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How Voluntary Movements Affect Cross-modal Temporal Perception

Taiki Ogata[1,2], Masayasu Furusato[2], Masanori Yokoyama[2], Takayuki Nozawa[2,3] and Yoshihiro Miyake[2]

[1]Intelligent Modeling Laboratory, The University of Tokyo, Tokyo, Japan
(Tel: +81-3-5841-7651; E-mail: ogata@iml.u-tokyo.ac.jp)
[2]Department of Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, Yokohama, Japan
[3]Institute of Development, Aging and Cancer, Tohoku University, Sendai, Japan

Abstract: We investigated the effect of voluntary movements on cross-modal simultaneous perception using auditory-tactile Temporal Order Judgment (TOJ) task in which participants judged which stimuli had been presented first. In experiment 1, we examined which voluntary movement or proprioceptive information affected TOJ. In experiment 2, we examined the effects of the duration of the voluntary movement and the prediction of the timing of stimuli presentation. When the prediction was available, not the proprioceptive information but the voluntary movements enhanced the temporal resolution of TOJ. According to the increasing of the duration, the point of subjective simultaneity shifted from auditory-first presentation to tactile-first presentation. This result could be attributed to decreasing of attention to the tactile sensation by voluntary movement.

Keywords: voluntary movement, simultaneous perception, temporal order judgment, temporal prediction

1. INTRODUCTION

As manifested by musical ensembles and sports, we interact with the environment using multi-sensory inputs and act in real-time. Nevertheless, it remains unclear what relations there are between voluntary movement and cross-modal temporal perception.

Previous studies have considered cross-modal simultaneous perception in the context of pure sensory integration. For example, participants perceived pairs of visual and auditory stimuli and pairs of visual and tactile stimuli as simultaneous when the visual stimuli were presented earlier; additionally, participants perceived pairs of auditory and tactile stimuli as simultaneous when tactile stimuli preceded auditory stimuli [1, 2]. This asymmetry in point of subjective simultaneity (PSS) is affected by stimulus intensity, selective attention [3, 4], and spatial location [3, 5-8], and by a few minutes of exposure to paired stimuli presented repeatedly with a fixed time lag [9-12]. However, people do not always judge passively the simultaneity of signals from the environment, but do so in active involvement with the environment; that is, while generating movement.

Recent studies investigated the effect of voluntary movements on temporal perception [13, 14]. Shi et al. examined the effect of voluntary movement on visual-tactile Temporal Order Judgment (TOJ) task in which participants judged the temporal order of the two stimuli. Under voluntary movement condition, the PSS of TOJ was altered and the resolution of TOJ (Just Noticeable Difference; JND) was higher than that under no movement condition [13].

The result of the previous study seemed to demonstrate that voluntary movement altered simultaneous perception and that the perception with voluntary movement is not only the matter of purely sensory integration but also the matter of sensory-motor integration. However, the study had not divided the effects of voluntary movement and proprioceptive information accompanied by the voluntary movement. If proprioceptive information alone affected the TOJ, then the simultaneous perception accompanied by voluntary movement would be a purely sensory phenomenon.

In this paper, the effects of voluntary movement and proprioceptive information on the perception of simultaneity was examined in a differentiating manner (experiment 1). Then, we investigated how voluntary movement or/and proprioceptive information affect simultaneous perception (experiment 2). Correa et al. found that the prediction of the presentation timing of target stimuli in TOJ tasks narrowed JNDs [15]. In experiment 2, it was investigated whether the effect of voluntary movement on TOJ was related to the prediction effect or not. Furthermore, we examined whether the effect of voluntary movement on TOJ was also observed between other modalities. We used auditory-tactile TOJ tasks in experiment 1 and 2.

2. EXPERIMENT 1

2.1 Method

2.1.1 Participants

Written informed consent was obtained from 12 paid participants (age range, 22-30 years: seven males and five females). All participants had an appropriate auditory threshold and normal touch and exhibited no problems in moving their right arms. They all were right-handed.

