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PAPER

Effects of Voluntary Movements on Audio-Tactile Temporal Order Judgment

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SUMMARY The present study aims to investigate the effect of voluntary movements on human temporal perception in multisensory integration. We therefore performed temporal order judgment (TOJ) tasks in audio-tactile integration under three conditions: no movement, involuntary movement, and voluntary movement. It is known that the point of subjective simultaneity (PSS) under the no movement condition, that is, normal TOJ tasks, appears when a tactile stimulus is presented before an auditory stimulus. Our experiment showed that involuntary and voluntary movements shift the PSS to a value that reduces the interval between the presentations of auditory and tactile stimuli. Here, the shift of the PSS under the voluntary movement condition was greater than that under the involuntary movement condition. Remarkably, the PSS under the voluntary movement condition appears when an auditory stimulus slightly precedes a tactile stimulus. In addition, a just noticeable difference (JND) under the voluntary movement condition was smaller than those under the other two conditions. These results reveal that voluntary movements alternate the temporal integration of audio-tactile stimuli. In particular, our results suggest that voluntary movements reverse the temporal perception order of auditory and tactile stimuli and improve the temporal resolution of temporal perception. We discuss the functional mechanism of shifting the PSS under the no movement condition with voluntary movements in audio-tactile integration.

key words: *voluntary movements, subjective simultaneity, temporal order judgment, audio-tactile stimuli integration*

1. Introduction

We perceive the external world subjectively through multisensory information integration. The time series of the events that we experience are constructed based on subjective temporal perception. However, it remains unclear how subjective temporal perception affects temporal order judgment (TOJ) of sensory stimuli. In particular, the mechanism of subjective simultaneity is an important element in communication between humans and machines. If the mechanism were elucidated, we could expect the development of various applications, from remote control technologies in the field of medical engineering and space engineering to man–machine interfaces in the field of robot engineering.

Subjective simultaneity is measured by TOJ tasks. A TOJ task is a simple and common experiment in the study of subjective temporal perception [1]–[9] and [10]. In this task, a pair of stimuli is presented to participants with various time lags, called "stimulus onset asynchronies (SOAs)," and the participants are then instructed to judge the temporal order of the stimuli. The performance is usually evaluated by a point of subjective simultaneity (PSS) and a just noticeable difference (JND). The PSS represents the point where a participant is most uncertain about the temporal order of the stimuli. In this sense, the PSS indirectly represents the subjective simultaneity. Because the subjective simultaneity is not identical to the objective (physical) simultaneity in multisensory integration [11], the PSS also indicates the gap between the subjective and objective simultaneities. On the other hand, the JND represents the resolution of temporal perception. For these reasons, the PSS is used to show the change in the subjective temporal perception, and the JND is used to explain sensitivity of the subjective temporal perception.

Recent studies [4], [7], [12]–[14], and [15] suggest that voluntary human behaviors affect the TOJ of sensory stimuli in multisensory integration. The fact that only animals have nervous systems shows that voluntary movements play a very important role in multisensory integration. Shi et al. [18] investigated whether active human motor control shifts the subjective simultaneity of temporal perception. They therefore performed TOJ tasks in visual–haptic integration under two conditions: no movement and movement. Under the movement condition, participants were instructed to move their right hand. The PSS and the JND were then measured under the two conditions. Here, a haptic stimulus was applied to the participant's right index finger during movement of the right hand. As a result, they reported that active human motor control changes both the PPS and the JND under the movement condition. This report is quite interesting in elucidating the mechanism by which temporal perception is changed in multisensory integration by voluntary human behaviors.

However, their experiment still includes the effect of feedback information of the proprioceptive sensation generated by the hand movement itself. This effect needs to be clearly distinguished from that of voluntary movements to investigate how voluntary movements affect the temporal perception of multisensory integration. In this context, Kitagawa et al. reported that perception resolution (JND) increased under the voluntary finger movement condition in

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audio-haptic TOJ tasks but not under the involuntary finger movement condition [16]. This report is very interesting because it suggests that voluntary movements play an active role in temporal perception. However, they did not measure PSS, and therefore it is unknown how voluntary movements affect temporal perception in audio-haptic TOJ tasks. Yokoyama et al. measured the PSS as well as the JND under both voluntary and involuntary finger movement conditions in audio-haptic integration [17]. They reported that voluntary movements had an effect on temporal perception. However, because their tasks were not TOJ tasks but simultaneity judgment (SJ) tasks, it is difficult to compare Yokoyama et al.'s study with that of Kitagawa et al. In contrast, Frissen et al. reported the opposite result to that of Kitagawa et al.; that is, the resolution of temporal perception was improved under the passive finger movement condition but not under the active finger movement condition [18]. They further reported that haptic stimuli came before auditory stimuli under the passive finger movement condition, whereas the opposite result was obtained under the static and active finger conditions. Although their experiments were accurately conducted and improved on Kitagawa et al.'s experiments, their result regarding the PSS obtained under the static condition is different from the well-known finding that subjective simultaneity is perceived in the auditory stimuli dominant region [5], [6], and [9].

