3.15 THE EFFECT OF VOLUNTARY MOVEMENT IN AUDIO-HAPTIC TEMPORAL ORDER JUDGMENT TASK

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Abstract – Perception of simultaneity between sensory modalities is important for multi-modal integration. In this study, we investigated the effect of voluntary/ involuntary motion on audio-haptic temporal order judgment. PSS (Point of Subjective Simultaneity) and JND (Just Noticeable Differences) were measured under voluntary condition,in voluntary condition, and passive condition. For every condition, when the haptic stimulus was presented before the auditory stimulus was presented, the two stimuli were more likely to be perceived as simultaneous. JND under voluntary condition was significantly smaller than under involuntary and passive condition. JND under involuntary condition was not significantly different from under passive condition. These results suggest that the efference copy in voluntary motion affect temporal order judgment for audio-haptic stimulus, while the proprioceptive information solely does not affect temporal order judgment.

Keywords: simultaneity, temporal order judgement, cross-modal, audio-haptic, efference copy

1. INTRODUCTION

The ability to accurately perceive events in the surrounding environment is essential for survival. Indeed, accurate perception is possible due to brain processes that integrate information gathered via different sensory systems. Several studies have reported that the integration of diverse types of information, originating from the same stimulus event, requires the realignment of temporal simultaneity.[1], [2] Therefore, the investigation of cross-modal processing fortemporal synchrony perception may yield important information towards the understanding of brain mechanisms underlying sensory integration.

Simultaneity judgment (SJ) task[3], [4] and temporal order judgment (TOJ) task[5], [6] are often used to investigate cross-modal synchrony perception. Studies employing these tasks have focused primarily on the point of subjective simultaneity (PSS) and just noticeable difference (JND) between stimuli. It is thought that the knowledge from the studies using TOJ is useful for clarifying the cause of dyslexia, because the dyslexics have larger JND than healthy subject on TOJ[7]. Studies on TOJs have shown that subjects perceived simultaneity with pairs of visual and auditory stimuli and pairs of visual and haptic stimuli when the visual stimuli come earlier; additionally, subjects perceive simultaneity with pairs of auditory and haptic stimuli when haptic stimuli precede auditory stimuli.[5], [6] Such asymmetry in PSS was reported to be affected by stimulus intensity and selective attention[7] in addition to spatial location.[8], [9] Furthermore, in a study on audiovisual synchrony perception, human participants exposed to a fixed audiovisual time lag for several minutes exhibited shifts in their PSS toward the particular lag, in addition to a larger JND.[3]

As illustrated above, previous research on TOJ and SJ has primarily focused on simultaneity perception in the situation where the participants get the stimuli passively. On the other hand, simultaneity perception in the situation where the participants receive the stimuli voluntary such as active touch was marginally investigated. In studies of TOJ in the field of virtual reality research, a TOJ task using visual and haptic stimuli revealed that PSS occurred nearer to the point of physical simultaneity under conditions of active motor control with concurrent visual feedback than under conditions without active motor control.[18] This finding suggests that perceived simultaneity is influenced by active motor control, although the nature and extent of this influence has yet to be resolved. Moreover, little is known about the effects of active motor control on audio-haptic synchrony detection. Motor-related factors that may affect synchrony perception include the efference copy of a motor command and the proprioceptive sensation which represents body orientation and movement. The efference copy signal is thought to influence activity in the sensory areas indirectly.[19] Libet and colleagues[21] have suggested that the efference copy signal for an active motor control occurs around 250 ms before the movement. The efference copy may, therefore, be used to predict the consequences of the movement.[22] Information derived from proprioceptive sensation, on the other hand, has been suggested to be used to judge whether the sensory stimulus provides feedback information of the body movement.[20]

The effects of these motor-related factors on the perception of simultaneity should be analyzed in a differentiating manner. In this study, we examined whether the audio-haptic TOJ is influenced by voluntary motion or not. Specifically, we investigated the effect of efference copy and proprioceptive information on the audio-haptic TOJ.

2. METHODS

2.1. Subject

23- to 30-year-old (mean 26), healthy, right-handed paid participants (7male, 3female) were recruited for this study. They had an appropriate auditory threshold and exhibited no problems in moving their right index finger.

