multimodal human-machine interaction: Intention of movement alternates simultaneous perception in auditory-tactile temporal order judgment

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Abstract:

We investigated the effect of voluntary movement on temporal multimodal integration using a psychological experiment. The present study used auditory-tactile Temporal Order Judgment (TOJ) task to measure the differences in Point of Subjective Simultaneity (PSS) and Just Noticeable Difference (JND). To distinguish the effect of voluntary movement and proprioceptive feedback, we prepared three conditions: Voluntary condition, Involuntary condition, and No-movement condition. Voluntary movement and Involuntary movement shifted PSS to the point where an auditory stimulus presented prior to a tactile stimulus compared to No-movement condition. Furthermore, the shift of PSS in Voluntary condition was larger than that in Involuntary condition. JND of Voluntary condition was smaller than those of the other two conditions. These results revealed that voluntary movement improved temporal resolution between auditory and tactile stimuli. Moreover, it was demonstrated that voluntary movement also alternates audio-tactile temporal integration.

1. INTRODUCTION

What is matter in designing of interactions between humans and machines that use multi-modal sensory inputs is the simultaneity of information presented through different sensory signals [1,2]. People tend to judge more two different-modal stimuli as simultaneous when one stimulus is presented several milliseconds before the other stimulus than when the stimuli are presented simultaneously. It is also well known that temporal resolution of judging simultaneity depends on which modalities were used for presenting of stimuli. These asymmetries of perceptual order and variable temporal resolution have been investigated at varied conditions [3-10].

In the almost all studies, participants had judged simultaneity without voluntary or active movement. In daily life, people, however, act voluntarily for the environment and with such voluntary movement they perceive the multimodal inputs form the environment. Recently, some studies revealed the effect of voluntary movement on temporal perception [11-13]. If this is the case, it will be necessary to be aware of such effect of intentional movement in design of human-machine interactions.

Shi *et al*. [13] attempted to reveal the effects of voluntary movement using the visual-tactile Temporal Order Judgment (TOJ) task. In TOJ task, pair of stimuli was presented at various Stimulus Onset Asynchronies (SOAs) and participants judged which stimulus came first. The performance of TOJ was usually evaluated by Point of Subjective Simultaneity (PSS) and Just Noticeable Difference (JND). PSS is the time point at which one stimulus has to be presented before the other stimulus for the both stimuli to be perceived as occurring simultaneously. JND corresponds to temporal resolution of TOJ. Shi and his colleagues performed the visual-tactile TOJs under with voluntary movement condition and without voluntary movement condition. As the results, both PSSs and JNDs were different between the conditions.

However, this result did not necessarily reveal that voluntary movement affected temporal multimodal integration because in their experiment the effect of proprioceptive feedback information, which is sense of body movement of self, was not eliminated. This means that their results may be due to proprioceptive information, not to voluntary movement. That is, whether intentional movement or voluntary movement changes temporal perception or not has not been studied sufficiently.

The purpose of the present study was to investigate whether voluntary movement itself affected temporal integration or not despite the exclusion of the effect of proprioceptive information. For this purpose, we performed auditory-tactile TOJ tasks under three conditions: Voluntary, Involuntary, and No-movement conditions. In Involuntary condition, participants' finger was moved by a device. To compare the results of Voluntary and Involuntary condition, the effect of voluntary movement on TOJ could be able to investigate.

2. METHOD

2.1 Participants

Eighteen paid participants (males; mean age of 23.6) attended the experiment. They were all right-handed, had a normal auditory threshold and normal touch, exhibited no problems in moving their right index finger. They all gave

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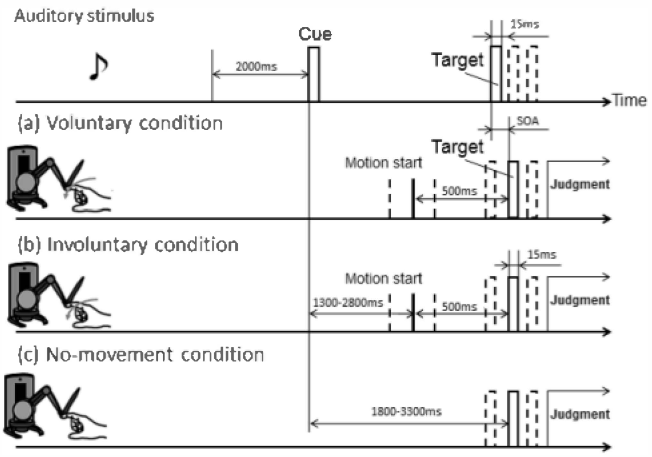

Fig. 1. Schematic illustration of the three conditions: Voluntary, Involuntary, and No-movement conditions.

informed consent before the experiment.