Against this background, we performed TOJ tasks in audio-tactile integration under three conditions: no movement, involuntary movement, and voluntary movement. Under the involuntary and voluntary movement conditions, participants were instructed to move their right index finger, and a tactile stimulus was applied to the participant's right index finger during this movement. By comparing the movement conditions, we examined how two motor factors, the proprioceptive sensation generated by finger movement and the voluntariness of the movement, affect temporal perception. In particular, we compared the voluntary movement condition with the involuntary movement condition to examine the effect of voluntary movements.

2. Methods

2.1 Participants

Eighteen healthy participants aged 21 to 30 years (men with a mean age of 23.6) participated in our experiment. The participants were right-handed and had normal hearing as well as a normal sense of touch. Our experiment was approved by the ethics committee of the Tokyo Institute of Technology. All the participants provided informed consent in writing before the experiment and received payment in return in accordance with committee guidelines.

2.2 Stimuli

Fig. 1 Experimental environment. A sinusoidal wave sound was presented to the participants through earphones. The haptic device was attached to the right index finger of the participants. Under the involuntary movement condition, the haptic device moved their right index finger.

Figure 1 shows our experimental environment. The auditory stimulus was a sinusoidal wave sound (2000 Hz, 50 dB, for 15 ms). The sound was presented to the participants in both ears through earphones (HP-RHF41, Radius, Japan) covered with sound-insulating earmuffs. The tactile stimulus was an impulse force consisting of a rectangular pulse (3N, for 15 ms) applied to the participant's right index finger on the palmar side. It was exerted by the PHANToM® Desktop haptic device (SensAble Technologies, MA, USA). This haptic device was attached to the participant's right index finger. The timing of stimuli presentation and the movement of the device were controlled within an error margin of 1 ms. This sensory stimulation system was operated by a PC workstation (HP xw4600/CT, Hewlett-Packard, CA, USA), and developed using the OpenHaptics software development toolkit (SensAble Technologies, MA, USA) on the Microsoft® Visual C++ 2008 platform (Microsoft, WA, USA).

2.3 Experimental Objective, Conditions and Procedure

The experimental objective of the present study was to investigate the effect of voluntary finger movement on subjective simultaneity perception in audio-tactile integration. We thus operated audio-tactile TOJ tasks under three conditions: no movement, involuntary movement, and voluntary movement. In the experiment, the participants judged which stimulus was presented first. A pair of auditory and tactile stimuli was presented to the participants. The auditory stimulus was presented with an SOA value from the presentation of the tactile stimulus. The SOA value was set at −200, −90, −60, −30, 0, +30, +60, +90, or +200 ms, where the negative values indicate that the tactile stimulus preceded the auditory stimulus. Under the involuntary movement condition, the haptic device was used to move the right index finger inward involuntarily. Under the voluntary movement condition, the participants voluntarily moved their right index finger toward the palmar side. The experiment was carried out in a darkened and sound-attenuated room. The participants were seated in front of the sensory stimulation system with their right index finger held in the haptic device. During the experiment, they wore earmuffs over the earphones,