2.2. Experimental Apparatus and Stimulus

The subjects were presented with auditory white noise stimuli (50 dB, 15 ms) in both ears through earphones (MHPEP5,Empress). The timing of the presentation was controlled to an error margin of 1 ms. The PHANTOM® Desktop haptic device (SensAble Technologies, Inc.) was used to provide haptic stimuli (3N, 15 ms, rectangular pulse). The movement of the haptic device was also controlled within an error margin of 1 ms. These sensory stimulation systems were operated by computer programs installed on a PC workstation (HP xw4600/CT, Hewlett-Packard Japan, Ltd.,Tokyo), which were developed using the Open Haptics software development toolkit (SensAble Technologies, Inc.) on the Microsoft® Visual C++ 2008 platform (Microsoft Japan, Tokyo).

Tests were conducted in a sound-attenuated room free from noises that could possibly interfere with the auditory stimulation. The subjects wore sound-insulating earmuffs over the earphones during the experiments.

2.3. Experimental Design

The audio-haptic TOJ tasks were performed under three conditions: voluntary condition, involuntary condition, and passive condition. The experimental design was developed to make the following comparisons: 1) results of the passive condition and the voluntary condition to reveal the effect of voluntary movement on the audio-haptic TOJ; 2) results ofthe voluntary and involuntary condition to clarify the effect of the efference copy; 3) results of the passive condition and the involuntary condition to examine the effect of the proprioceptive sensation.

Voluntary condition (Figure 2a): The subjects were seated in front of the stimulation systems with the palmar side of their right index finger touching the haptic test device (Figure 1). For each run of trials, a single tone was generated to announce that the recording was ready. The subjects started to move the right arm voluntarily at their own timing. On a preliminary experiment, the temporal gap between the presentation of the single tone and the start of the arm movement was 1300 to 2800 ms. The start time of motion was defined as the time when the arm moves 10mm from the initial position. A haptic stimulus was presented at 900 ms from the start of the arm movement. Additionally, the white noise stimulus was presented in sync with the haptic stimulus. The subjects was then given a two-alternative forced choice test to provide the temporal discrimination of the auditory and haptic stimulus pairs by answering which stimulus was perceived earlier. The time for starting the auditory stimulus relative to the haptic stimulus was selected from the following stimulus onset asynchrony (SOA) values: -200, -90, -60, -30, 0, +30, +60, +90, and +200 ms (where the negative values indicate thatthe haptic stimulus preceded the auditory stimulus).

Involuntary condition (Figure 2b):Similar to the voluntary action condition, a single tone was generated to indicate the start of the recording. The haptic test device started to move the subject's right arm 1300 to 2800 ms after the tone. This temporal gap between the presentation of the single tone and the start of the device arm movement was determined to reproduce the variance in the onset timing of voluntary movement in a preliminary experiment results. The speed of the arm movement was chosen for each experimental run from 76, 88, 100, 112, and 124 mm/s, which 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.

Passive condition (Figure 2c):

A single tone indicating the start of the recording was generated, and a haptic stimulus was presented after a 2200 to 3700 ms (1300 to 2800 + 900 ms) delay from the presentation of the tone signal. In this experiment, the subjects completed five blocks (each block consisting of 45 trials) for each test conditions. The sequential order of the blocks was chosen randomly. There was a 2000 ms interval between trials. In order to learn to move their arm at a speed close to 100 mm/s, the subjects underwent three blocks of practice sessions for the voluntary condition before embarking on the formal test trials. In addition, they conducted practice runs of 5 to 10 trials just before each blocks under the voluntary condition. During the practice sessions, only the haptic stimulus was presented, and no auditory stimulus was delivered for temporal judgment. In order to allow the subjects experience with the 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 six minutes for the subjects to complete one block of trials. They were given several minutes of rest between blocks. The subjects completed a total of 900 runs (including practice runs), and the entire procedure took roughly three hours. In order to eliminate confounding effects by visual stimuli, the subjects were instructed to close their eyes during the experiments. Additionally, we asked the subjects to pay constant attention to the haptic stimuliduring the trials in order to control for the 'prior entry' effect[7] on the test results under different testing conditions, which relatively facilitates an attended stimulus compared with an unattended stimulus.

Fig. 1. Apparatus.