2.2 Apparatus and stimuli

Auditory stimuli were sinusoidal wave sound (2000 Hz, 50 dB, 15 ms) in both ears through earphones (HP-RHF41, radius, Japan). The timing of the presentation was controlled to an error margin of 1 msec. Tactile stimuli were impulse force (3N, 15 ms, rectangular pulse) provided by The PHANToM@ Desktop haptic device (SensAble Technologies, USA). The movement of the 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).

2.3 Conditions and procedure

The experiment was carried out in a darkened sound-attenuated room. The participants were seated in front of the stimulation systems with their palmer side of their right index finger held in the haptic device. They are also wore sound-insulating earmuffs over the earphones during the experiments.

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

Voluntary condition (Fig. 1(a)): For each run of trials, a single tone was generated to announce start cue. The participants started to move their right index finger voluntarily at their own timing. The start of motion was defined as the time when the finger moves 10 mm from the initial position. A tactile stimulus was presented at 500 ms from the beginning of the finger movement. Additionally, the high-pitched tone stimulus was presented in synchronization with the tactile stimulus. The participant then judged 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 SOA values: -200, -90, -60, -30, 0, +30, +60, +90, and +200 ms (where the negative values indicate that the tactile stimulus preceded the auditory stimulus).

Involuntary condition (Fig. 1(b)): Similar to the Voluntary condition, a single tone was generated to indicate start cue. The haptic device started to move the participant's right index finger 1,300 to 2,800 ms after the tone. This temporal gap between the presentation of the single tone and the start of the device was determined to reproduce the variance in the onset timing of voluntary movement in a preliminary experiment. A tactile stimulus was presented at 500 ms after 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. 1(c)): A single tone indicating start cue was generated, and a tactile stimulus was presented after 1,800 to 3,300 ms (1,300 + 500 to 2,800 + 500 ms) delay from the presentation of the tone signal.

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 randomized. Interval between trials was a 2,000 ms. The participants underwent one block of practice sessions for the Voluntary condition before embarking on the formal test trials so as to adjust to move their finger at a speed as close to 100 mm/s as possible. 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. 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 trials (including practice trials), and the entire procedure took about three hours. They were instructed to close their eyes during the experiments to eliminate confounding effects by visual stimuli. Additionally, we asked them to pay constant attention to the tactile stimuli during the trials in order to control for the 'prior entry' effect [7,9,10] on the test results under different testing conditions, which relatively facilitates the processing of an attended stimulus compared with an unattended stimulus.

2.4 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 [14]. 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 'sound first' responses. MATLAB Statistics Toolbox@ (MathWorks USA) was used for the statistical regression calculation and graphic representation 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 [15].

Psychometric curves were fitted to the distribution of the mean TOJ data for the Voluntary, Involuntary, and No-movement condition. We determined the PSS and JND values for each participant using the regression analysis (Eq. (1) and (2)), and processed the data statistically to obtain the mean and standard error values for each condition.

3. Results

As shown in figure 2, the mean PSS on the Voluntary/Involuntary conditions were shifted to the side in which sound presented first, compared to No-movement condition. In addition, figure 3 shows the JND under the Voluntary condition was smaller than those under other two conditions.

The results of PSS and JND were examined by one-way repeated-measures analysis of variance (ANOVA) with motor conditions as the within participants factor. The difference of PSS among the three conditions was significant [$F(2, 34) = 35.78$, $p < 0.001$, $\eta_p^2 = 0.60$]. In the JND, a significant difference in conditions was also found [$F(2, 34) = 16.62$, $p < 0.001$, $\eta_p^2 = 0.50$]. Holm-Bonferroni method evaluated the between-group differences in each of PSS and JND values. The results (Fig.2) 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 ($p < 0.01$), and the No-movement condition ($p < 0.001$). Furthermore, under Involuntary condition the PSS shifted to the point where auditory stimulus was presented first, compared with the No-movement condition($p < 0.001$). The results (Fig. 3)