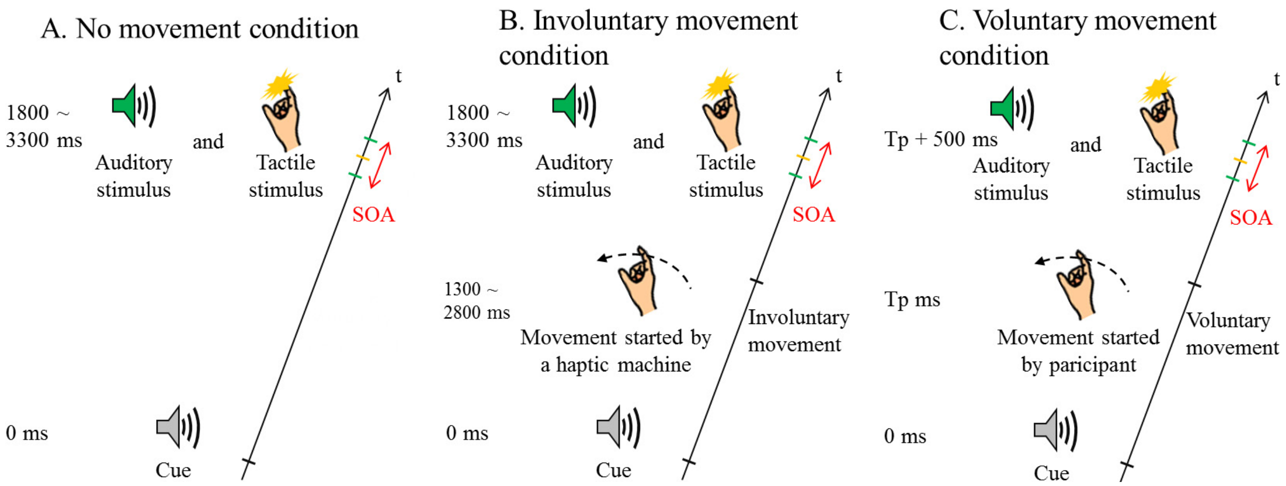

Fig. 2 Schematic illustration of audio-tactile TOJ tasks under the three conditions: no movement, involuntary movement, and voluntary movement. Under the involuntary movement condition, the haptic device started to move the right index finger of the participants 1,300 to 2,800 ms after the cue. Under the voluntary movement condition, the participants started to move their right index finger voluntarily at some time point after the cue.

and closed their eyes to eliminate confounding effects from visual stimuli. We also asked them to pay constant attention to tactile stimuli during the trials to control for prior entry effects [1]–[3], which facilitate the processing of an attended stimulus compared with an unattended stimulus.

Under all conditions, a single tone was presented as a cue for each run of trials. After the cue, a pair of auditory and tactile stimuli, as the target of TOJ, was presented with an SOA selected from the above values. After presentation of the stimuli, the participants nominated which stimulus was first by pressing the X or Z key on a keyboard. The X key indicated "auditory stimulus first," whereas the Z key indicated "tactile stimulus first." After a pause of 2,000 ms, the next trial began.

Under the no movement condition (Fig. 2A), a tactile stimulus was generated at a random timing between 1,800 and 3,300 ms (1,300 +500 to 2,800 +500 ms) after the presentation of the cue, and an auditory stimulus was presented with an SOA selected from the above values.

Under the involuntary movement condition (Fig. 2B), the haptic device started to move the participant's right index finger at a random timing between 1,300 and 2,800 ms after the presentation of the cue. The speed of the finger movement for each trial was either 76, 88, 100, 112, or 124 mm/s. A tactile stimulus was presented 500 ms after the start of the finger movement, and an auditory stimulus was then presented with an SOA selected from the above values.

Under the voluntary movement condition (Fig. 2C), the participants moved their right index finger at a time of their choosing (Tp) between about 1,000 and 3,000 ms. At 500 ms from the start of the finger movement, a tactile stimulus was generated, and an auditory stimulus was then presented with an SOA selected from the above values.

The participants participated in 45 trials (i.e., five trials for each SOA value) as one block for each of the three conditions, and eventually completed five blocks. The order of trials in each block and the order of blocks under each condition were randomized. Furthermore, before the experiment commenced, the participants practiced moving their right index fingers under the voluntary movement condition for five trials to adjust their finger movements to a speed as close to 100 mm/s as possible. During this practice session, only the tactile stimuli were presented. In addition, to accustom the participants to TOJ tasks, they participated in one preliminary block for each condition before the start of the experiment. In this experiment, it took approximately five minutes to complete one block for each condition, and participants were given several minutes of rest between blocks. As a result, a total of 880 trials including practice runs were conducted over the entire process, which took approximately three hours. In addition, a counterbalance was achieved among the participants in terms of the order of the three conditions in both the practice runs and the experiment.

