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著者(和文)	カク巧
Author(English)	Qiao Hao
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Voluntary Movement Affects Simultaneous Perception of Auditory–tactile Stimuli in TOJ Task

Doctoral Dissertation

Qiao Hao

Department of Computational Intelligence and Systems Science
Interdisciplinary Graduate School of Science and Engineering

Abstract

The simultaneous perception of multimodal sensory information has a crucial role for effective reactions to external environment, especially during voluntary movement. Up until now, there are a few studies to investigate whether voluntary movements affect simultaneous perception of multimodal sensory information or not. Furthermore, these previous studies reported contradictory effects of voluntary movements on simultaneous perception of visual or auditory and tactile stimuli, when tactile stimulus was presented to the moving body part. With the same location of voluntary movements and tactile stimulus in previous studies, little is known about spatial limits on the effect of voluntary movements on simultaneous perception, especially when tactile stimulus is presented to a non–moving body part. This study aimed to investigate the effect of voluntary movement on the simultaneous perception of auditory and tactile stimuli (chapter 3's experiment) and the aforementioned effect, when tactile stimulus is presented to a non–moving body part (chapter 4's experiment) by temporal order judgment (TOJ) task. In a TOJ task, the point of subjective simultaneity (PSS) and the just noticeable difference (JND) are measured. The PSS is a time point in which the two stimuli is perceived at the same time subjectively. The JND is the smallest interval that participants can clearly judge the order of two stimuli, as a measure of participants' "temporal resolution". In chapter

3’s experiment, the tactile stimulus was presented to the moving right index finger, whereas in chapter 4’s experiment, the tactile stimulus was presented to the non–moving left index finger. In both experiments, participants were asked to voluntarily move their right index finger and judge the temporal order of auditory and tactile stimuli (voluntary movement condition). Further, the passive movement condition was designed to exclude the effect of proprioceptive information of the movements, in which participants’ right index fingers were moved by device, while no movement condition was used as the control condition. In chapter 3’s experiment, the results show that the PSS during voluntary movement shifted from the tactile stimulus being first during passive movement or no movement to the auditory stimulus being first, whereas there was no difference of PSSs between passive movement and no movement conditions. There was no significant difference in the JNDs among the three conditions, which means voluntary movement, compared with passive movement and no movement, did not affect the JND. The results of chapter 3’s experiment show that voluntary movement affected the PSS in auditory–tactile simultaneous perception, while voluntary movement did not affect the JND. In chapter 4’s experiment, the results show that there were significant differences of PSSs between voluntary movement and passive movement conditions, between voluntary movement and no movement conditions, whereas there was no significant difference between passive movement and no movement conditions. On the other hand, voluntary movement and passive movement, compared with no movement, significantly increased the JNDs. Voluntary movement, compared with passive movement, increased the JND. These results of chapter 4's experiment show that voluntary movement also affected simultaneous perception of auditory and tactile stimuli, even when the tactile stimulus was presented to a non–moving body part, not just to a moving body part as has been shown in chapter 3's experiment. These results of this study mean that voluntary movement affected the simultaneous perception of auditory and tactile stimuli, and that the shift effect of voluntary movement, compared with passive movement and no movement, on the PSS occurred, when tactile stimulus was presented not only to a moving body part, but also to a non–moving body part. The inconsistent effect of voluntary movement and passive movement on the temporal resolution, in which voluntary movement and passive movement, compared with no movement, did not affect the JND in chapter 3's experiment, but increased the JND in chapter 4's experiment, might be attributed to the attention divided by the movements of the right index finger in chapter 4's experiment. These findings indicate that attention is not enough to affect the PSSs, as a prior entry effect reported by previous studies, the unique mechanism in voluntary movement (motor information, such as efference copy) might also affect the PSSs. In this study, it is concluded that voluntary movement affects simultaneous perception of auditory and tactile stimuli, when tactile stimulus is presented to both of the moving body part and the non–moving body part.

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Chapter 1 Introduction

To refer to time perception, we usually raise a question what is time itself? However, "time is not a thing that, like an apple, may be perceived" (Woodrow, 1951). For instance, we could see the apple, touch it, smell it, and then eat it. After that, we establish the concept of apple. For time itself, we have no direct way to feel it by our sense organs.

Although it is impossible to directly define "time", human could indirectly experience many kinds of time perception, such as the lasting time of a self–introduction or an interesting movie, the rest between classes, the orders of lighting and thunder. However, even we could have many kinds of time perception, we still do not own a clear idea about how time perception works until now, especially temporal integration of events. Therefore, it is necessary to pay attention to what is the time perception, which is important for human to react to other people and/or the external environment.

The perception of our external environment is often a multimodal sensory experience, in which the different information, such as auditory, tactile and visual stimuli, is integrated in brain, though the integration of unimodal sensory information is also important for human. With smooth temporal integration of multimodal sensory information by our various sensory organs, we could ensure the communication with other people or the external environment. For example, we enjoy the synchronous sound and flash of movie at the theatre. In fact, the speed of sound is much more slowly than the speed of flash (330 m/sec vs. 300,000,000 m/sec) in the air, whereas the neural processing time of visual stimulus is slower than that of auditory stimulus (approximately 50 ms vs. 10 ms, respectively). That is, to be perceived simultaneously, the two stimuli should happen at a distance of about 10–15 m away from the observer (Pöppel, 1985; Pöppel et al., 1990), which is caused by the physical and neural differences of visual and auditory information. Therefore, it is interesting that how do people, who are at different distances away from screen, successfully enjoy the movie at the theatre. Although this question of how does the brain integrate the multimodal sensory information still remains to be solved, we could know something about the temporal integration from previous studies. Here, we pay more attention to the temporal integration of auditory and tactile information.

Simultaneity judgment (SJ) task (Schneider and Bavelier, 2003; Vogels, 2004; Zampini, Brown et al., 2005) and temporal order judgment (TOJ) task (Hirsh and Sherrick, 1961; Mitrani et al., 1986; Spence et al., 2001; Zampini et al., 2003; Miller and Schwarz, 2006; Cardoso-Leite et al., 2007; Boenke et al., 2009; Van Eijk et al., 2009; Kwon et al., 2014) are used to study the temporal integration of events. In a SJ task, two stimuli are presented at various stimulus onset asynchronies (SOAs) and the participants are required to judge whether the two stimuli are simultaneous or not. In a TOJ task, the participants are required to judge the temporal order of the two stimuli, which could be the unimodal sensory information and/or multimodal sensory information.

In the TOJ task, the point of subjective simultaneity (PSS) (Slutsky and Recanzone, 2001; Lewald and Guski, 2003; Kayser et al., 2008; Shi et al., 2008; Nishi et al., 2014) and the just noticeable difference (JND) (Keetels and Vroomen, 2005, 2008; Zampini, Guest et al., 2005) are measured. The TOJ task shows that observers usually perceive different modal sensory stimuli as simultaneous, when the two stimuli are presented with a short lag (Slutsky and Recanzone, 2001; Lewald and Guski, 2003; Kayser et al., 2008; Shi et al., 2008; Nishi et al., 2014; Zampini et al., 2003; Keetel et al., 2005; Van Eijk et al., 2009; Nishikawa et al., 2015). More specifically, the PSS differs from the point of physical simultaneity. Furthermore, temporal resolution is usually evaluated by the JND, which represents difference threshold of TOJ task, with a lower JND indicating higher temporal resolution, and vice versa. JNDs differ for different combinations of multimodal sensory information types (Spence et al., 2001; Zampini et al., 2003; Zampini, Guest et al., 2005; Zampini, Brown et al., 2005; Keetels and Vroomen, 2005, 2008).

Until now, some previous studies investigated the temporal integration of auditory and tactile stimuli in no movement conditions (Hirsh and Sherrick, 1961; Fujisaki and Nishida, 2009; Spence et al., 2003; Zampini, Brown et al., 2005; Kitagawa et al., 2005), whereas other previous studies focused on the spatial effects on the temporal integration of auditory and tactile stimuli (Zampini, Brown et al., 2005; Kitagawa et al., 2005; Occelli et al., 2008). These previous studies chose TOJ task and then measured PSSs and JNDs to evaluate the temporal integration of auditory and tactile stimuli. On the other hand, attention is also suggested to affect the temporal integration (i.e. the PSS), and this effect is called as the prior entry effect (Spence and Parise, 2010; Shore and Spence, 2005; Vibell et al., 2007). While it is also known that voluntary movements can affect temporal integration of visual or auditory and tactile stimuli (Shi et al., 2008; Nishi et al., 2014; Hao et al., 2015).

1.1 Temporal integration of auditory and tactile information

Multimodal sensory experience is necessary and significant for human. Some evidences showed that the human fetus respond to multimodal sensory stimuli from very early development (Kisilevsky et al., 1992). However, compared with sensory pair of auditory and visual stimuli or sensory pair of visual and tactile stimuli, there are quite few studies on sensory pair of auditory and tactile stimuli. Actually, a growing empirical evidence showed that there are similarities in hearing and touch (von Békésy, 1959; Nicolson, 2005; Soto-Faraco and Deco, 2009). Some research reported that the same type of mechanical stimuli, for example, a specific vibratory rate, could activate both the basilar membrane of the inner ear and that of the mechanoreceptors of the skin. That is, the propagation of travelling waves are determined, either when a vibrating body touched the skin or when the stapes footplate of the ear is stimulated (von Békésy, 1959; Nicolson, 2005). Additionally, both of the vibrotactile and auditory perception likely originated from tactile and auditory sensory systems (von Békésy, 1959; Soto-Faraco and Deco, 2009). This is partly same with the development of sensory systems in time (Lickliter, 2000; Lickliter and Bahrick, 2000; Lagercrantz and Changeux, 2009), see figure 1.1 (Occelli et al., 2011).

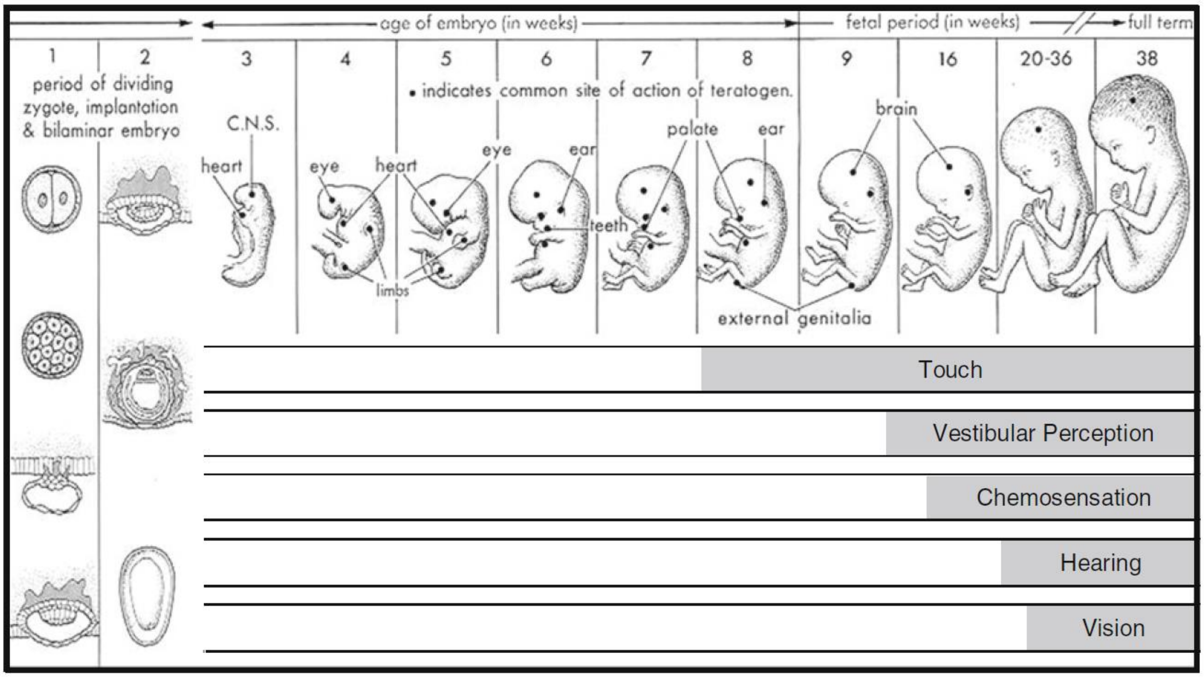

Figure 1.1 The time of sensory systems' development in human.

(Occelli et al., 2011)

The first study on temporal integration with auditory and tactile stimuli dates back to around 1960s (Gescheider, 1966, 1967, 1970), in which the temporal integration of auditory and tactile stimuli was measured. Hirsh and Sherrick (1961) compared how participants indicate the temporal order of two unimodal sensory stimuli (i.e., the pairs of auditory and auditory, visual and visual stimuli, and tactile and tactile stimuli) and multimodal sensory stimuli (i.e., the pair of auditory and visual stimuli, visual and tactile stimuli, and auditory and tactile stimuli) for the first time. It is surprised that Hirsh and Sherrick (1961) showed that the temporal resolution between the two stimuli was nearly 20 ms in both unimodal and multimodal sensory stimuli (see Table 1.1). After that, many subsequent studies reported the inconsistent results with Hirsh and Sherrick's results (Fujisaki and Nishida, 2009; Spence et al., 2003; Zampini, Brown et al., 2005; Kitagawa et al., 2005). To resolve the question of temporal resolution in multimodal sensory information, Fujisaki and Nishida (2009) performed the auditory and visual, visual and tactile, and auditory and tactile TOJ tasks. Participants were required to judge the temporal order of the two multimodal sensory stimuli and provided with trial–by–trial feedback regarding the accuracy of their performances. Fujisaki and Nishida (2009) found inconsistent results with the results of Hirsh and Sherrick (1961), and that the temporal resolution of auditory and tactile stimuli was higher than the temporal resolutions of auditory and visual stimuli, and visual and tactile stimuli (see Table 1.1). Fujisaki and Nishida (2009) suggested two different explanations for this phenomenon, which are mutually associated. One explanation is that the temporal resolution depends on the various senses. The accurate performance of auditory and visual stimuli, and visual and tactile stimuli are worse because of a lower temporal resolution of visual stimulus than either that of auditory stimulus or tactile stimulus (Welch and Warren, 1980). The other explanation is related to the different operation of a "comparator" (i.e. the independent channels model by Sternberg and Knoll (1973)) for auditory and tactile stimuli. From their model, a central decision mechanism or "comparator" is used to evaluate the time, and decide the temporal order of the two stimuli.

Additionally, some previous studies investigated the spatial effects on the temporal integration of auditory and tactile TOJ task (Zampini, Brown et al., 2005; Kitagawa et al., 2005; Occelli et al., 2008; also see Table 1.1). All of these studies asked participants to indicate the temporal order of auditory and tactile stimuli, when tactile stimuli were presented from the same, different positions in frontal, and rear space of participants. They reported that spatial information did not affect the PSS of auditory and tactile TOJ performance. While the effects of the spatial information on the JNDs are divergent (see Table 1.1). Kitagawa and his colleagues (2005) showed that the temporal resolution of same position is better than that of different position, when tactile stimulus was presented behind the participants' head on the same or opposite side. Zampini, Brown, and his colleagues (2005) suggested that the factor of spatial position might be a less important factor in the auditory and tactile TOJ task, while they found that practice could improve the temporal resolution in their Exp. 2 and Exp. 3. In accord with the results of Zampini's study, Occelli's study provided no effect of spatial information on the temporal integration of auditory and tactile TOJ task. Taken together, these results reveal that vision (Occelli et al., 2008) or visual information, as occurred behind a participant's head (Kitagawa et al., 2005), is important for accurate temporal resolution, instead of the PSS, while there was no spatial effect on the temporal integration, when tactile stimulus was presented from the frontal space (Zampini, Brown et al., 2005).