2.1.2 Apparatus and stimuli

Auditory stimuli (50 dB, 15 ms, white noise) were presented via earphones (MHP-EP5, JESTAX, Japan). Tactile stimuli (3 N, 15 ms, rectangular pulse) were presented and involuntary movements were made by a desktop haptic device (PHANTOM, SensAble Technologies, USA). All signals were operated by computer programs installed on PC (HP xw4600/CT, Hewlett-Packard, USA), which were developed using the OpneHaptics software development toolkit (SensAble Technologies, USA).

2.1.3 Task and Conditions

The tasks were auditory-tactile TOJs under three conditions: voluntary condition with voluntary movement and proprioceptive information, involuntary condition without voluntary movement but with proprioceptive information and no-movement condition without voluntary movement or proprioceptive information.

The experimental design was developed to allow the following comparisons: 1) results of the NO-MOVEMENT and INVOLUNTARY conditions, to examine the effect of the proprioceptive sensation, and 2) results of the VOLUNTARY and INVOLUNTARY conditions, to identify the effect of voluntary movement itself.

We prepared nine Stimulus Onset Asynchrony (SOA) (-200, -90, -60, -30, 0, +30, +60, +90, and +200) between auditory and tactile stimuli. The negative values indicate that the tactile stimulus preceded the auditory stimulus.

2.1.4 Design

This experiment had three movement conditions (voluntary, involuntary and no-movement) $\times$ nine SOA conditions (-200, -90, -60, -30, 0, +30, +60, +90 and +200).

2.1.5 Procedure

1. Voluntary condition

   Tests were conducted in a sound-attenuated room that was free from noises that could interfere with the auditory stimulation. During the experiments, participants wore sound-insulating earmuffs over the earphones. In addition, their right index finger and wrist were held in a brace, to control the movement of their arms.

   The participants were seated in front of the experimental apparatus with the palmar side of their right index finger touching the device. After an auditory cue which announced that the recording was ready, the participants started to make a voluntary right-arm movement horizontally from right to left at their own timing. A tactile stimulus was presented on the right index finger at 900 ms from the onset of the arm movement, and an auditory stimulus was presented one of SOAs after the tactile stimulus. Then participants judged which stimuli presented first. 2,000 ms after the participant's judging, an auditory cue which announced the next trial was presented.

   To eliminated the effect of visual stimuli, the participants were instructed to close their eyes during the experiment. Additionally, they were also asked to pay constant attention to the tactile stimuli during the trials, to control for the prior entry effect [3, 4, 16, 17] on the test results under different testing conditions; this facilitates the processing of a stimulus to which one attends relative to one that one does not.

2. Involuntary condition

   Similar to the voluntary condition, an auditory tone generated to indicate the beginning of the recording. The device stared to move the participants' right arm 1,300 to 2,800 ms after the tone. This temporal gap between the presentation of the single tone and the start of the device-controlled arm movement was used to reproduce the variance in the onset of the voluntary movement in a preliminary experiment under voluntary condition. The speed of the involuntary arm movement chosen for each experimental run was 76, 88, 112 or 124 mm/s. The occurrence rates were calculated from the distribution of the data collected in the preliminary experiment. A tactile stimulus was presented 900 ms after the onset of the involuntary arm movement and an auditory stimulus was presented one of SOAs after the tactile stimulus. The other procedures were the same as those used in the voluntary condition.

3. No-movement condition

   A tactile stimulus was presented after a 2,200-3,700 ($1,300+900$ to $2,800+900$ ms) delay from the presentation of the tone which announced the beginning of a trial. The auditory stimulus was presented one of SOAs after the tactile stimulus. In this condition, participants did not move their arm either voluntarily or involuntarily. The other procedures were the same as those used in the voluntary condition.

This experiment consisted of some blocks. In the block, the movement condition remained the same and each block consisted of 45 trials, i.e., five trials for each SOA. The order of blocks (movement conditions) and the order of trials (SOA conditions) in one block were randomized. Ten participants completed five blocks and two participants completed four blocks each for test conditions.