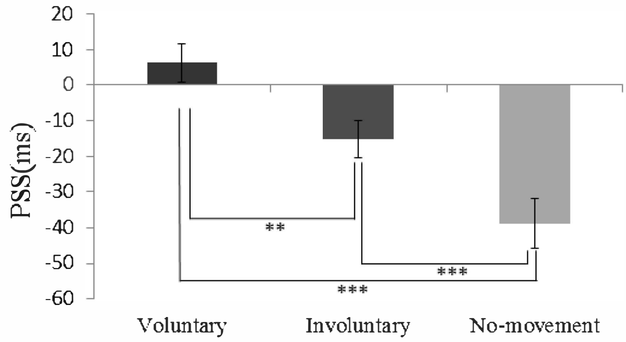

Fig. 2. The mean PSSs under the three conditions. Error bars represent the standard errors of means. **p < 0.01, ***p < 0.001.

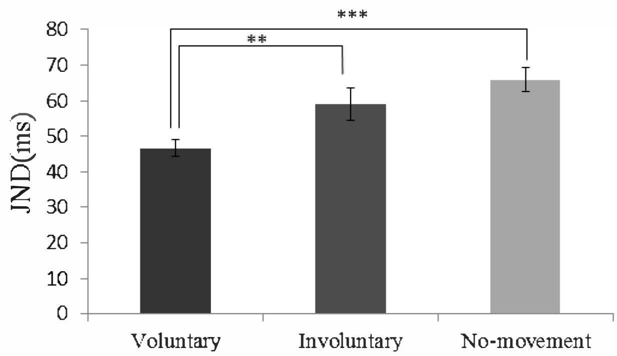

Fig. 3. The mean JNDs under the three conditions. Error bars represent the standard errors of means. **p < 0.01, ***p < 0.001.

indicated that the JND of Voluntary condition was smaller than that of Involuntary condition ($p < 0.01$) and No-movement condition ($p < 0.001$).

4. Discussion

The present study found statistically significant difference at PSS among the three conditions. The PSS under the No-movement condition demonstrated that the tactile stimulus had to be presented prior to auditory stimulus about 30 ms for people to perceive simultaneity. This result corresponded to the previous studies which investigated audio-tactile TOJ without movement [4,5]. As illustrated in Fig. 2, the PSS under the Voluntary/Involuntary conditions shifted to the points where auditory stimulus was presented prior to tactile stimulus. And the shift of Voluntary condition was larger than that of Involuntary condition. This result showed that what people act voluntarily to environment alternate their temporal integration of multi-modal inputs from the environment. In addition, proprioceptive feedback information also affected judging of the order between auditory and tactile signals. Some previous studies suggested PSS was affected from attention [7,9,10]. Attended stimulus was tended to be perceived prior to other stimuli when multimodal stimuli were presented to participant. In our study, although we asked participants to pay attention to tactile stimulus to eliminate the effect of attention, it was seemed that the attention on tactile stimuli in Voluntary and Involuntary conditions might become strong compared to No-movement condition. However, Hanson *et al*., [16] demonstrated that temporal tactile perception was fixed despite any attentional load. Therefore it is difficult to account for the present results by the effect of attention.

The present study also found that the JND under the Voluntary condition was smaller than those under the other conditions. That is, voluntary movement improved temporal resolution of order judgment. This result of the JND as with the PSS showed that when people act voluntarily to the environment, temporal perception changed.

These results could be explained by predictive feedback by efference motor copy. Recently neuroscience studies showed effect of the efference copy on perception. The efference copy information derived from voluntary action is thought to influence activity in the sensory areas indirectly [15]. Libet and colleagues [17] have suggested that the efference copy signal for an active motor control occur around 250 ms before the movement. The efference copy could, therefore, be used to predict the consequences of the movement [18]. This prediction might affect auditory-tactile TOJ. It is, however, unclear yet what relations are there between efference copy and temporal perception. Therefore, further studies are necessary to fully demonstrate how voluntary movement affects temporal perception and integration.

5. Conclusion

The auditory-tactile TOJ task under the three conditions was performed to investigate the effect of voluntary movement on temporal perception. The results showed that the PSS and JND under voluntary condition was significant different from other two conditions. These findings demonstrated that voluntary movement alternates temporal perception and integration of multimodal information.

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