At early perceptual stages, sensory processing of emotional stimulus, for example, emotional faces, pictures of threat, and emotional sounds or voices, showed higher processing speed than that of neutral stimuli (Eimer and Holmes, 2007; Pessoa et al., 2002). With little knowledge about the effect of emotional visual stimulus on temporal integration, Jia's study (2013, also see Table 1.1) addressed this question by studying the potential effect of neutral, positive, and negative visual threat on the auditory and tactile TOJ task. Meanwhile, they also examined the spatial effect on temporal integration by presenting auditory and tactile stimuli from the same location straight ahead of participants or from different side of participants. When the two stimuli were presented from the same position, participants needed to judge "which stimuli came first". Whereas, when the two stimuli were presented from different sides of participants, participants needed to judge "which side came first". Their results showed that emotional visual threat did not affect the temporal integration of the auditory and tactile TOJ task, when the two stimuli were presented from the same position. But emotional visual threat affected the temporal integration when auditory and tactile stimuli were presented from different positions. Furthermore, compared with the neutral, remote threats, only near–body visual threat induced a shift of simultaneous perception toward the tactile stimulus in auditory and tactile TOJ task.

Table 1.1 Summary of auditory and tactile temporal integration studies by TOJ

Author(s)	Purpose	Stimuli and Design	Results
Hirsh and Sherrick (1961; Exp. 4)	To compare people's ability to judge the temporal features of stimuli presented either within or across different pairs of sensory modalities.	Three sessions, one for each stimulus pairing (i.e., auditory and visual, visual and tactile, and auditory and tactile)	JND of around 20 ms for all stimulus combinations
Kitagawa et al. (2005; Exp. 1)	To research a spatial modulation of auditory	Auditory and tactile pairs of stimuli, presented either	Exp1: JND: 64 ms (Same) vs. 55 ms (Different); $p < 0.05$

	and tactile TOJ performance.	from the same or from different positions in rear space	PSS: -4 ms (Same) vs. 8 ms (Different); P = 0.14
Zampini, Brown et al. (2005)	To investigate the effect of relative position (i.e., same vs. different) on the temporal precision of auditory and tactile TOJ performance.	Auditory tactile pairs of stimuli, presented either from the same or from different positions in frontal space	Exp 1: JND: 75 ms (Same) vs. 82 ms (Different); n.s. PSS: 1 ms (Same) vs. 7 ms (Different); n.s. Exp 2: JND: 45 ms (Same) vs. 42 ms (Different); n.s. PSS: 19 ms (Same) vs. 13 ms (Different); n.s. Exp 3: JND: 44 ms (Same) vs. 44 ms (Different); n.s. PSS: 9 ms (Same) vs. 8 ms (Different); n.s.
Occelli et al. (2008)	To examine the potential effect of spatial factors on auditory and tactile TOJ performance in both the sighted and blind.	Auditory and tactile pairs of stimuli, presented either from the same or from different positions in frontal space	Sighted, JND: 69 ms (Same) vs. 70 ms (Different); n.s. PSS: 27 ms (Same) vs. 29 ms (Different); n.s. Blind, JND: 73 ms (Same) vs. 61 ms (Different); P = 0 .005 PSS: 24 ms (Same) vs. 30 ms (Different); n.s.
Fujisaki and	To examine the	Four sessions (i.e., auditory	JND: 36 ms (auditory and visual), 29

Nishida (2009; Exp. 4)	difference in temporal resolution of synchrony perception between auditory and visual, visual and tactile, and auditory and tactile combinations.	and visual, visual and tactile, auditory and tactile, tactile and tactile)	ms (visual and tactile), 25 ms (auditory and tactile), 17 ms (tactile and tactile); n.s.
Jia et al. (2013)	To investigate the influence of emotional (visual) pictures on auditory and tactile TOJ performance.	Auditory and tactile pairs of stimuli, presented either from the same location straight ahead of participants or one (auditory or tactile stimuli) to the left and the other (tactile or auditory stimuli) to the right side in emotional and non–emotional conditions (i.e., neutral, positive, and negative).	Exp 1: JND: 71 ms (Neutral) vs. 81 ms (Positive) vs. 80 ms (Negative) n.s. PSS: 13 ms (Neutral) vs. 10 ms (Positive) vs. 13 ms (Negative) n.s. Exp 2: JND: 70 ms (Neutral) vs. 69 ms (Positive) vs. 83 ms (Negative) P < 0 .05 PSS: -6 ms (Neutral) vs. 4 ms (Positive) vs. 9 ms (Negative) P < 0.05 Exp 3: JND: 81 ms (Neutral) vs. 81 ms (Near–body threat) vs. 81 ms (Remote) n.s. PSS: -22 ms (Neutral) vs. -6 ms (Near–body threat) vs. -16 ms (Remote) P < 0.01

1.2 Attention and temporal integration

Titchener (1908, p. 251) wrote that ‘‘the object of attention comes to consciousness more quickly than the objects which we are not attending to.” This effect is also called as a prior entry effect (Spence and Parise, 2010; Shore and Spence, 2005; Vibell et al., 2007). The existence of the prior entry effect is supported by the significant difference of the PSSs (e.g., in an auditory and tactile TOJ task), when participants pay their attention to one stimulus (e.g., auditory stimulus) or another stimulus (e.g., tactile stimulus), respectably. (Shore et al., 2001; Spence et al., 2001; Kitagawa et al., 2005; Zampini, Shore et al., 2005). The shift in the PSS, any change of the JND instead, is claimed to be the important evidence of the prior entry effect in Titchener’s (1908). This effect of attention, especially attended to one of the two stimuli, on the JND is divergent, in which attention improved or did not affect or impaired the temporal resolution (Stelmach and Herdman, 1991; Nicol et al., 2009; Yeshurun and Levy, 2003). Thus, the shift in the PSS, any change of the JND instead, is the performance measure to support the prior entry effect (Spence and Parise, 2010). However, it is still unknown the mechanism of the effect of attention on the PSS shift. The PSS shift might be caused by changes in decision criteria in prior entry (i.e. attention) effect, since attention might be hard to affect the propagation speeds, just like the ‘hard wired’. In addition, in animal experiments, there is still little evidence that neuronal response latencies is affected by attention (Anderson et al., 2014).

Both of endogenous attention and exogenous attention might affect the processing of attended modality. For example, the endogenous attention, as voluntary or goal–driven attention (Macaluso, 2010), modality–specific selective attention (paying attention to a modality) and divided–modality attention (paying attention to multimodalities) are used to investigate how attention affect the temporal integration. That is, participants pay attention to visual, auditory, or to both auditory and visual information. If they pay attention to visual or auditory stimuli, it is modality–specific selective attention. If they pay attention to both auditory and tactile stimuli, it is divided–modality attention.

These selective attention and divided attention differentially modulate multisensory processing. Some following previous researches investigated the effect of the divided attention to different modalities on temporal integration. With electrophysiological experiment, the results indicated that the response times and accuracy was best, when participants pay attention to both of auditory and visual stimuli (Barutchu et al., 2013). Moreover, sensory gating could be regulated, when attention is divided across modalities, rather than modality–specific selective attention (Anderson and Rees, 2011; Talsma et al., 2007). In other words, after stimulus onset, within 100 ms multisensory integration could occur and it seems very earlier (Giard and Peronnet, 1999; Talsma et al., 2007). In some previous studies, when attention is divided to multimodalities, instead of modality–selective attention, superior temporal cortex is reported to be enhanced both in study of ERP (Magnée et al., 2011; Talsma et al., 2007) and in study of fMRI (Degerman et al., 2007).

However, Degerman (2007) reported that behavioral responses to auditory and visual stimuli were more accurate, when attention was paid to the visual or auditory modality than when attention was paid to different modalities. Further, one previous study reported that the reduced neural processing attributed to the improvements of multisensory performance in divided–modality attention condition, compared with modality–selective attention condition in an ERP study (Mishra and Gazzaley, 2012). Especially, it has been found that temporal resolution is impaired in the TOJ task of two visual stimuli when available attentional resources are reduced by an initial visual target stimulus presented 280 ms before the TOJ task (Pérez et al., 2008). This effect would be minimal or absent if the visual target stimulus appeared 1030 ms before the TOJ task. On the other hand, these investigators reported that the subjective simultaneity was not affected, whether the available attentional resources were reduced or not.

These results of selective–modality and divided–modality attentions on temporal integration suggested that there might be differential modulation of multisensory processing in the conditions of selective–modality and divided–modality attentions (Tang et al., 2015).

Additionally, previous studies suggested that the manipulation of spatial and temporal attention could improve the responses in temporal–discrimination tasks (Chica and Christie, 2009; Correa et al., 2006). Moreover, exogenous and endogenous attention could cause PSS shift to the attended stimulus (i.e. participants judged the attended stimulus as the first one), both in unimodal TOJ tasks (visual, auditory and tactile stimuli) (Kanai et al., 2007; Shore et al., 2001; Yates and Nicholls, 2009; McDonald et al., 2005; Vibell et al., 2007; Spence et al., 2001) and in multimodal TOJ tasks (Zampini et al., 2003) by modern experimental psychologists.

1.3 Voluntary movement and temporal integration

Up until now, many studies of simultaneous perception of multimodal sensory information have focused on no movement, in which participants simply receive information from external environment. Whereas, such temporal perceptions of multimodal sensory information often accompany voluntary movements.

1.3.1 Voluntary movement

In daily life, there are many different examples of voluntary movement. For example, when human voluntarily walks, talks and lifts things. Additionally, human has conscious control over the excretory functions, making the voluntary movements as well. Therefore, voluntary movement is important for human.

Predictive processing is crucial for accurate performance during voluntary movement as in figure 1.2 (Bubic et al., 2010), for example, a forward model (Jordan and Rumelhart, 1992; Wolpert and Miall, 1996), is suggested to be used for such predictive processing, which is a prediction of future states of movement (Johnson-Laird, 1983; Wolpert et al., 1995; Grush, 2004). One recent review study suggests that this cerebellar forward model plays a critical role in matching the causes and effects of motor control in voluntary limb movement (Ishikawa et al., 2015).

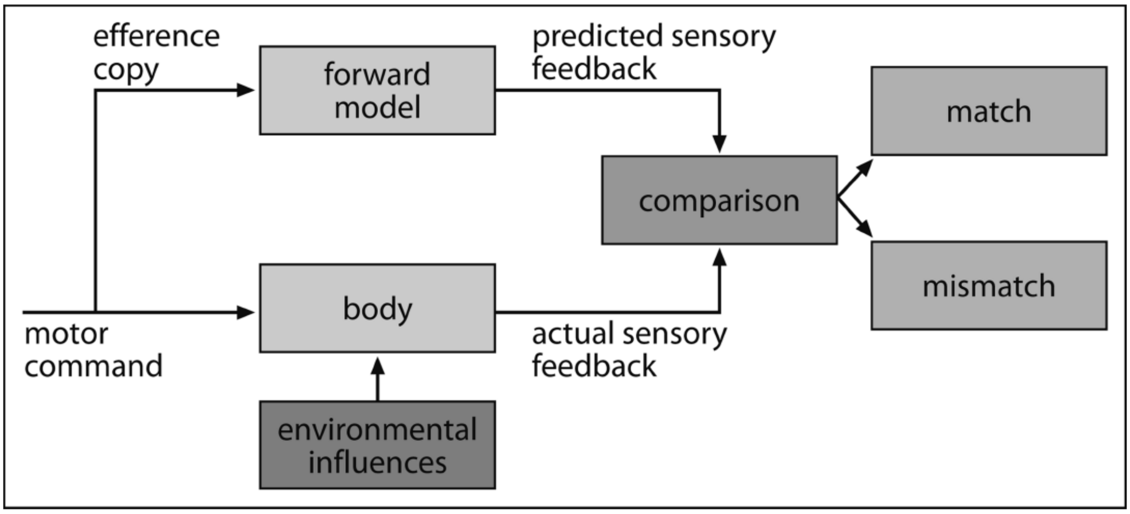

Figure 1.2 Prediction in performance of voluntary movement.

(Bubic et al., 2010)

Specifically, to predict the sensory consequences of voluntary movement, there are two inputs in the forward model. One is efference copy generated in voluntary movement, which is a copy of motor command. Efference copy is suggested to expect sensory performance of movement (von Holst and Mittelstaedt, 1950; Blakemore et al., 1999; Gentsch and Schütz-Bosbach, 2011; Weiss et al., 2011). The other is afferent sensory signal including muscle (proprioceptive) and cutaneous (exteroceptive) afferents. Shortly, a motor command was transformed to predict the sensory performance of a movement in the forward model transforms by using efference copy. Then, the brain compared these predictions of the forthcoming sensory input, then there will be a “match”, formulating exact predictions, or a “mismatch”, causing an incorrect prediction. The comparison between sensory feedback and the efference copy monitors the ongoing movement, which enables more precise movements. This processing of comparing also contributes to recognition of who generates the observed action. Some previous studies suggested that the action is detected as self–generated, only if the efference copy is in a “match” with sensory feedback, (Blakemore et al., 2001, 2002; Jeannerod, 2003). Hence, in the forward model, an output is based on the integration of motor information (i.e., efference copy) and sensory inputs.

For the mechanism of the forward model, one previous study indicates that single granule cell (GC) in the region of the cerebellum integrates the efference copies and somatosensory afferent inputs. The evidence comes from the paramedian lobule in mice.

Huang et al. (2013) reported that individual GCs were the location of the convergence of inputs, which come from the external cuneate nucleus and the basilar pontine nucleus (BPN). Moreover, they reported that BPN neurons accept putative motor inputs coming from M1 to project the paramedian lobule. Then, lots of GCs allow the combinations of these input signals. Therefore, it seems that this morphological organization is proper to integrate these inputs, which come from M1 and somatosensory feedback signals. On the other hand, this processing of integration seems to extend even to Purkinje cells (PCs), since some researchers found that almost all PCs coming from M1 show pre–movement modulation, which are highly reacted to stimuli from somatosensory (Ishikawa et al., 2014; Tomatsu et al., 2015). In other words, these PCs are suggested to be multimodal function, since they are responsive to both the information of motor and sensory. In addition, previous studies on human suggested that the cerebellum may be a location of the forward model (Ito, 1970; Wolpert and Miall, 1996; Wolpert et al., 1998; Jeannerod, 2001; Wolpert and Flanagan, 2001; Wolpert et al., 2003; Schubotz, 2007; Miall et al., 2007; Nowak et al., 2007; Izawa et al., 2012).

1.3.1.1 Efference copy

As abovementioned, the efference copy is a copy of motor command (von Holst and Mittelstaedt, 1950; Blakemore et al., 1999; Gentsch and Schütz-Bosbach, 2011; Weiss et al., 2011) and could generate the prediction to estimate the sensory performances of the motor command. While, after the real sensory performances of the motor command and the efference copy are compared, the central nervous system (CNS) is informed about the level of prediction related to the action matching its real action. The efference copy could also be used for the preparation of the opposite sensory modalities (visual, proprioception/somatosensory, and auditory) (Haarmeier et al., 1997; Ford and Mathalon, 2005) for reafferent feedback (as in figure 1.3) (Pynn and DeSouza, 2013). Therefore, efference copies are suggested to play some roles in some modulatory functions on the basis of the requirements of every sensory network.