2.4 Data Analysis

The ratio of answers indicating that an auditory stimulus came first was calculated for each SOA value. Logistic regression using a generalized linear model was conducted for the ratio data [20]. The following equation was applied to the regression analysis:

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

where y represents a percentage of correct answers and x denotes the value of the SOA. α was an estimated value of the PSS and β was a value related to the JND as follows:

$$JND = \frac{x_{75} - x_{25}}{2} = \beta \log 3 \tag{2}$$

where x_y represents the value of the SOA with y% correct

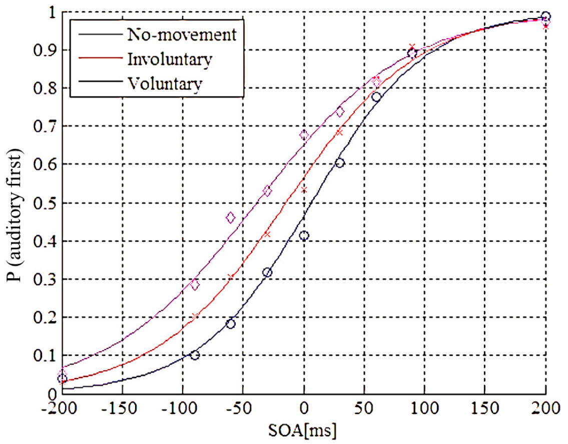

Fig. 3 Average psychometric curves of a participant across all experiments under the three conditions. Positive SOA values denote that the auditory stimulus is presented before the tactile stimulus.

answers. Here, the PSS was defined as:

$$PSS = x_{50}. \tag{3}$$

The statistical regression was calculated using MATLAB Statistics Toolbox® (MathWorks, MA, USA). We determined the PSS and JND values for each participant using regression analysis (Eqs. (1) and (2)), and processed the data statistically to obtain the mean and standard error values for each condition. Figure 3 represents the psychometric curves of a participant fitted to the distribution of the mean TOJ data for each condition.

Regarding the trials under the voluntary movement condition, we regarded the data on finger movement speeds within the range of 60 to 150 mm/s as effective in minimizing the variability of movement speeds among the participants [19]. Less than 5% of the data acquired for each participant was ineffective. Moreover, we did not give information on the finger speed to the participants, except during the practice session.

3. Results

As shown in Fig. 4, the mean PSS values under the voluntary and involuntary movement conditions become larger than those under the no movement condition. In addition, Fig. 5 shows that the mean JND value under the voluntary movement condition is smaller than those under the other two conditions. Table 1 presents the means and standard deviations of the PSS and JND values under the three conditions. In Table 1, positive PSS values indicate that an auditory stimulus is presented before a tactile stimulus. We conducted a one-way repeated-measures analysis of variance (ANOVA) for each PSS and JND result with motor conditions as the within-participants factor. The difference in the PSS between the three conditions was significant [$F(2, 34) = 35.78$, $p < 0.001$, $\eta_p^2 = 0.60$]. For the JND, a significant difference among the conditions was also found [$F(2, 34) = 16.62$, $p < 0.001$, $\eta_p^2 = 0.50$]. We further conducted a repeated-measures t-test of the differences in the PSS and JND between conditions, using the Holm–Bonferroni correction method for multiple comparisons. Figure 4 shows statistical evidence that the voluntary movement condition shifts the PSS to a value such that the interval between the presentations of auditory and tactile stimuli is smaller compared with that in the involuntary movement condition ($p < 0.01$) and the no movement condition ($p < 0.001$). Remarkably, the PSS under the voluntary movement condition appears when an auditory stimulus slightly precedes a tactile stimulus. Figure 5 also shows that the JND under the voluntary movement condition is statistically smaller than that under the involuntary movement condition ($p < 0.01$) and the no movement condition ($p < 0.001$).

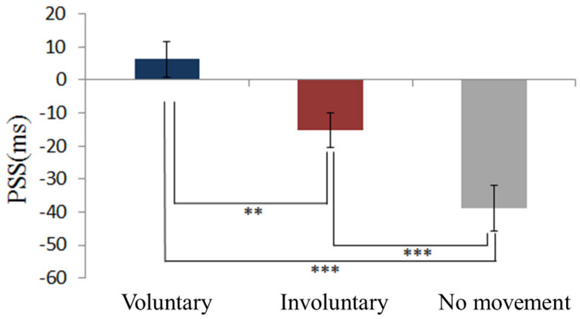

Fig. 4 Mean PSS values under the three conditions. The error bars represent the standard errors. $^{**}p < 0.01$, $^{***}p < 0.001$.