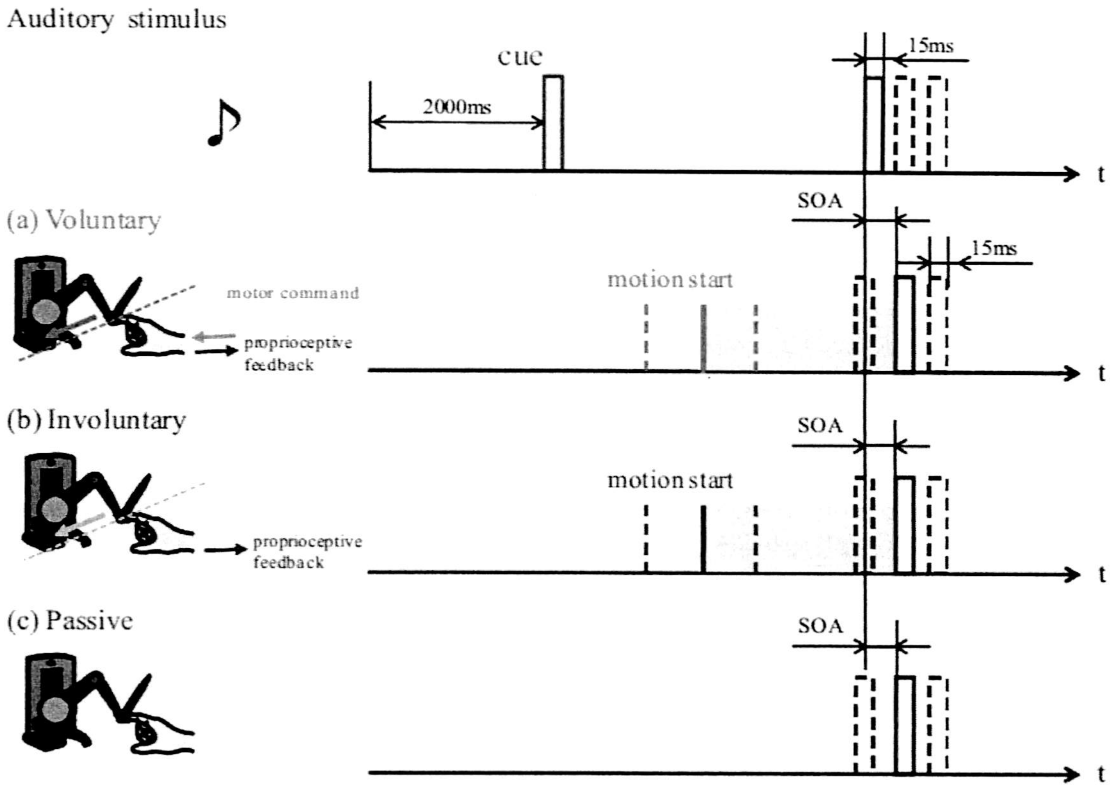

Fig. 2. Voluntary, Involuntary and Passive condition.

2.4. Analytical Procedure

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 subject. The following equation was applied to the regression analysis:

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

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

$$JND = \frac{x_{0.75} - x_{0.25}}{2} = \beta \log 3 \tag{2}$$

MATLAB Statistics Toolbox™ (MathWorks, Inc.) was used for the statistical regression calculation and graphic presentation of the results.