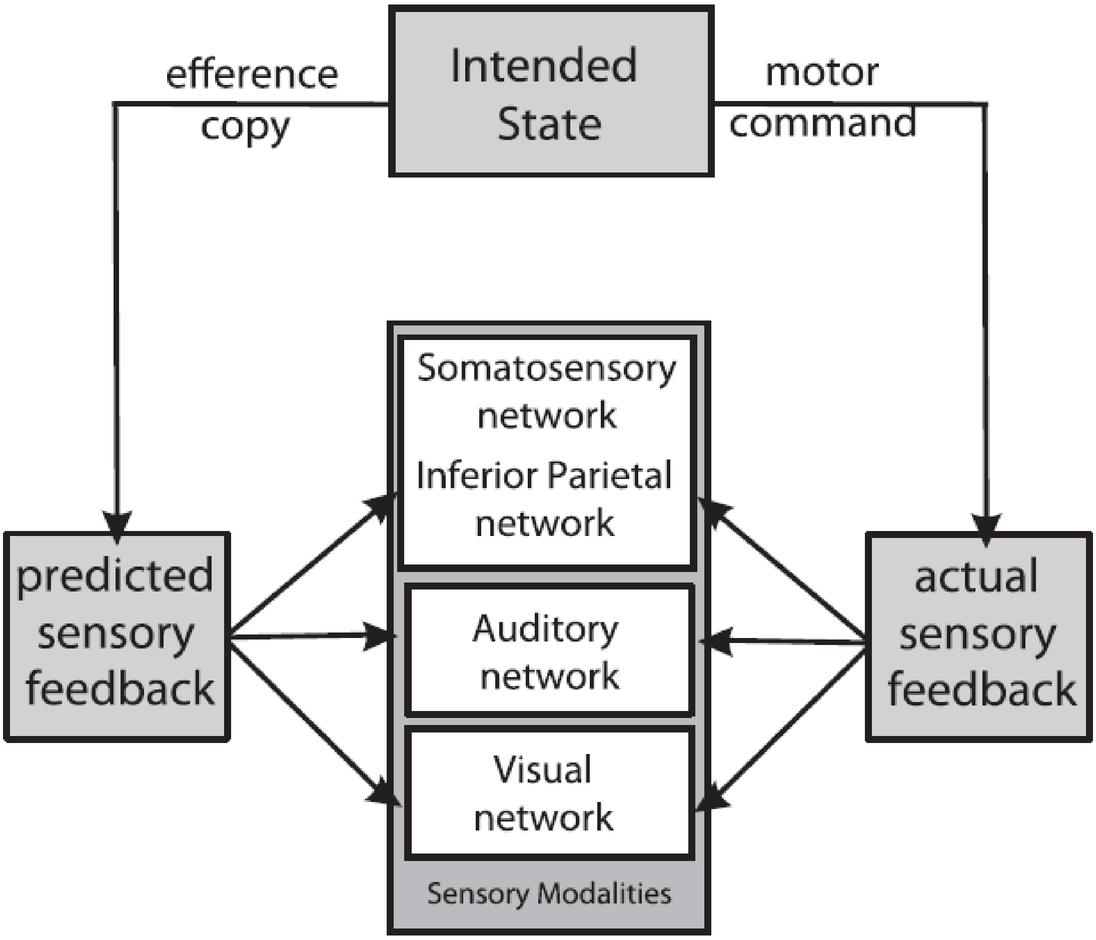

Figure 1.3 The efference copy mechanism in some sensory modalities.

(Pynn and DeSouza, 2013)

For example, in the somatosensory system, efference copy is suggested to be the reason that we can't tickle ourselves (Blakemore et al., 2000). It may be the efference copy to message the somatosensory network that tactile stimulation is produced by the person himself (Blakemore et al., 2002). Here, there were some indirect evidence from human neuroimaging studies that efference copies affected the processing of afferent somatosensory information (Blakemore et al., 1998). This is also because efference copy could modulate some properties of the expected stimuli, for instance, the temporal aspect or spatial aspect, and such manipulations lead to an increasing perception of tickle sensation. These findings support the possible role of efference copy in the elongated somatosensory cortex response (Blakemore et al., 1999). Moreover, some previous studies reported the correlation between efference copy and primary and secondary somatosensory cortex activity (Blakemore et al., 1999) and including efference copy's role, which process predicted versus unpredicted somatosensory stimuli (Gao et al., 1996).

Efference copy is also suggested to be important for agency (Blakemore et al., 1999). Agency usually occurs, when an executed action is realized as being generated by the body parts of oneself. In other words, a sense of agency occurs only during voluntary movement. This implies that it is internal motor signals (i.e., motor commands) to play an important role in generating the agency. Whereas the comparator model was suggested to explain agency (Blakemore et al., 1999). Additionally, Blakemore et al. (1998) suggested that, movement should be defined as voluntary movement, when an efference copy can cancel the sensory information from the moving arm.

Efference copy might affect kinesthetic sensations. For example, in voluntary movements, it is the changed or diminished tactile and kinesthetic sensations to give a reflection on how efference copies affect the ascending afferent volleys or the state estimation (Azañon and Malenka, 1982; Bays et al., 2005; Blakemore et al., 1998; Chapman et al., 1987; Shergill et al., 2003; Voss et al., 2006).

Additionally, efference copy is also called by the term “corollary discharge (CD)” by some researchers (Sperry, 1950; Crapse and Sommer, 2008; Sommer and Wurtz, 2002), and when information from any step of motor output are discussed, the CD is suggested to influence some parts from the early steps to higher order sensory processing.

1.3.1.2 Proprioceptive information

Our CNS uses the information of visual and proprioception to evaluate the locations of our body parts, which make us to move and complete our daily actions. Actually, humans can evaluate the location of our body part without error in the absence of vision by using proprioception. Proprioception is the sense of localization of the articulated body parts, when the person is in a movement, a posture, and a space, and plays a crucial role in daily life. It is a collective term referring to non–visual input to tell us where our body is in space. Proprioception is termed as the “muscular sense” by Sherrington (see Matthews, 1982), since the proprioceptors of skeletal striated muscles (or muscle spindles), tendons (or Golgi tendon organ), and the fibrous capsules in joints (Gandevia, 1996; Matthews, 1982; Proske, 2006) supply such information. It needs to be distinguished from exteroception, which is used for the perception of the external world, and interoception, and the perception of pain, hunger, and the movement. Proprioception is necessary for the correct generation and performance of movement (Todorov and Jordan, 2002; Yousif et al., 2015).

On the other hand, Paillard and Brouchon (1968) suggested that proprioception was the voluntary movement and the self–maintained posture at movement termination which is used to accurately localize our body part. Furthermore, one previous study reported the similar proprioceptive localization accuracy was found under active and passive conditions, because there was no difference in localizing the hand in the two conditions (Jones et al., 2010). Capaday et al. (2013) also reported that there is no difference in localization accuracy, or variability, between active and passive conditions. In addition, for proprioceptive reaching, Haggard et al. (2000) found that localizing the right hand were much better than localizing the left hand, in which left hemisphere (i.e. dominating the dominant hand) for proprioceptive localization might be better than that of right hemisphere at estimating hand position.

1.3.2 Voluntary movement and temporal integration

We perceive the world using multimodal sensory information from the external environment. For instance, in watching a basketball match we usually see that the ball hits the ground and bounces and simultaneously hear the sound of the ball hitting the ground as the player is dribbling. Although light and sound originating from this event propagate through the air at different speeds, we perceive the visual and auditory information as a single event. That perception of visual and auditory information is perceived as simultaneous is surprising, given the lags in arrival and processing time of multimodal sensory information in brain. This raises the question about how simultaneous perception of multimodal sensory information is integrated in the brain to own a coherent representation of the world. Up until now, many studies of simultaneous perception of multimodal sensory information have focused on no movement, in which participants simply receive information from external environment.

Such temporal perceptions of multimodal sensory information often accompany voluntary movements. It is necessary to study simultaneous perception of multimodal sensory information during voluntary movement, instead of no movement only.

Mach and Uexkuell proposed that motor activity affects sensory processing in a direct way early in the 20^{th} century (Bridgeman, 2007). Recently, previous studies investigated the temporal order of voluntary movement and sensory information from visual, auditory, and tactile channels (Stetson et al., 2006; Winter et al., 2008). While, one previous research studied how voluntary movement and passive movement affect the temporal order of two cutaneous stimuli (Wenke and Haggard, 2009). On the other hand, there are also some previous studies, which investigated whether voluntary movement affect temporal integration of multimodal sensory information or not by using TOJ task. That is, voluntary movements affected the PSSs and/or JNDs of visual and tactile stimuli (Vogels, 2004; Shi et al., 2008) and of auditory and tactile stimuli (Kitagawa et al., 2009; Frissen et al., 2012; Nishi et al., 2014) in SJ and TOJ tasks compared with conditions without voluntary movement. However, those investigations of the effect of voluntary movements on the PSSs and JNDs in the auditory and tactile TOJ tasks reported divergent results, when the voluntary movement and tactile stimulus were designed to the same location. Kitagawa et al. (2009) found that voluntary movement did not affect the PSS, whereas Nishi et al. (2014) found that voluntary movement caused the PSS to be associated with a preceding auditory stimulus. In addition, Frissen et al. (2012) found that involuntary movement caused the PSS to be associated with a preceding tactile stimulus. On the other hand, although Frissen et al. (2012) observed no effect of voluntary movement on the JND, Kitagawa et al. (2009) and Nishi et al. (2014) reported that voluntary movement decreased the JND.

1.4 Remaining questions, purpose and overview of this dissertation

1.4.1 Remaining questions and purpose of this study

Therefore, it remains unknown that whether voluntary movement affects the simultaneous perception and the relating mechanism, because the results of these experiments are not completely consistent. Moreover, how far will this effect extend, if this effect exists? In other words, does voluntary movement affect simultaneous perception of auditory and tactile stimuli presented to a non–moving body part?

The main purpose of this dissertation was to investigate these questions, which were the effect of voluntary movement on simultaneity perception, and the effect of voluntary movement on simultaneous perception, when tactile stimulus was presented to a non–moving body part.

1.4.2 Overview of this dissertation

This dissertation consisted of six chapters. As just mentioned, the background was showed in chapter 1.

In chapter 2, the contradictory effects of voluntary movements on the temporal integration of auditory and tactile stimuli in previous studies were summarized. These differing results may have been caused by unexpected effects associated with the different experimental methods used in the previous studies, such as the predictability of the stimulus and the amount of movement. For instance, in the studies of Kitagawa et al. (2009) and Nishi et al. (2014), participants were able to predict the occurrence of the stimulus, which led to the improvement of the temporal resolution, because a predictable stimulus can directly decrease the JND (Petrini et al., 2009; Yokoyama et al., 2009; Vroomen and Stekelenburg, 2010). However, in Frissen et al.'s study (2012), the lack of short–range SOAs or large–scale movement might have concealed the difference between voluntary movement and no movement conditions.

In chapter 3, the purpose was to examine whether voluntary movement affect simultaneity perception, because previous studies showed divergent results on the effect of voluntary movement on simultaneous perception of multimodal sensory information. In this experiment, participants were asked to judge the temporal order of auditory and tactile stimuli presented to right index finger, where was also the moving body part. To investigate the possible mechanism, three conditions were designed, in which passive movement was used to separate the potential effect of proprioception in the voluntary movement of right index finger. Then the PSSs and JNDs were analyzed in the three conditions. The results showed that the PSS during voluntary movement shifted from the tactile stimulus being first during passive movement or no movement to the auditory stimulus being first. Whereas there was no significant difference of JNDs in the three conditions. The results of experiment in chapter 3 suggested that voluntary movement can occasionally affect simultaneous perception. This means, that voluntary movements affected simultaneous perception of auditory and tactile stimuli.

However, little is known about spatial limits of the effect of voluntary movements on simultaneous perception, especially when tactile stimulus is presented to a non–moving body part. Hence, in chapter 4, the effect of voluntary movement on the simultaneous perception of auditory and tactile stimuli presented to a non–moving body part was investigated by utilizing a temporal order judgment task. Three conditions including voluntary movement, passive movement and no movement were used in this experiment. Specifically, in voluntary movement condition, participants were asked to voluntarily move their right index finger and judge the temporal order of auditory and tactile stimuli presented to their non–moving left index finger. The results showed that, in voluntary movement condition, the auditory stimulus needed to be presented earlier than tactile stimulus to be perceived as simultaneity, and the time interval between the two stimuli was significantly larger than those in passive movement and no movement conditions. And, the temporal resolutions were obviously impaired in voluntary movement and passive movement conditions compared with that in no movement condition. Further, the temporal resolutions were significantly impaired in voluntary movement condition compared with in passive movement condition. These results indicate that voluntary movement affected the simultaneous perception of auditory and tactile stimuli, even when tactile stimulus was presented to the non–moving body part.

Finally, the findings obtained throughout this dissertation and relating mechanism were discussed and summarized in chapter 5, then concluded in chapter 6.

Chapter 2 Contradictory effects of voluntary movement on simultaneous perception in previous studies

Until now, there are contradictory effects of voluntary movements on the simultaneous perception (e.g., the PSSs and/or JNDs) of auditory and tactile stimuli (Kitagawa et al., 2009; Frissen et al., 2012; Nishi et al., 2014) in TOJ tasks compared with conditions without voluntary movement (see also in Table 2.1). Kitagawa et al. (2009) found that voluntary movement did not affect the PSS, whereas Nishi et al. (2014) found that voluntary movement caused the PSS to be associated with a preceding auditory stimulus. In addition, Frissen et al. (2012) found that involuntary movement caused the PSS to be associated with a preceding tactile stimulus. On the other hand, although Frissen et al. (2012) observed no effect of voluntary movement on the JND, Kitagawa et al. (2009) and Nishi et al. (2014) reported that voluntary movement decreased the JND.

Table 2.1 The effect of voluntary movement on temporal integration of multimodal sensory information by TOJ task (Hao et al., 2015)

Study	**Conditions of movement**	**Stimulus pair**	**Moving body part**	**Effect on PSS**	**Effect on JND**
Shi et al. (2008)	Vol No	V and T	Right index finger	V Shifted to near 0 ms	L (Vol. movement)
Kitagawa et al. (2009)	Vol Pa Pr No	A and T	Right index finger	N.S.	L (Vol. movement)

Frissen et al. (2012)	Vol Pa No	A and T	Forearm, hand, and finger	A shifted to T (Inv. movement)	N.S.
Nishi et al. (2014)	Vol Pa No	A and T	Right index finger	T shifted to A (Vol. movement)	L (Vol. movement)

“Vol”, “Pa”, “Pr”, and “No” indicate the voluntary, passive, predictable, and no movement conditions. “A”, “T” and “V” mean auditory stimulus, tactile stimulus and visual stimulus. For the effect on PSS, “N.S.” means no significant difference. “A shifted to T” means the PSS in the passive movement condition shifted from the auditory stimulus first as in the no movement condition to the tactile stimulus first, where “A” and “T” indicate the auditory and tactile stimuli. “T shifted to A” means the PSS in the voluntary movement condition shifted from the tactile stimulus first as in the no movement condition to the auditory stimulus first. For the Effect on JND, “L” and “H” indicate that the temporal resolution was improved (lower JND) or impaired (higher JND) by voluntary movement.

Shi and his colleagues (2008) designed four conditions to investigate how voluntary movement (i.e., active motor control) and additional visual feedback affect the temporal integration of visual and tactile stimuli. They asked participants to voluntarily move their right index finger and judge the temporal order of visual and tactile stimuli presented on their moving finger with/without visual feedback. Then, they also required participants to keep their right index finger stationary and judge the order of the two stimuli with/without visual feedback. As the results, they found that the PSS was significantly shifted from 21 ms, in which visual stimuli were presented first, to 4 ms, when participants voluntarily moved their right index finger with visual feedback. At the same time, the JND was significantly decreased by voluntary movement, even without visual feedback. Thus, for the PSS shifting towards zero, they suggested that it might be the on–line visual feedback to let visuo–motor system rapidly to predict forthcoming events, in which fine control of the movement is performed by the closed–loop visuo–motor processes (Keele, 1986). Whereas, for the improvement of temporal resolution by voluntary movement might be caused by motor command, which could be used by the central nervous system (CNS). It is the motor command combining with internal models of both hand and visual feedback, to predict the resulting load force and the position of the object by CNS (Wolpert and Ghahramani, 2000; Wolpert et al., 1995).

To investigate whether voluntary movement affect temporal perception (i.e., the PSS and JND) or not, Kitagawa and his colleagues (2009) conducted the TOJ task under four conditions: voluntary, passive, predictable, and no movement. In the passive movement condition, participants' right index fingers were moved by device. From the results, they reported no significant difference in the PSSs among all of the four conditions. Whereas the authors concluded that voluntary movement decreased the participants' JND, because there was no improvement in the temporal resolution of the passive, predictable, and no movement conditions. Thus they suggested that predictability of timing and kinesthetic cues cannot explain the improvement of temporal resolution in voluntary movement condition, and then they indicated the efference copy of the motor command induced the improvement.