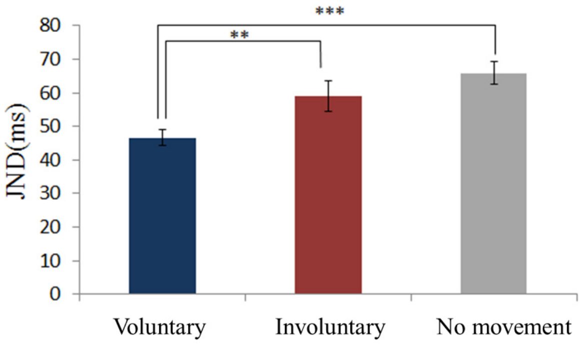

Fig. 5 Mean JND values under the three conditions. The error bars represent the standard errors. $^{**}p < 0.01$, $^{***}p < 0.001$.

Table 1 Mean values and standard deviations of the PSS and JND. Positive PSS values indicate that an auditory stimulus was presented before a tactile one.

Condition	PSS (Mean)	PSS (SE)	JND (Mean)	JND (SE)
No movement	–37.7	7.2	66.1	3.5
Involuntary movement	–13.1	5.7	59.2	4.8
Voluntary movement	5.3	5.8	46.8	2.4

4. Summary and Discussion

The present study shows a statistically significant difference in the PSS among the three conditions: no movement, involuntary movement, and voluntary movement. In particular, we find that the voluntariness of the movement affects TOJ in audio-tactile integration.

First, our experiment shows that the JND under the voluntary movement condition is smaller than those under the other conditions. This result supports the experimental findings of Kitagawa et al. [16]. According to previous studies [13], [14], voluntary movements slow the subjective passage of time and improve the resolution of TOJ. This result suggests that when we voluntarily work in an environment, we become able to distinguish various events clearly. However, in our experiment, the increase in the JND under the no movement condition may be influenced by a long temporal difference between the cue, which is an auditory stimulus, and the first stimulus, which is an auditory or tactile stimulus. Even if that is the case, Frissen et al. [18] reported the similar result as our study. That is, the JND under the no movement condition became greater than that under the involuntary movement condition despite a smaller temporal difference than in our experiment. This indicates that the temporal difference between the first cue and the second cue, which is the start of finger movement, does not necessarily have a large influence on the JND. It therefore appears that the temporal difference between the first and second cues does not change the essence of our results.

Second, our results show that voluntary movements reverse the order of temporal perception of auditory and tactile stimuli in judgments of subjective simultaneity. The previous studies regarding audio-tactile TOJ tasks with no movement, [5], [6], and [9], indicate that humans perceive subjective simultaneity at the time when a tactile stimulus is presented at about 30 ms before an auditory stimulus. Figure 4 shows that both voluntary and involuntary movement conditions shift the PSSs to smaller absolute values for the interval between the presentations of auditory and tactile stimuli than that in the no movement condition. That is, both involuntary and voluntary movements affect judgments of the temporal order of auditory and tactile stimuli. However, the PSS under the involuntary movement condition is smaller than that under the voluntary movement condition. Remarkably, the PSS under the voluntary movement condition appears when an audio stimulus slightly precedes a tactile stimulus. This result suggests that voluntary movement changes the temporal order of multisensory stimuli input from the environment in the judgment of subjective simultaneity.

Below, we discuss functional mechanisms for shifting the PSS under the involuntary and voluntary movement conditions in audio-tactile integration. In general, it is known that the neurotransmission speed of sensory stimuli depends on the physical properties of nerve cells (such as presence or absence of myelin, axon diameter, and membrane capacitance), temperature, and age. In our experiment, there are no factors contributing to changing these quantities. Hence, the change in temporal perception under the involuntary and voluntary movement conditions in our experiment is not accounted for in terms of afferent neurotransmission alone.

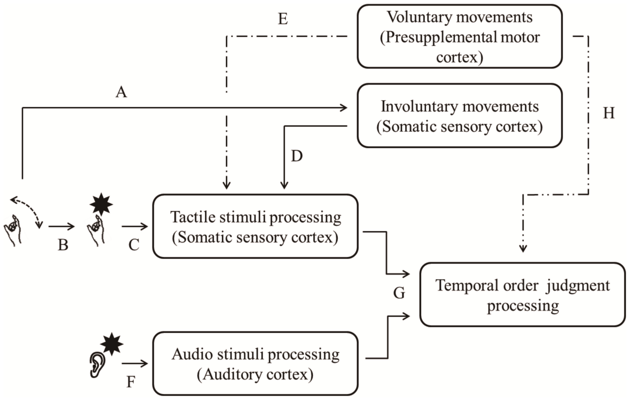

Fig. 6 Functional model of PSS shift under the involuntary and voluntary movement conditions.