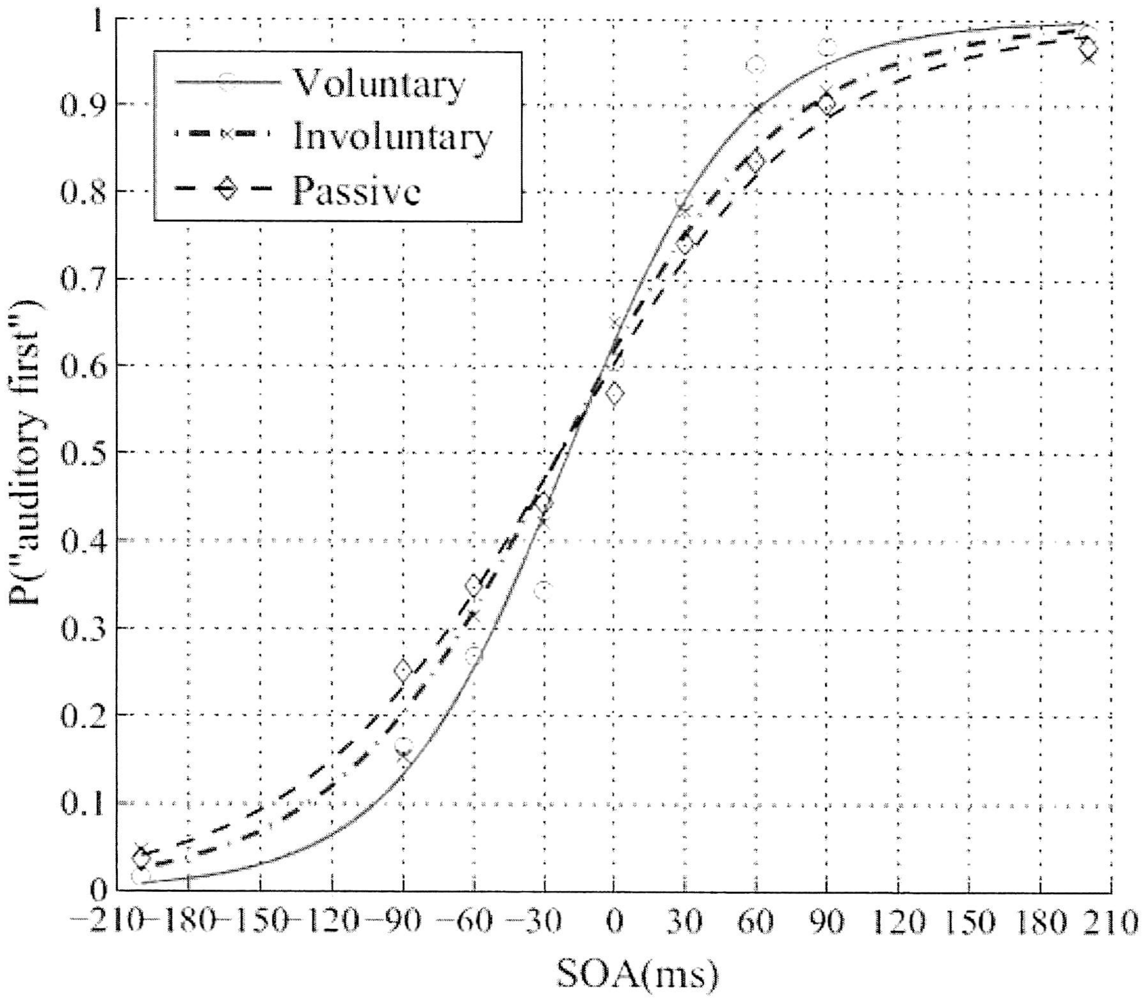

Fig. 3. TOJ data and average psychometric functions across all subjects under the three conditions.

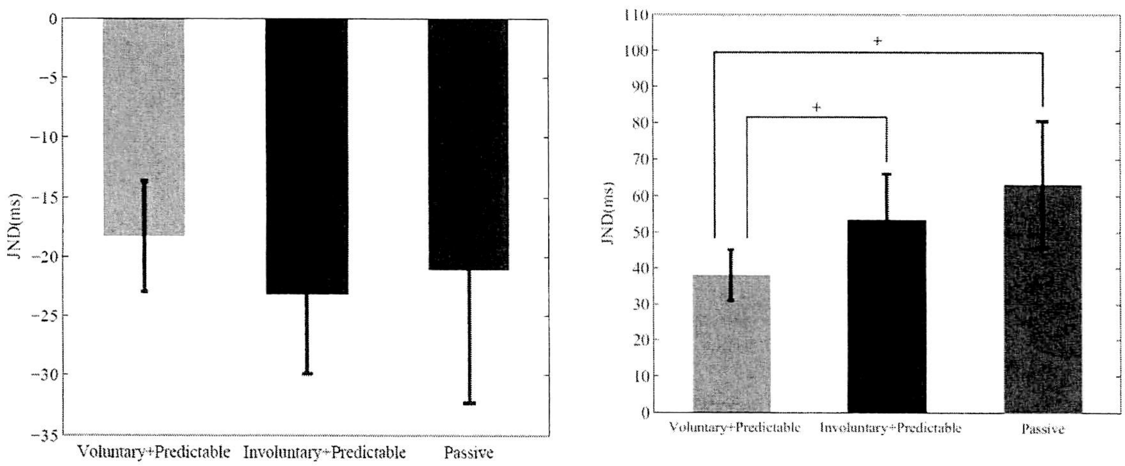

Fig. 4. Point of Subjective Simultaneity (PSS) and Just Noticeable Difference (JND) under the three conditions.