Frissen and his colleagues (2012) used TOJ task to investigate the effect of voluntary movements on temporal perception of auditory and tactile stimuli in their experiment 1. They designed three conditions including voluntary movement, passive movement and no movement to separate the contributions of the cutaneous, proprioceptive, and motor command information. Their results showed that, compared with passive movement and no movement, voluntary movement did not affect the PSS and JND. Oppositely, they reported that passive movement significantly affected the PSS. Then, they suggested that the no significant difference of JND might be caused by processing noise of comparing the different modal sensory signals, even though there is efference copy in voluntary movement, which can be used to improve the processing of proprioceptive signals (Gritsenko et al., 2007; Winter et al., 2005).

With the same aim of studying the effect of voluntary movement on the temporal integration of auditory and tactile stimuli, as the aim of Frissen et al.'s study (2012), Nishi and his colleagues (2014) conducted TOJ task in voluntary movement, passive movement and no movement conditions. Inconsistent with the results of Frissen et al.'s study, Nishi and his colleagues reported that voluntary movement, instead passive movement and no movement, shifted the PSS from tactile stimulus first to auditory stimulus first, and improved the temporal resolution (i.e. JND). They suggested that the efference copy in voluntary movement might speed up the processing of tactile stimulus, rather than auditory stimulus, or the efference copy might affect the TOJ task itself, and then shifted the PSS. It might be the predictability of efference copy to improve the temporal resolution.

Although these previous studies reported that voluntary movements affect the PSSs and/or JNDs between visual and tactile stimuli (Shi et al., 2008) and between auditory and tactile stimuli (Kitagawa et al., 2009; Frissen et al., 2012; Nishi et al., 2014) in TOJ tasks compared with conditions without voluntary movement. However, those investigations of the effect of voluntary movements on the PSSs and JNDs in the auditory and tactile TOJ tasks reported divergent results. Shi et al. (2008) reported the effect of voluntary movement on temporal perception (i.e., the PSS and the JND). Kitagawa et al. (2009) found that voluntary movement did not affect the PSS, but improved the temporal resolution (i.e. JND). Whereas Nishi et al. (2014) found that voluntary movement caused the PSS to be associated with a preceding auditory stimulus and improved the temporal resolution. In addition, Frissen et al. (2012) found that passive movement caused the PSS to be associated with a preceding tactile stimulus and observed no effect of voluntary movement on the JND.

Hence, the purpose of chapter 3's experiment was to examine whether voluntary movement affect simultaneity perception, when tactile stimulus was presented to right index finger, which was also the moving body part. The purpose of chapter 4's experiment was to examine whether voluntary movement affect simultaneity perception, when tactile stimulus was presented to the non–moving left index finger, while right index finger was voluntarily moved in voluntary movement condition.

Chapter 3 Voluntary movement affects simultaneous perception of auditory and tactile stimuli

3.1 Introduction

Although voluntary movement has been found to compress or dilate subjective time under certain circumstances (Yarrow et al., 2001; Morrone et al., 2005), current knowledge about the effect of voluntary movement on auditory and tactile simultaneous perception is still unsettled. In particular, it is unclear whether voluntary movement affects the simultaneous perception of auditory and tactile stimuli.

Some previous studies have shown that voluntary movements affect the PSSs and/or JNDs between visual and tactile stimuli (Shi et al., 2008) and between auditory and tactile stimuli (Kitagawa et al., 2009; Frissen et al., 2012; Nishi et al., 2014) in TOJ task compared with conditions without voluntary movement. To investigate the effect of voluntary movement on simultaneous perception, the effect of proprioceptive sensation attending the movement must be separated from that of voluntary movement. If PSS and/or JND changes are observed even when the proprioceptive information effect is excluded, we can say that the voluntary movement has some influence on simultaneous perception. Therefore, voluntary movement, passive movement, and no movement conditions were used in previous studies (Kitagawa et al., 2009; Frissen et al., 2012; Nishi et al., 2014). Because a device moved the participants' body parts in the passive movement condition in the previous studies, the passive movement was attended by proprioceptive information only. Therefore, the comparison between the passive movement and no movement conditions showed the effect of the proprioceptive information, and the comparison between the voluntary movement and passive movement conditions revealed the effect of voluntary movement exclusive of proprioceptive information.

However, those investigations of the effect of voluntary movements on the PSSs and JNDs in the auditory and tactile TOJ tasks reported contradictory results as also shown in Table 2.1. Kitagawa et al. (2009) found that voluntary movement did not affect the PSS, whereas Nishi et al. (2014) found that voluntary movement caused the PSS to be associated with a preceding auditory stimulus. In addition, Frissen et al. (2012) found that passive movement caused the PSS to be associated with a preceding tactile stimulus. On the other hand, although Frissen et al. (2012) observed no effect of voluntary movement on the JND, Kitagawa et al. (2009) and Nishi et al. (2014) reported that voluntary movement improved the temporal resolution. These differing results may have been caused by unexpected effects associated with the different experimental methods used in the previous studies, such as the predictability of the stimulus and the amount of movement as also shown in Table 2.1, Predictability of the stimulus and Moving body part rows. For instance, a predictable stimulus could directly improve the JND (Petrini et al., 2009; Yokoyama et al., 2009; Vroomen and Stekelenburg, 2010). The spatial information in large–scale movement could obscure the effect of passive movement on the PSS.

Kitagawa et al. (2009) conducted the TOJ task under four conditions: voluntary, passive, predictable, and no movement. The authors concluded that voluntary movement improved the participants' temporal resolution, because there was no improvement in the JNDs of the passive, predictable, and no movement conditions. However, in Kitagawa et al.'s (2009) procedure, tactile stimulation was generated as a result of voluntary finger movement. This effect induced the participants to predict the onset of the tactile stimulus, and improved the temporal resolution in the voluntary movement condition. Nishi et al. (2014) conducted the TOJ task under three conditions: voluntary, passive, and no movement. The authors used a device that presented tactile stimulus during voluntary finger movement to solve the problem in Kitagawa et al.'s (2009) procedure. Nevertheless, this prediction effect on the improvement of temporal resolution associated with voluntary movement also occurred in Nishi et al.'s (2014) study, because the tactile stimulus was always presented 500 ms after the finger movement. It was easier to predict the stimulus onset in the voluntary movement condition.

This predictability of stimulus onset did not appear in the Frissen et al.'s (2012) study. The authors used a device that presented the tactile stimulus for the TOJ task at random interval in the voluntary movement condition, to prevent the stimulus predictability. As a result, Frissen et al. (2012) reported that voluntary movement did not affect the JND. This result suggests that the predictability of the stimulus decreased the JNDs both in the Kitagawa et al.'s (2009) and Nishi et al.'s (2014) studies. On the other hand, Frissen et al. (2012) reported that the tactile stimulus occurring first was perceived as the PSS in the passive movement condition. However, the spatial information in large–scale movement could have obscured the effect of movement on the PSS in Frissen et al.'s (2012) study. The large–scale movement could lead to a tactile version of a flash–lag effect (FLE) (Kitagawa et al., 2005). In this phenomenon, observers perceived a flash lag behind a spatially aligned moving stimulus (Nijhawan, 2002).

Therefore, the aim of the present study was to investigate whether voluntary movement affects the simultaneous perception of auditory and tactile stimuli, that is, independent of the effects of stimulus predictability and the spatial information inherent in large–scale movement (which were thought to be the causes of the divergent results in previous studies). There is one hypothesis that the PSS would shift from the tactile stimulus first in the passive movement or no movement condition to the auditory stimulus first in the voluntary movement condition. Thus, the interval between the start of movement and the first stimulus was randomized to prevent the participants from predicting the stimulus onset. In addition, small–scale movement was used to minimize the effect of spatial information on perceived simultaneity.

3.2 Method

3.2.1 Participants

Eighteen participants (3 females and 15 males, mean age 23 years, age range 21–28 years) completed the experiment. All of the participants were right–handed, with normal auditory thresholds and senses of touch, and they did not exhibit any difficulty moving their right index fingers. Informed consent was obtained in writing from all the participants prior to their participation in the experiment. The participants were paid for their participation, and the experiment was approved by the ethics committee of the Tokyo Institute of Technology.

3.2.2 Apparatus and stimuli

The auditory stimulus was a sinusoidal wave sound (2000 Hz, 50 dB, 10 ms) presented in both ears simultaneously via earphones (Radius HP-RHF41; Machida, Tokyo, Japan). The tactile stimulus was an impulse force (5N, 10 ms, rectangular pulse) provided by a

PHANTOM Desktop haptic device (SensAble Technologies, Woburn, MA, USA) and orthogonal to the finger movement. The 10 ms duration for auditory and tactile stimuli was selected to avoid a problem of the procedure in the Frissen et al.'s (2012) study. In that study, the duration of the auditory stimulus (100 ms) was considerably longer than that of the tactile stimulus (10 ms). Stimulus duration has been found to create an attractor effect on the PSS in audiovisual TOJ task (Boenke et al., 2009). In other words, with increasing stimulus duration, positive PSSs shift towards negative values (because the visual stimulus must precede the auditory stimulus for simultaneous perception), and negative PSSs shift towards positive values. Hence, the same duration was used for the two stimuli. The timing of the two presentations and the movement of the device were controlled to 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, Palo Alto, CA, USA), and were developed with the Open Haptics software development toolkit (SensAble Technologies) on the Microsoft Visual C++ 2008 platform (Microsoft, Redmond, WA, USA).

3.2.3 Task and conditions

For the TOJ task, auditory–tactile stimulus pairs were presented to participants with varying SOAs (intervals between the within–pair onsets of the auditory and tactile stimuli), and the participants judged the temporal order of the two stimuli. The SOAs were ± 240, ± 120, ± 60, ± 30, and 0 ms (where the positive values indicate that the auditory stimulus was presented before the tactile stimulus, and vice versa). These SOAs were chose to improve the procedures in the Frissen et al.'s (2012) study. In that study, they used a 75 ms increment between their SOAs (300, 225, 150, 75, and 0 ms), which is a little larger than the increments used in previous auditory–tactile integration studies (Zampini, Guest et al., 2005; Fujisaki and Nishida, 2009). Thus, a smaller increment was used for SOAs.

There were three conditions in this experiment: voluntary, passive, and no movement. The passive movement trajectory was reproduced from voluntary movement data collected in the preliminary experiments. The mean rate of movement of the participants' fingers was 81.08 mm/s (standard deviation (SD) = 7.33) in the voluntary movement condition and approximately 78.23 mm/s (SD = 1.44) in the passive movement condition (as guided by the haptic device). The participants were seated in a darkened, sound-attenuated room in front of the stimulation systems, with the palmar side of their right index fingers held on the haptic device. They also wore sound–insulating earmuffs over their earphones and an eye mask to eliminate the confounding effect of visual stimuli during the experiment (Figure 3.1). In each condition, the participants were asked to indicate the temporal order of the auditory and tactile stimuli by using the Z and X keys on a keyboard. The Z indicated that the auditory stimulus occurred first and the X indicated that the tactile stimulus occurred first.

Figure 3.1 Experimental environment. (Hao et al., 2015)

3.2.4 Procedure

3.2.4.1 Voluntary movement condition

For each trial (Figure 3.2(A)), the participants voluntarily and naturally began to move their right index fingers from right to left at their own pace. As they did, a cue sound (distinct from the target auditory stimulus) indicated that the TOJ task was forthcoming. The first stimulus (either tactile or auditory) was then presented with a random delay of 600–700 ms after the cue sound onset. The second stimulus (auditory or tactile, whichever was not presented first) followed the first stimulus, offset by one of the nine SOAs previously mentioned. The participants then indicated which stimulus occurred first using a two–alternative forced–choice test (as described above). If the participants did not move at a speed of 50–110 mm/s, they were given one more trial, randomly chosen from the remaining trials.

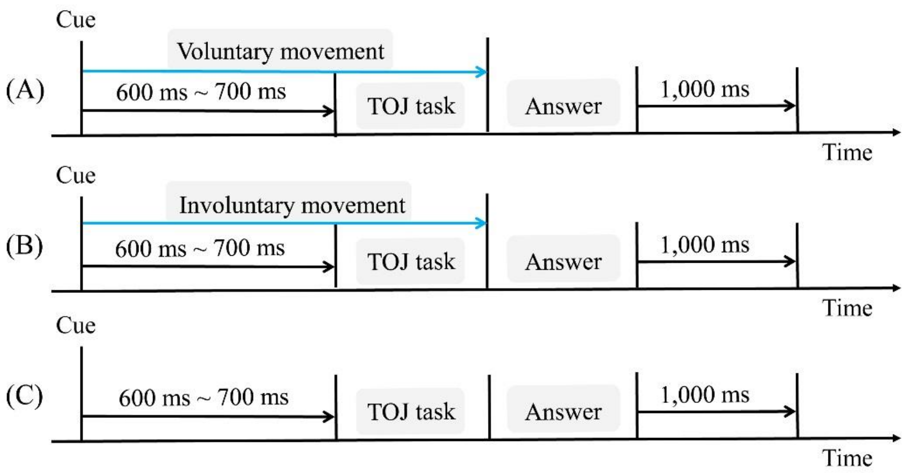

Figure 3.2 Schematic flow chart for one trial in each of the three conditions.

(A) Voluntary movement condition, in which participants voluntarily started to move their right index fingers; (B) Passive movement condition, in which the haptic device moved the participants' right index fingers; (C) No movement condition. The interval between the cue and the TOJ task was randomly set from 600 to 700 ms. The interval between trials was 1000 ms. (Hao et al., 2015)

3.2.4.2 Passive movement condition

Similar to the voluntary movement condition, the haptic device randomly started to move the participants' right index fingers from right to left for 500 to 1000 ms, to reproduce the variance in the onsets of voluntary movements in the preliminary experiments. The procedure for evaluating the temporal order of the two stimuli and the SOA values were the same as in the voluntary movement condition. A speed of 76 mm/s for the finger movement was set for each trial (Figure 3.2(B)), because this was considered to be a comfortable speed and representative of normal surface exploration.

3.2.4.3 No movement condition

The participants in the no movement condition remained stationary throughout each trial, with the palmar side of their right index fingers held on the haptic device (Figure 3.2(C)). The first stimulus (either tactile or auditory) was presented with a random delay (600–700 ms) after the cue sound onset. The presentation of the second stimulus and the procedure for evaluating the temporal order of the two stimuli were the same as in the voluntary and passive movement conditions. The 600–700 ms interval between the cue sound onset and the first stimulus was used to improve the procedure used in Nishi et al.'s study (2014). In that study, the interval between the cue sound onset and the first stimulus was 1800–3300 ms in the no movement condition, whereas it was 500 ms between the cue sound onset (or the start of movement) and the tactile stimulus for all trials in the voluntary and passive movement conditions. This may have affected the comparisons among the three conditions, because the different cue–target intervals activate distinct brain areas (Coull et al., 2000), affect temporal discrimination, and influence early perceptual processing (Sanders, et al., 2008).

Each participant completed three blocks of trials in each of the conditions in the present experiment. The conditions were presented in a random order, and the participants were blind to the order of the conditions. Each block consisted of 45 trials, comprising five trials for each SOA, randomly selected from the following values: ± 240, ± 120, ± 60, ± 30, and 0 ms. Thus, each participant completed 405 trials. The interval between trials was 1000 ms in each condition, and white noise was played in the background to effectively mask any sounds made by the haptic device. It took approximately 5 minutes for the participants to complete one block of trials. They were given several minutes of rest between blocks, according to their preferences. The order of the conditions was counterbalanced, and the entire procedure took approximately 2 hours. To accustom the participants in the voluntary movement condition to the appropriate finger speeds, they each completed a practice run of ten trials in which only the tactile stimulus was presented. To eliminate this compound effect (e.g., sensitization of the tactile channel), the participants were given 2–3 minutes of rest before each block of trials in the voluntary movement condition. Additionally, the participants were asked to pay constant attention to the tactile stimulus to control for the prior entry effect (Shore et al., 2001; Spence et al., 2001; Kitagawa et al., 2005; Zampini, Shore et al., 2005), which facilitates the processing of an attended stimulus relative to an unattended stimulus.