However, there is a strong possibility that the PSS obtained under the involuntary movement condition in our experiment is caused by the feedback information from the proprioceptive sensation generated by the right index finger movement itself (arrow A in Fig. 6). This afferent feedback information is transmitted from the finger to a somatic sensory area, and after 500 ms (arrow B in Fig. 6), the tactile stimulus provided on the finger is transmitted to the somatic sensory area (arrow C in Fig. 6). Given the neurotransmission speed of proprioceptive information (about 100 m/s) and tactile stimulus (about 50 m/s), it may be expected that before the arrival of the tactile stimulus in the somatic sensory area, this afferent feedback information accelerates the processing speed of the tactile stimulus faster than under the no movement condition (arrow D in Fig. 6).

Next, we consider a functional model for drastic shifts in the PSS under the voluntary movement condition. Some researchers have suggested that the PSS is affected by prior entry effects [1], [2], and [3]. When participants receive multisensory stimuli, they tend to perceive an attended stimulus before the other stimuli. Therefore, in our experiment we instructed the participants to pay attention to a tactile stimulus under all three conditions. However, attention to tactile stimuli under the involuntary and voluntary movement conditions may become intense compared with the no movement condition. In this respect, Hanson et al. [21] demonstrated that temporal tactile perception was fixed despite attentional load. Hence, it seems difficult to attribute our results to the effect of attention.

Moreover, it has been indicated that some stimulus predictability alternates the temporal order of subjective perception [22], [23]. However, even though the presentation timing of tactile stimuli was equal under the voluntary and involuntary movement conditions, the present study obtained different values for the PSS. Thus, stimulus predictability does not seem to be a valid explanation for the alternation of subjective temporal perception in our experiment.

The above eliminations lead us to suspect an efferent effect such as an efference copy. An efference copy is regarded as a copy of prepared motor command signals. This copy is generated in the presupplementary motor cortex and the premotor cortex only during voluntary movements [24], [25]. The premotor cortex prepares motor commands for voluntary actions triggered by external stimuli, whereas the presupplementary motor cortex prepares motor commands for "intentional" actions generated internally, which are then executed by the primary motor cortex. Blakemore et al. [6] suggested that the information signals of an efference copy derived from a voluntary action were indirectly influenced by neural activity in the somatic sensory cortex, and the efference copy could weaken the strength of tactile perception. Libet et al. [26] reported that the information signals of an efference copy for human active motor control occurred before actual movements. It has also been reported that an efference copy could be used to correct the consequences of movements [27], [28]. Therefore, although the relations between an efference copy and subjective temporal perception are not yet clear, there is a possibility that the information signals of an efference copy affect subjective simultaneity in audio-tactile TOJ tasks. That is, the efference copy may operate to enhance the abovementioned effect of the proprioceptive feedback under the involuntary movement condition in the somatic sensory cortex (arrow E in Fig. 6).

Furthermore, we can explore an alternative possibility. Desmurget et al. [29] reported that the information signals of an efferent copy were sent to the parietal cortex and used to predict sensory consequences of movements. The preparation of motor commands for voluntary movements by the presupplementary motor cortex causes a sense of urge. The inferior part of the posterior parietal cortex generates sensory representations of the predicted consequences of the movements. In this way, it has been suggested that an efference copy influences areas posterior to the somatic sensory cortex. On the other hand, Davis et al. [30] reported that the temporal parietal junction was activated during TOJ tasks, and therefore may be a crucial component of the "when" pathway. Considering the close relation between the locations of the posterior parietal cortex and the temporal parietal junction, we hypothesize that the posterior parietal cortex works with the temporal parietal junction in TOJ during voluntary movements. This suggests that the temporal order of a tactile stimulus (arrow C in Fig. 6) and an auditory stimulus (arrow F in Fig. 6) are judged in the posterior area of the somatic sensory cortex and the auditory cortex (arrow G in Fig. 6). This also suggests that an efference copy does not affect the processing speed of tactile stimuli, but rather the mechanism of TOJ itself (arrow H in Fig. 6). This mechanism may change the criteria for TOJ, and therefore an efferent copy may change the subjective temporal order of tactile and audio stimuli during voluntary movements.

However, there is yet another possibility, namely that voluntary movements reduce the processing speed of auditory stimuli compared with the no movement and involuntary movement conditions. We therefore need to explore the role of voluntary movements further in other TOJ tasks. Specifically, we plan to conduct audiovisual TOJ tasks under the same three conditions as the present study to explore whether the voluntary movements of a participant's finger affect the processing of stimuli other than tactile information.

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