3. RESULTS

As illustrated in Fig. 3, psychometric curves were fitted to the distribution of the mean TOJ data for the following conditions: voluntary, involuntary, and passive condition. We determined the JND and PSS values for each subjects using a regression analysis and further processed the data statistically to obtain the mean and SD values for each condition. As shown in Fig. 4, the mean PSS value was negative (range: -18.3 to -21.3 ms) for the three testing PSS(ms) JND(ms) conditions, indicating that the haptic-auditory stimulus pairs were perceived as simultaneous when the haptic stimuli preceded the auditory stimuli by approximately 20 ms. The result of JND and PSS were examined by Freedman test, and difference of PSS between three conditions was not significant. In the JND, significant difference was observed ($p < 0.04$) and the between-group differences in the JND values were evaluated by a Scheffe's paired comparison analysis, and the results suggested that the voluntary condition produced a smaller JND value compared with the involuntary and passive conditions ($p < 0.03$).

4. DISCUSSION

The results indicated that the PSS occurred under the three conditions when the haptic stimulus preceded the auditory stimulus. This suggests that auditory information is processed faster than haptic information in audio-haptic TOJ task, regardless of the presence/absence of voluntary movement. We also noted that the mean JND value was significantly smaller for the voluntary condition than the other two conditions (Fig. 4). The presence/absence of voluntary movement marks the essential difference between the voluntary and the other conditions. Therefore, this finding suggests that the presence of active motor control contributed to the JND decrease.

One possible mechanism for explaining the JND decrease associated with an active motor control involves the predictive feedback system based on an efference copy of the motor command. The cerebellum, when predicting sensory consequences, is thought to utilize an efference copy to generate a cancellation signal that decreases brain activity in the somatosensory cortex.[19] It is possible that the cancellation signal serves as a "cerebral filter" that passes only the signals transmitted within a predetermined time window, which results in a reduced JND value. The sensory information affected by the cerebellar output signal is integrated in the temporal parietal junction. Indeed, the temporal parietal junction has been reported to play an important role in TOJ tasks.[25]

Our results corroborate the results of a preceding study by Shi *et al.*,[18] despite the fact that our study yielded a comparatively smaller difference in the JND between the voluntary and passive conditions. The quantative discrepancy between these studies could be attributed to the different degrees of predictability under the voluntary condition. In the Shi *et al.* study, which examined the influence of visuomotor action on visual-haptic simultaneous perception, subjects could make precise predictions by the combination of visual information and motor efference copy. In our study, on the other hand, subjects predicted the motion based on efference copy alone. Thus, the relatively smaller JND difference between the voluntary and passive conditions in our study may be a consequence of the poor predictive performance of our subjects. Moreover, we did not find a significant difference in the JND between the involuntary and passive conditions. This suggests that the proprioceptive sensation alone does not affect the prediction of the time of arrival of the stimuli.

As illustrated in Fig. 4, no significant differences were found in the PSS among the testing conditions. This result accorded with the result on no feedback conditions In the Shi *et al.* study. On the feedback conditions, however, PSS was located in the point that adjacent to the point of physical simultaneity under conditions of active motor control with concurrent visual feedback than under conditions without active motor control in the Shi *et al.* study. From here onwards, it was suggested that the feedback information was not enough to change PSS.

5. CONCLUSIONS

In conclusion, our findings suggest that the audio-haptic TOJ performance is not influenced by proprioceptive information solely, and that the JND is narrowed by the functions of motor command copies. Furthermore, we could argue that the differences in the JND between the voluntary, involuntary, and passive conditions of this study originated from the variation in the type of the lag adaptation effect invoked in the presence and absence of active motor control.

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3.16 ヒトの時間順序判断におけるベイズ較正

宮崎　真

我々の時間順序判断は事前の経験により変調する。例えば、一定の時差をもった音-光刺激組を繰り返し経験すると、それらを同時と感じるように時間知覚が変調することが知られている[時差馴応 (Lag adaptation), Fujisaki et al. *Nat Neurosci* 2004]。音刺激と光刺激は、それらが同一の事象に起因したとしても中枢への到達時間に時差が生じうる。その要因の一つとなるのが物理的伝達時間差である。周知のように光の方が音よりも空間を早く伝達していく。例えば、対象が 30-40 m も離れれば 100 ms もの時差が生じる。また、もう一つの要因として神経伝達時差があげられる。聴覚信号の方が視覚信号よりも 40-50 ms 早く中枢に到達するとされている (e.g., King. *Curr*