For each trial in the practice sessions, the participants were asked to close their eyes and judge the order of the two stimuli and then open their eyes to see the feedback on the computer screen. With no information about the forthcoming condition, they completed 45, 20, and 20 trials in the voluntary, passive, and no movement conditions, respectively. The orders of the trials were counterbalanced, and the SOA was randomly chosen from ± 240, ± 120, and ± 60 ms. In addition, the short interval (600–700 ms) between the onset of the movement and the TOJ task may have produced a strong interaction between the tactile signals elicited by the onset of the movement and by the tactile stimulus in the TOJ task. Thus, there appears to be a risk that the results of this study may be unclear. In fact, movement onset has been found to impair the temporal order threshold immediately following operant actions, but then reverts in the later action–effect interval (450–850 ms) (Wenke and Haggard, 2009). Furthermore, the potential strong interaction did not appear to affect the tactile TOJ tasks in studies by Hermosillo et al. (2011) or Nishikawa et al. (2015), in which they used short intervals between the onset of movements and TOJ tasks. Therefore, the possibility of a strong interaction does not threaten the results of this study.

3.2.4.4 Data analysis

The MATLAB Statistics Toolbox (MathWorks, Natick, MA, USA) was used for the statistical regression calculations and graphic representation of the results. First, the proportion of the answers was calculated for each SOA, in which the auditory stimulus was perceived first. Then, logistic regressions were conducted using a generalized linear model with the ratio data for each condition. Psychometric curves were fitted to the distribution of the mean TOJ data for the voluntary, passive, and no movement conditions, as shown in figure 3.3.

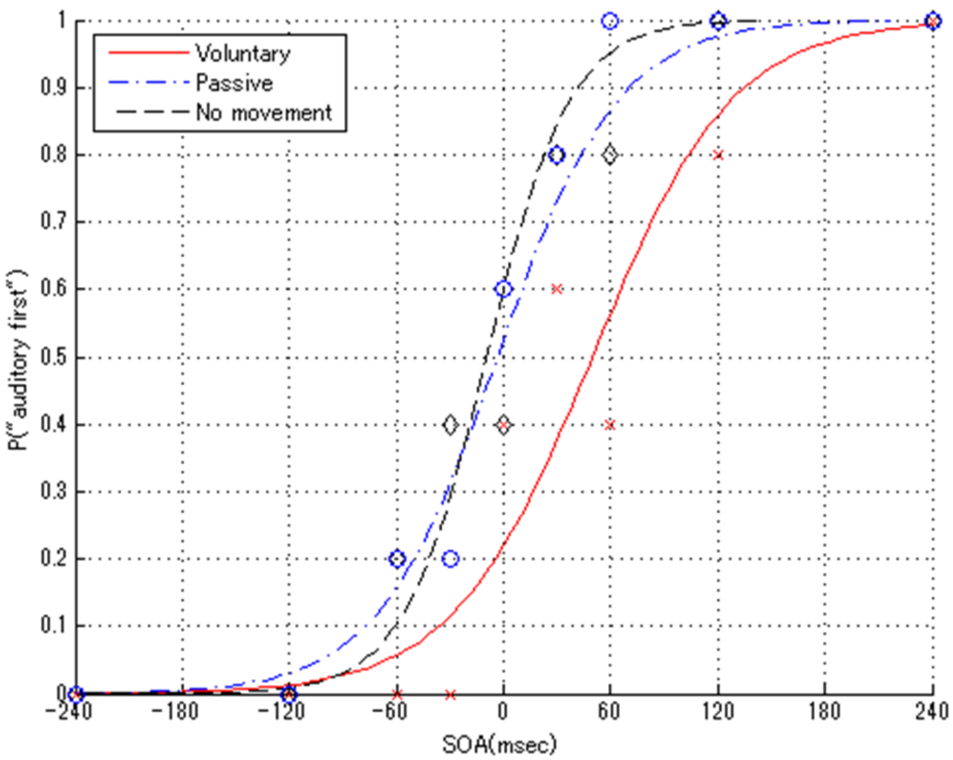

Figure 3.3 Average psychometric functions among all blocks in the voluntary, passive, and no movement conditions for one participant.

Positive SOA values mean that the auditory stimulus was presented before the tactile stimulus, and vice versa. (Hao et al., 2015)

The values of the PSS and JND were calculated for each participant in the regression analysis based on three equations (Finney, 1952):

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

$$\mathrm{PSS} = a \tag{2}$$

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

Here, a represents the estimated PSS, x denotes the SOA, β is related to the JND, and x_p represents the SOA with p as the percent of "auditory first" responses. Then, a statistical analysis of the data was conducted to obtain the mean and standard error values for each condition.

3.3 Results

The PSSs of the voluntary movement, passive movement, and no movement conditions were 14.5 ms (standard error (SE) = 12.5), –4.6 ms (SE = 11.7), and –9.8 ms (SE = 10.3), respectively, as shown in figure 3.4. A one-way repeated measures analysis of variance (ANOVA) with movement condition as a factor showed a significant effect ($F(2, 34) = 12.74$, $P < 0.001$). Subsequently, Bonferroni–Holm paired *t*-tests revealed significant differences between the voluntary and passive movement conditions ($P = 0.001$), and between the voluntary and no movement conditions ($P = 0.008$). There was no significant difference between the passive and no movement conditions ($P = 0.70$), as shown in figure 3.4. The magnitude of the effect size in the PSS (eta squared = 0.43) was large (Cohen, 1988).

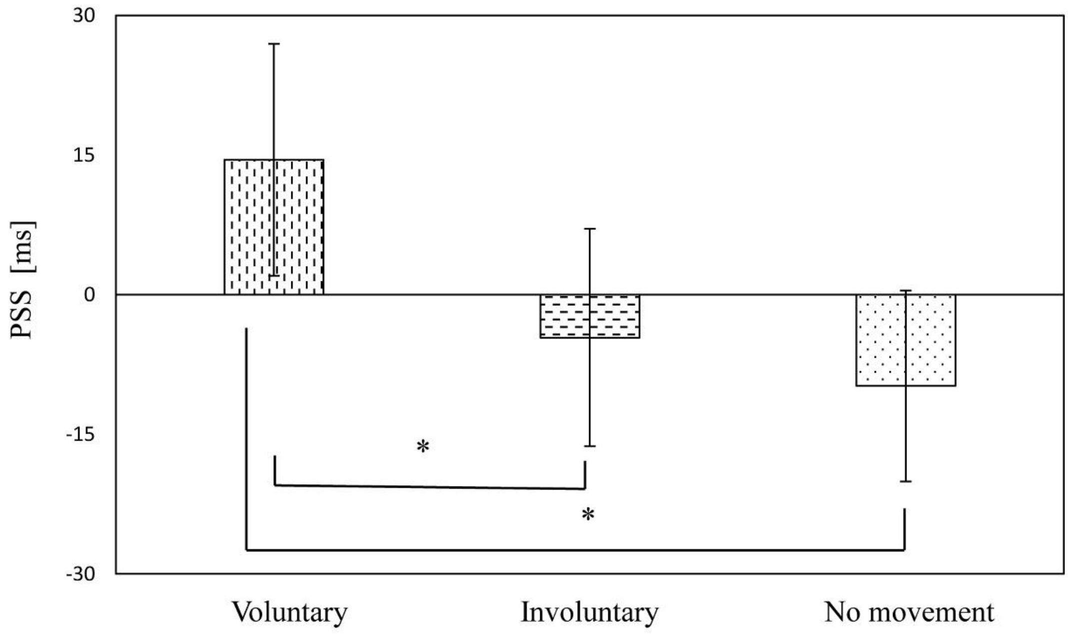

Figure 3.4 PSS results in the voluntary, passive, and no movement conditions. Error bars represent standard errors. * P < 0.01. (Hao et al., 2015)

The JNDs of the voluntary movement, passive movement, and no movement conditions were 55.5 ms (SE = 5.1), 45.4 ms (SE = 4.0), and 46.1 ms (SE = 4.7), respectively. A one–way repeated measures ANOVA with movement condition as a factor was not significant ($F(2, 34) = 2.28$, P = 0.12), with P = 0.26 between the voluntary and passive movement conditions, P = 0.30 between the voluntary and no movement conditions, and P = 1.0 between the passive and no movement conditions, as shown in figure 3.5. The magnitude of the effect size for the JND (eta squared = 0.12) was medium (Cohen, 1988).

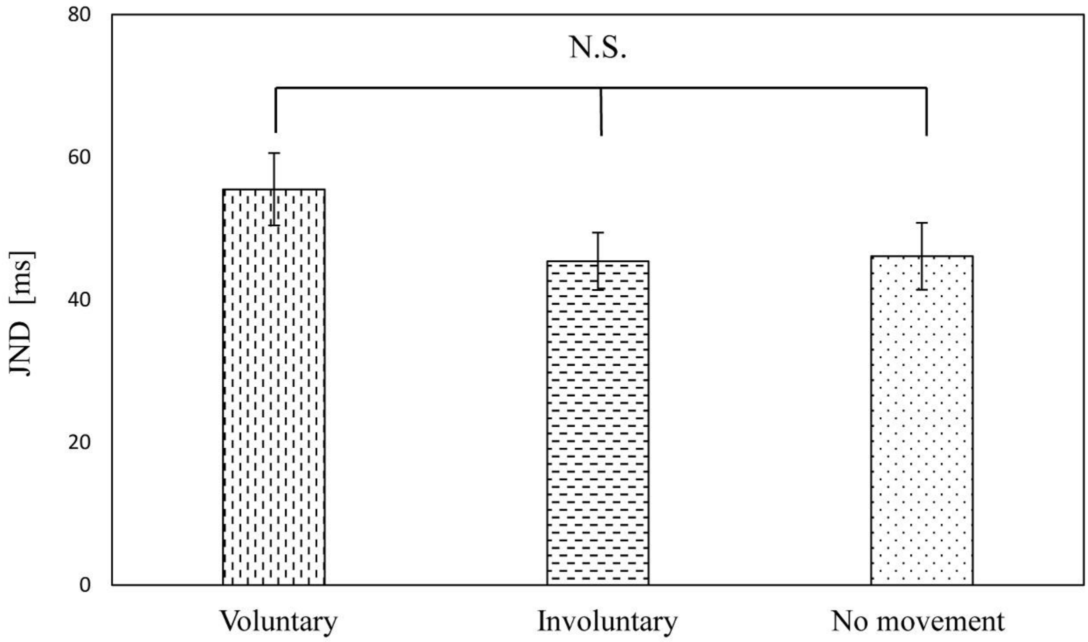

Figure 3.5 JND results in voluntary, passive, and no movement conditions. Error bars represent standard errors. (Hao et al., 2015)

3.4 Discussion

The aim of this study was to investigate the effect of voluntary movement on the simultaneous perception of auditory and tactile stimuli in a TOJ task. The results of this study replicated the effect of voluntary movement on the PSS (Nishi et al., 2014) in previous study. In this study, there was a significant shift in the PSS of the voluntary movement condition compared with the PSSs of the passive movement and no movement conditions. There was no significant difference in the PSS between the passive movement and no movement conditions. There was also no significant difference of JNDs among the three conditions. These differences are discussed in more detail below.

3.4.1 Discussion on PSSs and JNDs

As shown in Fig. 3.4, the PSS was significantly affected in the voluntary movement condition but not in the passive movement condition or no movement condition; there were significant differences in the PSSs between the voluntary movement and passive movement conditions, and between the voluntary movement and no movement conditions. The PSS in voluntary movement condition shifted to the point where auditory stimulus needed to be presented earlier than tactile stimulus, compared with the point where tactile stimulus needed to be presented earlier than auditory stimulus in passive movement and no movement conditions. This means that to be perceived simultaneously, the auditory stimulus needed to be presented before the tactile stimulus for a longer period in the voluntary movement condition than in the passive movement condition or no movement condition, in which to be perceived simultaneously, the tactile stimulus needed to be presented before the auditory stimulus for a longer period. Furthermore, there was not a significant difference between the passive movement and no movement conditions. It seemed that proprioceptive sensation in the movements did not affect the PSS.

As shown in Fig. 3.5, there were no significant difference between voluntary movement and passive movement conditions, between voluntary movement and no movement conditions. That is, voluntary movement, compared with passive movement and no movement, did not affect the JND. Further, there was no significant difference between passive movement and no movement conditions. This means proprioceptive information did not affect the JND.

3.4.2 Possible mechanisms

The significant effect of voluntary movement, but not proprioceptive sensation, on the PSS, instead of JND, of an auditory–tactile TOJ might attribute to the prior entry effect

(Shore et al., 2001; Spence et al., 2001; Kitagawa et al., 2005; Zampini, Shore et al., 2005). In the prior entry effect, there is a significant difference in the PSS between two conditions, in which one of the target stimulus is attended to, as compared to when the other stimulus is attended to instead. Both endogenous and exogenous attention to stimulus may change the PSS. In the present study, endogenous and exogenous attention may have been mixed. First, voluntary movement may enhance endogenous attention to tactile stimulus. The prior entry effect may have occurred and caused the PSS shift in the voluntary movement condition. Second, voluntary movement may decrease auditory exogenous attention, assuming that the auditory cue at the start of the trial increased auditory exogenous attention. The participants were asked to pay attention to a tactile stimulus in the three conditions to control for the prior entry effect (endogenous attention to tactile stimulus). However, voluntary movement may increase endogenous attention to tactile stimulus and decrease the effect of auditory exogenous attention. This attention shift may accelerate the speed of tactile processing and/or reduce the speed of auditory processing in the voluntary movement condition, which would lead to a PSS shift.

There is also another possibility that voluntary movement might accelerate the processing speed of the tactile stimulus, which is efference copy. Efference copy, which is a copy of the motor command, is generated in the presupplementary motor cortex and the premotor cortex (Tanji and Mushiake, 1996). Efference copy is issued to deal with forthcoming voluntary movements and possible multimodal sensory information to form a coherent representation of real–world in voluntary movements (Trinity et al., 2008). Efference copy affects sensory processing in myriad ways including temporal aspects (Feinberg et al., 1999; Ford et al., 2001; Trinity et al., 2008). Evidence from three lines of research—functional magnetic resonance imaging (fMRI) experiments in humans (Cui et al., 2014), the activation of Brodmann Area 2 (BA2) neurons in activity preceding the active movements of monkeys (Weber et al., 2011), and neurons recorded in the somatosensory cortex (SI, BA2 in particular) that only discharge during voluntary movements (London and Miller, 2013)—indicates that the efference copy can significantly influence the primary somatosensory cortices. The somatosensory cortex, which is also modulated by the premotor cortex during voluntary movements without proprioceptive feedback (Christensen et al., 2007), is an area of the brain that processes input from the various systems of the body, and is sensitive to touch. In addition, the efference copy is sent to the posterior parietal cortex (Desmurget et al., 2009), where tactile events are localized in external space (Azañon et al., 2010). Therefore, the efference copy of a voluntary movement may affect the processing speed of the tactile stimulus in the TOJ task used in this study.

3.4.3 Conclusion

The purpose of this study was to investigate the effect of voluntary movement on auditory and tactile simultaneous perception and the possible mechanism. Auditory and tactile TOJ task was conducted in voluntary movement, passive movement, and no movement conditions. Compared with passive movement and no movement, voluntary movement affected the PSS and shifted the PSS from the tactile stimulus being first in the passive movement or no movement condition to the auditory stimulus being first. The JNDs did not differ across the three conditions. These results reveal that voluntary movement shifted the PSS and affected simultaneous perception of auditory and tactile stimuli.

Chapter 4 Voluntary movement affects simultaneous perception of auditory and tactile stimuli presented to a non–moving body part

4.1 Introduction

The results of chapter 3's experiment (Hao et al., 2015) suggest that voluntary movement affected simultaneous perception of auditory and tactile stimuli. Specially, voluntary movement shifted the PSS to the point where auditory stimulus should be presented earlier than tactile stimulus. Voluntary movement did not affect the JND, because there is no significant difference among the three experimental conditions. Further, it is known that voluntary movements can affect simultaneous perception (Shi et al., 2008; Nishi et al., 2014; Hao et al., 2015). Shi et al. (2008) reported that voluntary movement affected the subjective simultaneity of visual and tactile stimuli. Our groups' previous study (Nishi et al., 2014) reported that voluntary movements affected the simultaneous perception of auditory and tactile stimuli. These studies including the chapter 3's experiment (Shi et al., 2008; Nishi et al., 2014; Hao et al., 2015) suggested that voluntary movements affected simultaneous perception of visual and tactile stimuli, and auditory and tactile stimuli, in which the tactile stimulus was presented to the moving body part. In other words, the movement and tactile stimuli involved the same body part.

However, little is known about spatial limits on the effect of voluntary movements on simultaneous perception, especially when tactile stimulus is presented to a non–moving body part. That is, do voluntary movements affect the simultaneous perception of a non–moving body part?

The present study examined this remaining question from previous studies and chapter 3's experiment and the spatial limits on the effect of voluntary movement on simultaneous perception of auditory and tactile stimuli presented to a non–moving body part by a temporal order judgement (TOJ) task, in which the order of auditory and tactile stimuli is judged. The possible mechanism for this effect was also discussed.

Three experimental conditions: voluntary movement, passive movement and no movement were used. In the voluntary movement condition, the participants were asked to voluntarily move their right index finger and judge the temporal order of auditory and tactile stimuli presented to their non–moving left index finger. In the passive movement and no movement conditions, the participants' right index finger were moved by a device or held stationary, respectively, and they judged the temporal order of auditory and tactile stimuli presented to their non–moving left index finger.

4.2 Methods

4.2.1 Participants

Eighteen participants (2 females, 16 males; mean age: 24.2 years; range: 23–28 years) completed the experiment and were compensated for their participation. All participants were naïve to the purpose of the experiment. They were all right–handed and none exhibited any difficulty in moving their right index finger. All participants had a normal auditory threshold and sense of touch. Before administering the experiment, written informed consent was obtained from each participant. The study was approved by the ethics committee of the Tokyo Institute of Technology and the methods were carried out in accordance with their approved guidelines.

4.2.2 Apparatus and stimuli

The tactile stimulus was an impulse force (3N, 10 ms, rectangular pulse) provided by a Geomagic® Touch™ Haptic Device (Geomagic, Rock Hill, SC, USA). It was presented to each participant's left index finger during movement or non–movement of the right index finger. Passive movement was provided by another Geomagic® Touch™ Haptic Device. The auditory stimulus was a sinusoidal wave sound (2000 Hz, 50 dB, 10 ms) simultaneously presented to both ears using earphones (HP-RHF41, radius, Tokyo, Japan). The response machine was a foot switch triple (Strich Technology, Huizhou, China). The timing of the two presentations and the movements of the device were controlled to a margin of error of 1 ms. These sensory stimulation systems were operated by computer programs installed on a PC workstation (Latitude E5430; DELL, Plano, TX, USA), developed with the Open Haptics software development toolkit (Geomagic) on Microsoft Visual C++ 2008 platform (Microsoft, Redmond, WA, USA).

4.2.3 Task and conditions

In the TOJ task, a pair of auditory and tactile stimuli was presented with varying SOAs (intervals between the auditory and tactile stimuli pair) and the temporal order of the two stimuli was judged by the participants. The SOAs were ±240, ±120, ±60, ±30, and 0 ms (in which the negative value indicates that the tactile stimulus was presented before the auditory stimulus, and vice versa). There were three experimental conditions: voluntary movement, passive movement, and no movement.

4.2.4 Procedure

Participants were seated in a dark, sound–attenuated room in front of the stimulation systems with the palmar side of their right and left index fingers held in the haptic devices with tactile stimulus on their left index finger. They also wore an eye mask to eliminate the confounding effects of visual stimuli during the experiment and sound–insulating ear muffs over the earphones (Fig. 4.1). Because both hands were engaged, participants were required to enter the temporal order of the auditory and tactile stimuli using a foot switch. The left key represented the presentation of tactile stimulus first and the right key represented the presentation of the auditory stimulus first. The mean rate of movement for the participants' fingers was 75.73 mm/s (SD = 5.13) in the voluntary movement condition, and the mean rate of movement of the haptic device was 71.75 mm/s (SD = 1.55) in the passive movement condition.

Figure 4.1 Experimental environment. (Hao et al., 2016)

4.2.4.1 Voluntary movement condition

Voluntary movement condition (Fig. 4.2): For each trial, the participants began voluntarily moving their right index finger from right to left at their own pace. As they did so, a cue sound (distinct from the target auditory stimulus) indicated that the TOJ task was forthcoming. The first stimulus (either tactile or auditory) was then presented with a random delay of 600–700 ms after the cue sound onset. The second stimulus (auditory or tactile, whichever was not presented first) followed the first stimulus, offset by one of the nine SOAs previously mentioned. Here, the tactile stimulus was presented to the participants' left index finger. The participants then indicated which stimulus was presented first using a two alternative forced–choice test to specify the temporal discrimination of the auditory and tactile stimuli pair. If the processing speed of the participants was not 50–110 mm/s, they were given one more trial, randomly chosen from the remaining trials.

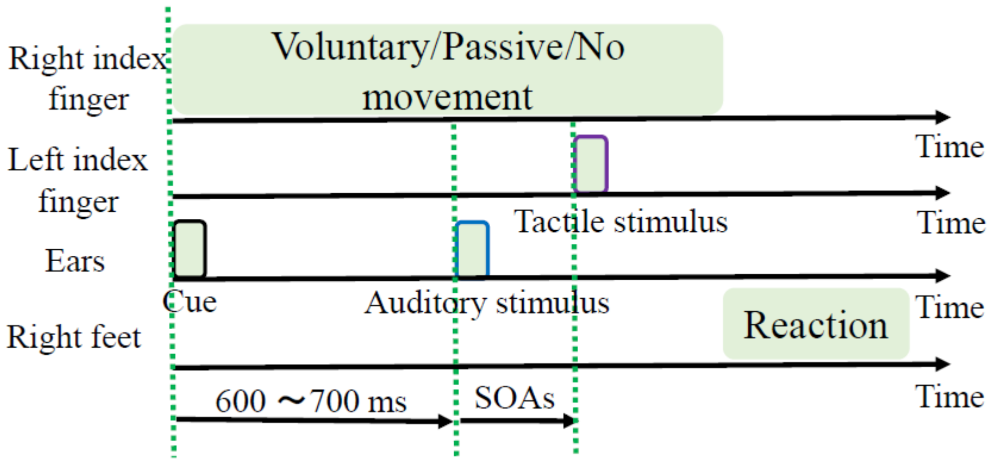

Figure 4.2 Schematic flow chart for one trial in each of the three conditions. "Voluntary/passive/no movement" means the voluntary, passive and no movements on the right index finger in voluntary movement, passive movement, and no movement conditions, respectively. The interval between the cue and the TOJ task was randomly

set from 600 to 700 ms. The durations of the cue, auditory stimulus and tactile stimulus were 10 ms. In the TOJ task, participants judged the temporal order of the auditory and tactile stimuli presented to the non–moving left index fingers. (Hao et al., 2016)

4.2.4.2 Passive movement condition

Passive movement condition (Fig. 4.2): Similar to the voluntary movement condition, one haptic device randomly started to move the participants' right index finger for 500 to 1000 ms to reproduce the variance in the onset of voluntary movements in the preliminary experiments, while another haptic device presented the tactile stimulus to the participants' left index finger. The other procedures were the same as in the voluntary movement condition, including evaluation of the temporal order of the two stimuli and the SOA values. A speed of 76 mm/s for the finger movement was set for each trial, which was considered a comfortable speed and representative of normal surface exploration. The movement trajectory of passive movement was reproduced by the movement trajectory of voluntary movements in the preliminary experiments.

4.2.4.3 No movement condition

No movement condition (Fig. 4.2): The participants remained stationary throughout the no movement experiment with the palmar side of their left and right index fingers held in the haptic devices. The first stimulus (either tactile or auditory) was presented following a random delay (600–700 ms) after the cue sound onset. The presentation of the second stimulus and the procedure for evaluating the temporal order of the two stimuli were the same as in the voluntary and passive movement conditions.

Each participant completed five blocks for all of the conditions in random order. Each block consisted of 45 trials; that is, five trials for each SOA randomly selected from the following values: ±240, ±120, ±60, ±30 and 0 ms. The interval between trials was 1000 ms in each condition and white noise played in the background to effectively mask any sounds made by the haptic device. It took about five minutes for participants to complete one block of trials. They were given several minutes to rest between blocks, according to their preference. The order of the conditions was counterbalanced and the participants completed a total of 675 trials in the formal experiment; the entire procedure took about 3.5 hours across two successive days. During the experiment, the participants were asked to pay constant attention to the tactile stimulus to control for the prior entry effect (Spence et al., 2001; Shore et al., 2001; Kitagawa et al., 2005; Zampini, Shore et al., 2005; Vibell, 2007; Spence and Parise, 2010), which facilitates the processing of an attended stimulus compared with an unattended stimulus.

In the practice sessions, participants were asked to close their eyes and judge the order of the two stimuli and then open their eyes to see the feedback on the computer screen for each trial. With no information about the forthcoming condition, they first completed 90 trials of the no movement condition, then 45 trials each of counterbalanced voluntary movement and passive movement conditions. The SOA during the practice session was randomly chosen from ± 240, ± 120, or ± 60 ms. In addition, participants each completed a practice run of 10 trials in which only the tactile stimulus was presented so they became accustomed to the appropriate finger speeds in the voluntary movement condition. They were given 2–3 minutes of rest before each block of trials in the voluntary movement condition to eliminate any potential practice effect.

4.2.4.4 Data analysis

The MATLAB Statistics Toolbox (MathWorks, Natick, MA, USA) was used for the statistical regression calculations and graphic representation of the results. First, the ratio of the answers was calculated for each SOA, in which the auditory stimulus was perceived first. Then the logistic regressions were conducted using a generalized linear model with the ratio from each condition. The psychometric curves were fitted to the distribution of the mean TOJ for the voluntary movement, passive movement and no movement conditions, as shown in Fig. 4.3. The PSS and JND values were calculated for each participant in the regression analysis, based on three equations (Finney, 1952):

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

$$\mathrm{PSS} = a \tag{2}$$

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

Here, a represents the estimated PSS, x denotes SOA, β is related to the JND and x_p represents the SOA with p as the per cent of “auditory first” responses. Next, statistical analyses of the data were conducted to obtain the mean and standard error values for each condition.

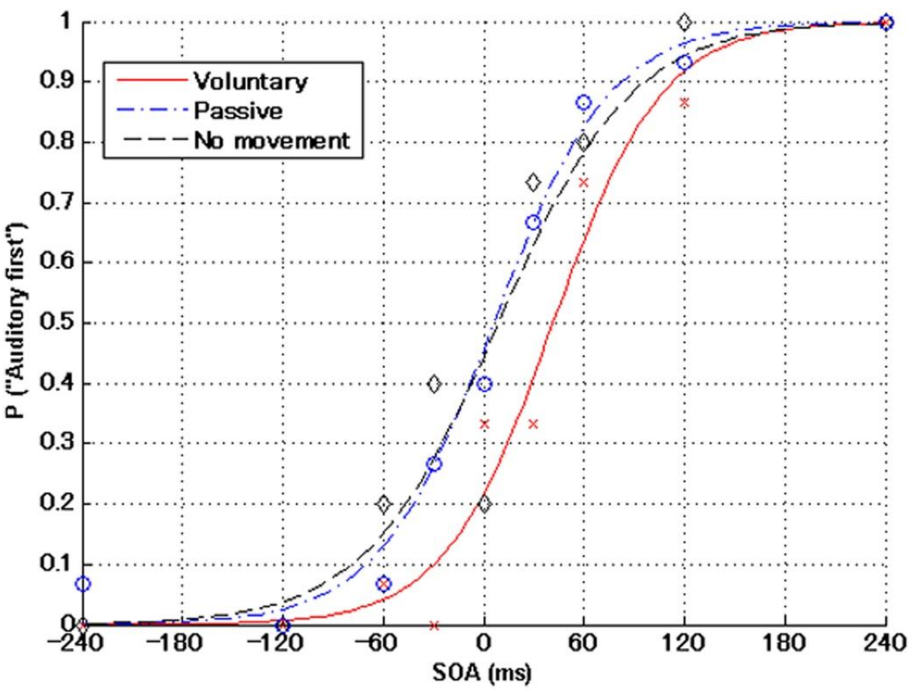

Figure 4.3 Average psychometric functions between all blocks in the voluntary movement, passive movement and no movement conditions for one participant.

On the abscissa are the SOAs. On the ordinate is the proportion of times that the auditory stimulus was perceived before the tactile stimulus. Negative SOA values mean that the tactile stimulus was presented before the auditory stimulus, and vice versa. The curves were estimated using the generalized linear model (see text for details). Voluntary represents the voluntary movement condition; Passive represents the passive movement condition; and No movement represents the no movement condition. (Hao et al., 2016)

4.3 Results

The mean PSS (±standard error, SE) was 35.6±9.0 ms for the voluntary movement condition, 14.8±8.7 ms for the passive movement condition, and 18.8±6.5 ms for the no movement condition. A one–way repeated measures analyses of variance (ANOVA) with movement condition as a factor showed a significant effect ($F(2, 34) = 7.60$, $P = 0.002$). Subsequently, Bonferroni–Holm paired *t* tests revealed significant differences between the voluntary movement and passive movement conditions ($P = 0.009$) and between the voluntary movement and no movement conditions ($P = 0.024$). There was not a significant difference between the passive movement and no movement conditions ($P = 1.0$), as shown in Fig. 4.4.

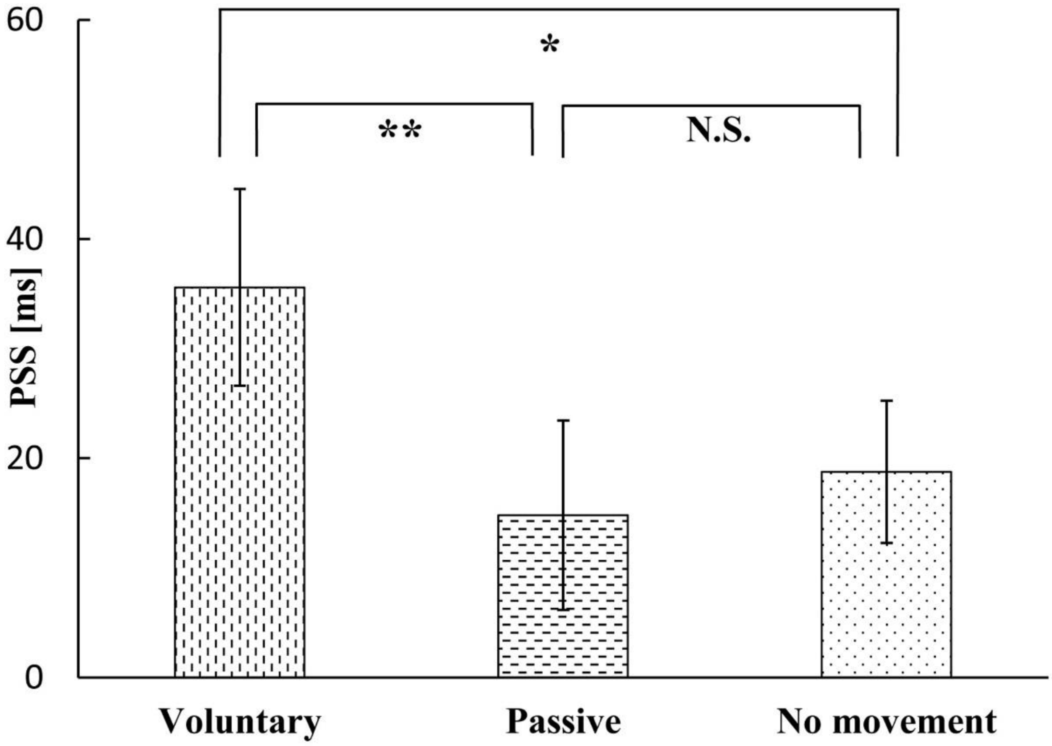

Figure 4.4 PSS results in the voluntary movement, passive movement and no movement conditions. On the abscissa are the three experimental conditions. On the ordinate is the PSS value. Error bars represent standard errors, *P < 0.05 and **P < 0.01. (Hao et al., 2016)

The mean JND (±SE) was 58.3±4.2 ms for the voluntary movement condition, 48.6±4.8 ms for the passive movement condition, and 36.2±2.8 ms for the no movement condition. A one–way repeated measures ANOVA with movement condition as a factor showed a significant effect ($F(2, 34) = 19.87$, $P < 0.001$). Subsequently, Bonferroni–Holm paired *t* tests revealed significant differences between the voluntary movement and no movement conditions ($P < 0.001$), between the voluntary movement and passive movement conditions ($P = 0.036$) and between the passive movement and no movement conditions ($P = 0.005$), as shown in Fig.4.5.

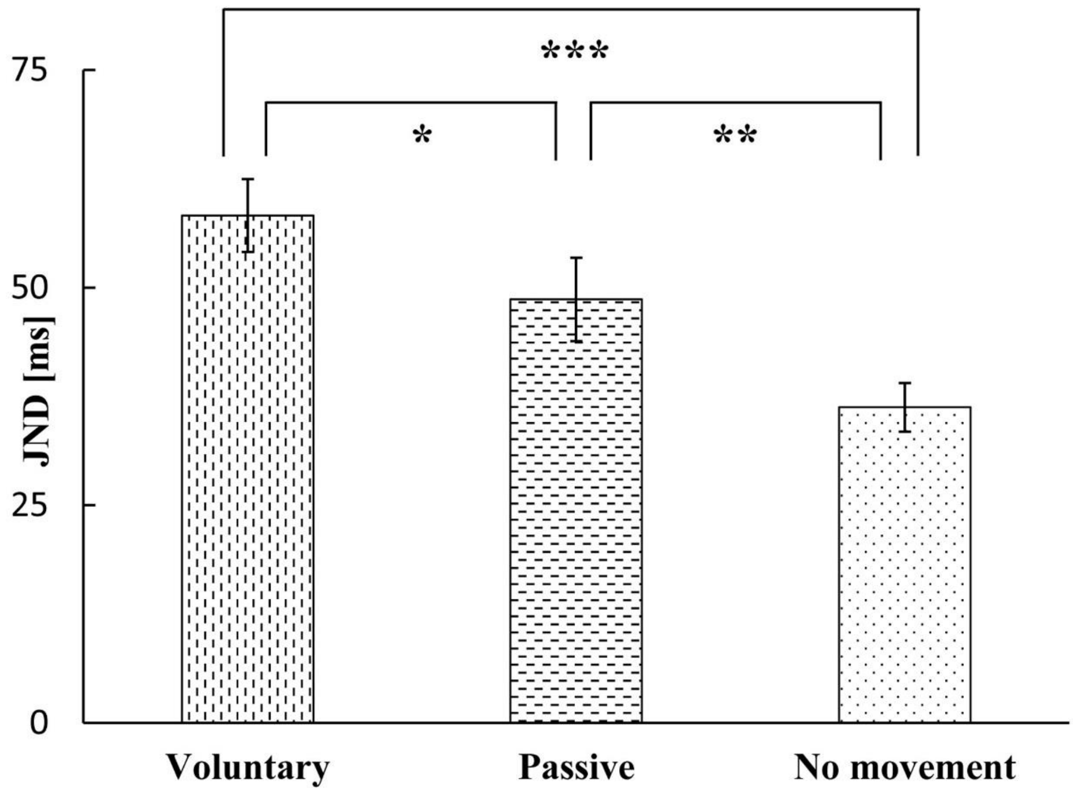

Figure 4.5 JND results in the voluntary movement, passive movement and no movement conditions. On the abscissa are the three experimental conditions. On the ordinate is the JND value. Error bars represent standard errors, $*P < 0.05$, $**P < 0.01$ and $***P < 0.001$. (Hao et al., 2016)

4.4 Discussion

The present study investigated whether the effect of voluntary movement on the simultaneous perception of auditory and tactile stimuli reaches a non–moving body part beyond the moving body part. Specifically, in the TOJ task, participants were asked to judge the temporal order of auditory and tactile stimuli presented to their non–moving left index finger, during they completed the voluntary movement of their right index finger. The PSSs and the JNDs were compared in three experimental conditions:

voluntary movement, passive movement and no movement. The passive movement condition, in which a device moved the participant's body part, was introduced to remove the effect of proprioceptive sensation on simultaneous perception. The voluntary movement was found to significantly affect the PSS compared with passive movement and no movement. Voluntary movement and passive movement significantly increased the JNDs, compared with no movement. These results of PSSs in chapter 3's and 4's experiments indicated that voluntary movement also affected simultaneous perception of auditory and tactile stimuli, even when the tactile stimulus was presented to a non–moving body part, not just to a moving body part as has been shown in previous study (Nishi, et al., 2014) and in chapter 3's experiment (Hao et al., 2015).

4.4.1 Discussion on PSSs and JNDs

As shown in Fig. 4.4, the PSS was significantly affected in the voluntary movement condition but not in the passive movement condition or no movement condition; there were significant differences in the PSSs between the voluntary movement and passive movement conditions, and between the voluntary movement and no movement conditions. This means that to be perceived simultaneously, the auditory stimulus needed to be presented before the tactile stimulus for a longer period in the voluntary movement condition than in the passive movement condition or no movement condition. Furthermore, there was not a significant difference between the passive movement and no movement conditions. That is, proprioceptive sensation in the movements did not affect the PSS. These results are consistent with those from in previous study (Nishi et al., 2014) and in chapter 3's experiment (Hao et al., 2015), in which voluntary movement was reported to affect the PSS of simultaneous perception of auditory and tactile stimuli to a moving body part. The results indicated that rather than proprioceptive sensation in the movements, the voluntary movement affected the PSS, even when a tactile stimulus was presented to the non–moving body part. Therefore, it is proposed that the effect of voluntary movement on the simultaneous perception of auditory and tactile stimuli might be extendable in spatial dimension.

As shown in Fig. 4.5, there were significant differences in the JNDs across the three experimental conditions. The JNDs were worse in the voluntary movement and passive movement conditions than in the no movement condition. In particular, this impairment was more obvious during voluntary movement than during passive movement. These impairment of temporal resolution by voluntary movement and passive movement in chapter 4's experiment are inconsistent with the no impairment of temporal resolution by voluntary movement and passive movement in chapter 3's experiment. This difference reminds us about the different method in these two experiment. In chapter 3's experiment, participants judged the order of auditory and tactile stimuli presented on their right index finger, while the locations of voluntary movement and passive movement were also on the right index finger. Whereas in chapter 4's experiment, participants judged the order of auditory and tactile stimuli presented on their left index finger and the voluntary movement and passive movement were on their right index finger. Moreover, Pérez et al. (2008) reported that JND was impaired in the TOJ task with two visual stimuli, after they used an initial visual target stimulus to reduce available attentional resource. That is, divided attention might impair temporal resolution.

4.4.2 Possible mechanism

The significant difference of JNDs among the three conditions in this experiment is inconsistent with the no significant differences of JNDs among the three conditions in chapter 3's experiment. This inconsistent might be related to the methodology difference in chapter 3's and 4's experiment. In chapter 3's experiment, participants judged the order of auditory and tactile stimuli presented on their right index finger moved by the device, whereas in chapter 4's experiment, participants judged the order of auditory and tactile stimuli presented on their left index finger and the voluntary movement and passive movement were on their right index finger. This means that in chapter 3's experiment, attention was focused on moving right index finger, whereas in chapter 4's experiment attention focusing on non–moving left index finger was divided by the voluntary movement and passive movement of right index finger. Further, Pérez et al. (2008) reported that JND was increased in the TOJ task with two visual stimuli, after they used an initial visual target stimulus to reduce available attentional resource. That is, divided attention might impair temporal resolution. This significant impairment of temporal resolution in chapter 4's experiment is consistent with the temporal resolution impairment shown in Pérez et al. (2008). The mechanism of impairment of temporal resolution by voluntary movement and passive movement in chapter 4's experiment might be similar to those described in Pérez et al. (2008), although they used a visual target stimulus to divide attention and two visual stimuli in the TOJ task. Therefore, the significant difference of JNDs among the three conditions might be attributed to the focusing attention to TOJ task (i.e. tactile stimulus presented to right index finger) in chapter 3's experiment. Whereas, compared with no movement condition, the obvious impairments of temporal resolution in voluntary movement and passive movement condition might be caused by the decreased attention drawing by the voluntary movement and passive movement of right index finger in chapter 4's experiment, in which the attention was paid to tactile stimulus presented to non–moving left index finger.

Previous studies reported that attention facilitates the processing of an attended stimulus relative to an unattended stimulus (i.e. prior entry effect) and then the PSS shift occurred (Spence et al., 2001; Shore et al., 2001; Kitagawa et al., 2005; Vibell et al., 2007; Spence and Parise, 2010). This PSS shift by attention is consistent with the result of PSS in chapter 3's experiment.

However, if only attention shifts the PSS in chapter 4's experiment, just as in voluntary movement condition, compared with in passive movement and no movement conditions, the PSS shifted, it might be the available attentional resource for the TOJ task. Compared with the attention to the TOJ task (i.e. focusing on the left index finger) in the no movement condition, the impairments of temporal resolution during the voluntary and passive movement conditions indicated that the endogenous attention to the TOJ task was differently drawn by voluntary movement and passive movement on the right index finger. Then, across the three experimental conditions, the available attentional resource for the TOJ task was lowest in the voluntary movement condition compared with the passive movement condition, and the available attentional resource for the TOJ task was lower in the passive movement condition compared with the no movement condition. Above all, the effect of the available attentional resource for the TOJ task in the voluntary and passive movement conditions on the PSSs cannot be larger than the effect in the no movement condition. The effect of the available attentional resource for the TOJ task in the voluntary movement condition on the JND also cannot be larger than the effect in the passive movement condition. With such available attentional resources across three experiment conditions, it is impossible to get the significant impairment JND in voluntary movement condition, rather than in passive and no movement conditions, since attention to TOJ task in voluntary movement condition is worst across the three conditions.

However, in the present study, compared to no movement, both of voluntary movement and passive movement significantly increased the JNDs. Therefore, it is indicated that the PSS shift in the voluntary movement condition is not affected only by attention, such as a prior entry effect suggested in previous studies (Spence et al., 2001; Shore et al., 2001; Kitagawa et al., 2005; Zampini, Shore et al., 2005; Vibell, 2007; Spence and Parise, 2010), but might be also affected by motor information (e.g., efference copy) related to voluntary movements.

There is a ubiquitous strategy for dealing with forthcoming voluntary movements and possible multimodal sensory information in order to form a coherent representation of the world in voluntary movements. This strategy is efference copy, which is a copy of the motor command (Tanji and Mushiake, 1996). Efference copy affects sensory processing in myriad ways, including temporal aspects. For instance, efference copy is a discriminatory mechanism that prevents maladaptive responses and sensory saturation by restricting or filtering information. It intervenes at the precise time of the motor movement to prevent an antagonistic reflex response in the sensory filtration system, in which timing is crucial (Trinity et al., 2008). Further, efference copy is used for cohesion of self–identity in aspects of cognition, such as thinking and decision–making (Feinberg et al., 1999; Ford et al., 2001). When the temporal functions of the efference copy and the processing of integration of multimodal sensory information and decision-making in our TOJ task are combined, it is suggested that the efference copy generated in voluntary movement is a possible reason for the effect of voluntary movement on simultaneous perception. Frissen et al. (2012) have suggested that the efference copy generated in voluntary movement might affect the temporal resolution of unimodal tactile stimulus pairs. The possible mechanism in the present study indicates that the efference copy might not only predict the sensory feedback of movements (Blakemore et al., 1999; Gentsch and Schütz-Bosbach, 2011; Weiss et al., 2011) and suppress self-generated sensory information (Barnett-Cowan and Harris, 2011), but may also play other unexpected roles in the brain such as potential effects on integration of multimodal sensory information during voluntary movements.

4.4.3 Conclusion

In conclusion, our results indicate that voluntary movement affected simultaneous perception of auditory and tactile stimuli, even when the tactile stimulus was presented to a non–moving body part. Furthermore, in the voluntary movement condition, the impairment of temporal resolution was affected by decreased attention because of voluntary movement of the moving body part, whereas the PSS shift might be affected by attention as well as other mechanism (e.g., efference copy) in voluntary movement.

Chapter 5 General discussion

5.1 Main findings

This study aimed to investigate whether voluntary movement affects the simultaneous perception of auditory and tactile stimuli by TOJ task, and if this effect exists, how far will this effect extend? In other words, does voluntary movement affect simultaneous perception of auditory and tactile stimuli presented to a non–moving body part? Two experiments in chapter 3 and 4 were used to investigate these questions. Chapter 3's experiment was used to investigate the effect of voluntary movement on simultaneous perception of auditory and tactile stimuli. While, chapter 4's experiment was used to study the effect of voluntary movement on simultaneous perception of auditory and tactile stimuli, when tactile stimulus was presented to a non–moving body part.

In chapter 3's experiment, the result of PSS in voluntary movement condition, compared with the results of PSSs in passive movement and no movement conditions, indicated that voluntary movement affected simultaneous perception. That is, it shifted the PSS to the point where auditory stimulus should be presented earlier than tactile stimulus. While in chapter 4's experiment, the PSS of voluntary movement condition shifted more to the point, where auditory stimulus was presented earlier than tactile stimulus, than the PSSs of passive movement and no movement conditions, when tactile stimulus was presented to the non–moving left index finger. Both the PSS shifts in voluntary movement condition, compared with the PSSs in passive movement and no movement conditions, in these two experiments suggest that voluntary movement affected the simultaneous perception of auditory and tactile stimuli. Further, the effect of voluntary movement on simultaneous perception (i.e. PSS) of auditory and tactile stimuli seems extendable in spatial dimension.

On the other hand, in chapter 3's experiment, there was no significant difference in the JNDs across the voluntary movement, passive movement, and no movement conditions. In chapter 4's experiment, compared with and no movement, voluntary movement and passive movement significantly increased the JND. The inconsistent effects of voluntary movement and passive movement on the temporal resolution might be caused by the different method in these two experiments.

In summary, one of the two remaining questions was whether voluntary movement affects simultaneous perception, and another one is whether voluntary movement affects simultaneous perception, when tactile stimulus is presented to a non–moving body part. For these two remaining questions, the results of these two experiments suggest that voluntary movement affected the simultaneous perception of auditory and tactile stimuli, when tactile stimulus was presented both to the moving body part and to the non–moving body part. That is, voluntary movement affected the PSS and shifted the PSS to the point where auditory stimulus was presented earlier than tactile stimulus. Further, this effect also extended to a non–moving body part, which means that voluntary movement affected the PSS and shifted the PSS to the point where auditory stimulus was presented earlier than tactile stimulus when tactile stimulus was presented to a non–moving body part.

5.2 Possible mechanism and future issues

The results of chapter 3's and chapter 4's experiments suggest that voluntary movement shifted the PSS, and impaired the temporal resolution in chapter 4's experiment, but not in chapter 3's experiment. To explain the results, there is one suggestion that the shift effect of PSS by the voluntary movement was not affected only by attention, according to a prior entry effect in previous studies (Shore et al., 2001; Spence et al., 2001; Kitagawa et al., 2005; Zampini, Shore et al., 2005). In the prior entry effect, there is a PSS shift when participants pay attention to one of the stimuli (e.g., auditory stimulus) and when participants pay attention to another stimulus (e.g., tactile stimulus). As previously mentioned, in chapter 4's experiment, the impairments of the temporal resolution occurring in voluntary movement and passive movement conditions might be caused by the decreased attentional resource for TOJ task, which was divided by the movements on the right index finger, according to the results in a previous study (Pérez et al., 2008). That is, the available attentional resource for the TOJ task in the voluntary movement condition may be smaller than in the passive movement and no movement conditions. The available attentional resource for tactile stimulus in the TOJ task may be smaller in the voluntary movement condition than in the passive movement and no movement conditions, because participants were asked to pay attention to tactile stimulus, rather than auditory stimulus. If this available attentional resource for tactile stimulus, rather than auditory stimulus, affects the PSS in the present study, as in a prior entry effect, the PSS in the voluntary movement condition may be smaller than the PSSs in the passive and no movement conditions. However, in the result of this experiment, the PSS in the voluntary movement condition was significantly larger than the PSSs in the passive and no movement conditions. Thus, only attention factor might not be enough to explain the results of PSSs in the three conditions. Additionally, this speculation might also occur in chapter 3's experiment as well since there was a significant PSS shift only in voluntary movement condition, but not in the passive movement and no movement conditions, though there was no decreasing available attentional resource by the movements (i.e. no significant difference of JNDs in the three conditions). This mechanism can be seen in the figure 5.1. Therefore, there is one suggestion that the PSS shift in the voluntary movement condition was not affected only by attention, according to the prior entry effect in previous studies (Shore et al., 2001; Spence et al., 2001; Kitagawa et al., 2005; Zampini, Shore et al., 2005), but might also be affected by a unique mechanism related to voluntary movement.

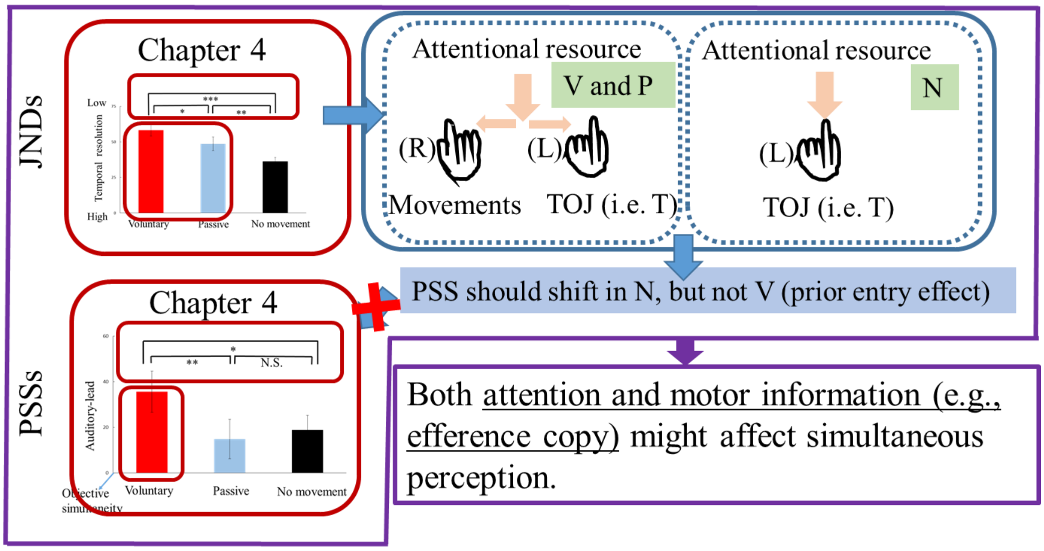

Figure 5.1 Possible mechanism to explain results of PSSs and JNDs in chapter 4's experiment. "V, P and N" represent the voluntary movement, passive movement and no movement conditions. "L and R" represent the right and left index fingers. "T" represents the tactile stimulus.

Efference copy is a copy of the motor command (von Holst and Mittelstaedt, 1950; Tanji and Mushiake, 1996), which generated in voluntary movement. During voluntary movement, efference copy seems to be the ubiquitous factor to form a coherent representation of the external world. A previous study suggested the efference copy might affect the temporal resolution, though their study was about the temporal perception of intramodal tactile stimulus pairs (Frissen et al., 2012). Furthermore, efference copy is generated in the presupplementary motor cortex and the premotor cortex (PMC) (Tanji and Mushiake, 1996), which was reported to modulate the somatosensory cortex (S1) (Christensen et al., 2007). This functional magnetic resonance imaging study reported the activations of PMC and S1, when participants were during voluntary movements in the absence of proprioceptive feedback (Christensen et al., 2007). S1 and the secondary somatosensory cortex (S2) adjacent to S1 process inputs including touch (Ledberg et al., 1995; Disbrow et al., 2000) from the various systems of the body. It is areas S2 in the left and right hemispheres to be densely interconnected, and it was suggested that stimulation from one side of the body will activate areas S2 in both hemispheres (Benarroch, 2006). As just mentioned, the efference copy might be a possible reason to explain the effect of voluntary movement on simultaneous perception of auditory and tactile stimuli in the present study. Thus, the efference copy may also play other unexpected side effect in the brain such as potential effects on integration of multimodal sensory information during voluntary movements, though efference copy is suggested to predict the sensory feedback of movements (Blakemore et al., 1995; Gentsch et al., 2011; Weiss et al., 2011) and suppress self-generated sensory information (Barnett-Cowan, and Harris, 2011).

Although, in this study, the effect of voluntary movement on the temporal integration of auditory and tactile stimuli was investigated, when tactile stimulus was presented to the moving and non–moving body parts, there are still some future issues need to be studied.

The results of this study indicate that voluntary movement affected simultaneous perception of auditory and tactile stimuli presented to the moving and non–moving body parts. However, in chapter 4’s experiment, the location of tactile stimulus was on left index finger, while the movement was on the right index finger, in which the areas in brain to control the right and left index finger is close to each other. For instance, one previous study reported that the secondary somatosensory cortex (S2) in the left and right hemispheres densely interconnects, and it was suggested that stimulation from one side of the body will activate areas S2 in both hemispheres (Benarroch, 2006). Thus, it will be also important to study the effect of voluntary movement on the simultaneous perception of auditory and tactile stimuli presented to other non–moving body part, e.g., the feet. In addition, little is known whether voluntary movement affects simultaneous perception of other multimodalities, for example, visual and tactile stimuli. Thus, it is useful to investigate whether voluntary movement affects auditory and visual stimuli, visual and tactile stimuli.

There is little research on the neural mechanisms of simultaneous perception of auditory and tactile stimuli during voluntary movement. fMRI studies reported that the temporal parietal junction (TPJ) plays crucial role in TOJ tasks between two visual stimuli (Davis et al., 2009) , and between two tactile stimuli (Takahashi et al., 2013) , as well as between auditory and visual stimuli (Adhikari et al., 2013). However, these studies of temporal perception are not during voluntary movement. Hence, it will be of interesting in studying the neural mechanism of the effect of voluntary movement on the simultaneous perception both of unimodal sensory information, such as two tactile stimuli, two auditory stimuli, and two visual stimuli, and multimodal sensory information, such as auditory and tactile stimuli, auditory stimulus or tactile stimulus and visual stimulus. Moreover, one previous study investigated the motor imaginary of finger movements by fMRI, they reported the regions of the rostral part of the contralateral primary motor cortex (M1, area 4a), the contralateral dorsal premotor cortex (PMD, area 6), and the cingulate motor area/supplementary motor area (CMAc/SMA) region that were associated with execution of finger movements were specifically activated during the imagery of finger movements (Ehrsson et al., 2003). Thus, it will be useful to add one more condition – motor imagery, in which participants just imagine the voluntary movement, to these two experiments by fMRI in future work, because the motor areas act during the processing of imagining.

In the present study, there is no ecological relevance of the finger movement. In order to investigate the mechanism of voluntary movement on the simultaneous perception of multimodal sensory information, the finger movement was chose to avoid the potential effect of action of muscle on the simultaneous perception, because there are a few muscle used in finger movement (Meinck et al., 1884) without metacarpophalangeal joint. Furthermore, the timing of tactile stimulus presented to participants was randomized to prevent participants to predict the onset of tactile stimulus. However, it will be interesting to design ecological relevance of the movements to investigate the effect of voluntary movement on simultaneous perception.

In these two experiments, there were more female participants than male participants, which may limit the generalizability of the results. Although previous research has shown that there is no gender effect on two tactile TOJ task in the uncrossed arms condition (Cadieux et al., 2010) or on the temporal order threshold of two types of paired tones stimuli (Bao et al., 2013), it is unknown whether a gender difference exists in multimodal integration. Thus, it would be useful in future research to include more female participants to determine whether there is gender difference in the multimodal integration of auditory and tactile information in TOJ task. Furthermore, it is necessary to collect participants from different countries or healthy participants and patients, or different careers to investigate the effect of voluntary movement on simultaneous perception from anthropology. One previous study reported superior temporal acuity for musicians, compared with nonmusicians, in which participants were asked to decide the longer interval in two different intervals with the range of milliseconds (Rammsayer and Altenmüller, 2006). On the other hand, it is also reported that patients with right hemisphere brain lesions, compared with control participants, needed, on average, the contralesional stimulus (left) to lead the ipsilesional stimulus (right) to achieve the PSS in TOJ task of two visual and two auditory stimuli (Sinnett et al., 2007). This means that it is possible to investigate the notion of differential roles for the two hemispheres in the effect of voluntary movement on simultaneous perception with left- and right-hemisphere patients.

Finally, although the results of these two experiments suggest the unexpected roles of motor information (e.g., efference copy) in the effect of voluntary movement on simultaneous perception, it is still unknown how to prove this unexpected roles by experiment. It was suggested that the "complete specification of the motor command" occurs before movement start in motor planning (Wong et al., 2015). For instance, efference copy could also happen before movement start. It might be a possible way to reflect the other unexpected roles of motor information (e.g., efference copy), if this interval before the movement onset is used to study the effect of voluntary movements on the simultaneous perception of multimodal sensory information. However, this improvement still needs to be considered as the future work.

Chapter 6 Conclusion

We perceive the world through multimodal sensory information, which come from the external environment. While, these temporal perceptions of multimodal sensory information often occur during voluntary movements. It is necessary to study the effect of voluntary movement on the simultaneous perception of multimodal sensory information, instead of no movement only. It still remained unknown whether voluntary movement affects the simultaneous perception of auditory and tactile stimuli or not, because previous studies reported contradictory results. Further, it is also unclear whether this effect extend to a non–moving body part or not, because, in previous studies, tactile stimulus was presented to the moving body part. Thus, this study aimed to investigate the abovementioned two remaining questions, in which the chapter 3's experiment was used to study the first question and the chapter 4's experiment was used to study the second question. In this study, the TOJ task was used, in which participants are asked to judge the order of auditory and tactile stimuli. The PSS and the JND were measured. In these two experiments, three conditions including voluntary movement, passive movement, and no movement, were designed. In particular, the tactile stimulus was presented to the moving right index finger in chapter 3's experiment, whereas the tactile stimulus was presented to the non–moving left index finger in chapter 4's experiment. The results of chapter 3's experiment indicate that voluntary movement affects simultaneous perception of auditory and tactile stimuli. Whereas, the results of chapter 4's experiment indicate that voluntary movement affects simultaneous perception of auditory and tactile stimuli, when tactile stimulus was presented to the non–moving body part. The results of chapter 3's and 4's experiments indicate that voluntary movement affected the simultaneous perception of auditory and tactile stimuli and this effect seems extendable. In other words, voluntary movement significantly affected the simultaneous perception compared with passive movement and no movement, when tactile stimulus was presented not only to the moving body part in chapter 3's experiment, but also to the non–moving body part in chapter 4's experiment. Furthermore, it is indicated that the PSS shift in the voluntary movement condition in these two experiments was not affected only by attention, according to the prior entry effect in previous studies, but might also be affected by a unique mechanism related to voluntary movement. Considering the ubiquitous factor of efference copy, as a copy of the motor command and seems to form a coherent representation of the external world, efference copy generated in voluntary movement might also be part reason for the effect of voluntary movement on the PSS of simultaneous perception of auditory and tactile stimuli.

In summary, the effect of voluntary movement on simultaneous perception of auditory and tactile stimuli (i.e. the PSS) was found, when tactile stimulus was presented either to the moving body part or to the non–moving body part. Further, the results of PSSs and JNDs of the two experiments indicate that attention by itself is not enough to explain these results, and the ubiquitous factor of voluntary movement (e.g., efference copy) might also play a role in the effect of voluntary movement on the PSS of auditory and tactile stimuli.

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List of publications

1. **<u>Qiao Hao</u>**, Taiki Ogata, Ken-ichiro Ogawa, Jinhwan Kwon, Yoshihiro Miyake. The simultaneous perception of auditory–tactile stimuli in voluntary movement. *Front. Psychol.* 2015 Sep 24; 6: 1429. doi: 10.3389/fpsyg.2015.01429. eCollection 2015.

2. **<u>Qiao Hao</u>**, Hiroki Ora, Ken-ichiro Ogawa, Taiki Ogata, Yoshihiro Miyake. Voluntary movement affects simultaneous perception of auditory and tactile stimuli presented to a non–moving body part. *Sci. Rep.* doi: 10. 1038/srep33336. 2016.

3. **<u>Hao Qiao</u>**, Ogata Taiki, Ogawa Ken-ichiro, Miyake Yoshihiro. Effects of voluntary movements on simultaneous perception of auditory and tactile stimuli presented on non–moving body site (Poster). IMRF 2015-16th International Multisensory Research Forum. June 13-16; Pisa, Italy.

4. **<u>Qiao Hao</u>**, Taiki Ogata, Ken-ichiro Ogawa, Jinhwan Kwon, Yoshihiro Miyake. The Study about the Effect of Voluntary Movement on Subjective Simultaneity of Auditory-tactile Stimuli in TOJ task. The 9th CME International Conference on Complex Medical Engineering CME 2015. June 18-21; Okayama, Japan.

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7. **<u>Hao, Q.</u>**, 小川健一朗, 緒方大樹, 三宅美博. The temporal simultaneous perception of auditory-tactile stimuli in voluntary movement. SICE システム・情報部門学術講演会. pp.85, 2014.

Appendix

Table A. The rough results of PSSs and JNDs in the three conditions in chapter 2.

Exp.1	PSSs			JNDs		
Participant ID	**Voluntary movement**	**Passive movement**	**No movement**	**Voluntary movement**	**Passive movement**	**No movement**
1	72.4	30.1	38.2	42.2	39.3	69.3
2	-1.2	-10.5	-7.5	43.0	36.5	27.1
3	-69.5	-75.2	-90.7	81.2	48.5	72.6
4	99.2	90.8	72.9	52.0	24.1	54.1
5	-41.1	-52.1	-54.2	58.5	82.0	69.4
6	-73.1	-90.5	-70.3	48.9	44.8	38.5
7	22.0	-15.8	-1.1	35.5	53.4	31.2
8	6.2	-18.8	-17.0	43.9	44.7	33.0
9	70.3	14.3	-10.8	49.4	50.1	40.0
10	-52.6	-22.5	-29.1	74.0	67.6	56.9
11	28.1	13.6	13.8	65.5	23.5	24.8
12	6.1	1.4	-26.7	117.1	38.1	46.0
13	-1.4	-75.2	-48.2	63.5	52.4	46.4
14	13.0	12.6	9.8	38.6	43.6	29.3
15	45.0	35.2	33.1	38.1	30.9	40.9
16	24.2	1.7	-7.3	34.8	25.3	22.0
17	38.4	28.4	-17.8	59.4	70.9	38.9
18	75.8	48.6	36.4	53.6	40.5	88.5

Table B. The rough results of PSSs and JNDs in the three conditions in chapter 3.

Exp.2	PSSs			JNDs		
Participant ID	**Voluntary movement**	**Passive movement**	**No movement**	**Voluntary movement**	**Passive movement**	**No movement**
1	20.4	-5.6	-4.8	48.5	39.0	43.6
2	55.7	8.2	26.7	49.9	19.8	19.2
3	31.9	41.3	8.8	51.5	39.6	32.4
4	37.4	28.0	40.7	75.1	57.0	45.7
5	-36.3	-47.3	-31.4	66.1	96.7	52.8
6	75.6	2.2	16.3	70.8	52.1	33.9
7	79.1	46.9	56.0	57.4	42.2	30.9
8	90.0	95.4	70.3	79.0	56.1	30.3
9	-6.5	-31.5	-20.4	54.7	59.3	52.2
10	52.4	14.0	12.5	44.2	27.1	31.3
11	-28.4	-13.8	-4.5	41.5	29.0	36.2
12	15.1	-19.6	17.3	70.5	41.0	29.8
13	-1.9	0.9	32.4	18.3	18.7	8.4
14	65.6	8.4	27.0	71.8	54.5	37.2
15	60.6	79.7	24.8	77.0	73.6	34.3
16	85.7	47.5	55.9	57.2	53.7	35.4
17	15.8	-4.2	-16.6	31.2	38.8	40.5
18	28.3	16.1	26.8	84.2	77.7	58.1