To learn to move their arm at a speed that was as close to 100 mm/s as possible, the participants underwent practice sessions for the voluntary condition before embarking on the formal test trials. In addition, under the voluntary condition, they conducted practice runs of five to ten trials immediately before each voluntary-condition block. During these practice sessions, only the tactile stimulus was presented; the auditory stimulus for temporal judgment was not. To allow the participants to become familiar with the TOJ task before starting the formal data collection trials, they were also provided with practice sessions for all test conditions. The completion of one block of trials required around 6 min. Participants were given several minutes of rest between blocks.

2.1.6 Method for calculating PSS and JND

We conducted a logistic regression analysis using a generalized linear model (eq. (1)) and the ratio data of

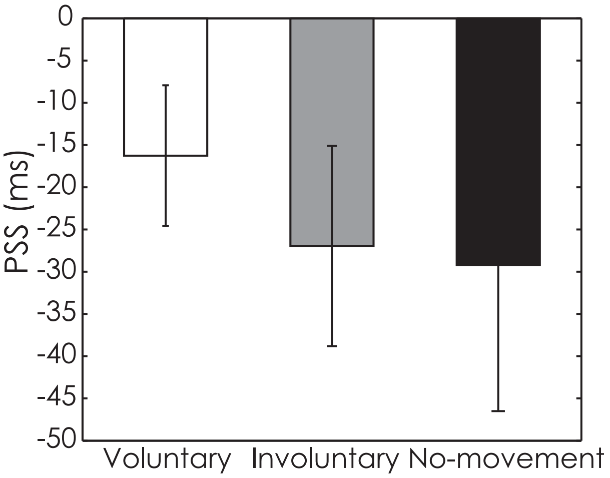

Fig. 1 Averaged PSSs in experiment 1. Error bars mean standard errors between participants.

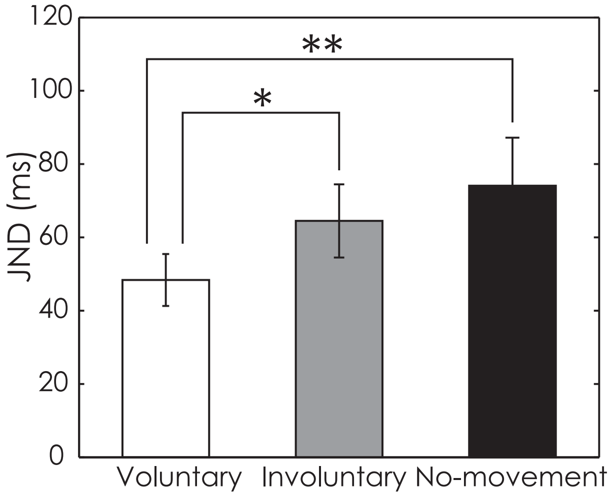

Fig. 2 Averaged JNDs in experiment 1. Error bars mean standard errors between participants.

auditory-first responses on each SOA [18].

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

where α represents the estimated PSS, x denotes the SOA, and β relates to the JND (eq. (2)).

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

X_p represents the SOA with p percent of auditory-first responses.

2.2 Results

Fig. 1 and 2 respectively show the results of PSSs and JNDs under each condition. We determined the JND and PSS values for each participant using regression analyses (Eqs (1) and (2)) and processed the data statistically to obtain the mean and standard error values for each condition. As shown in Fig. 1, the mean PSS values had a negative (range: –16.3 to –29.2 ms) for the three test conditions, which indicates that the auditory-tactile stimulus pairs were perceived as simultaneous when the tactile stimuli preceded the auditory stimuli by approximately 20 ms. In addition, the JND under the voluntary condition was smaller than that observed under the other conditions (Fig. 2).

The Friedman test showed no significant difference in PSSs (p = .205) but a significant difference in JND (p = .002). Scheffe's paired comparison analysis showed that the voluntary condition produced a smaller JND value compared with the involuntary (p = .017) and no-movement (p = .005) conditions.

3. EXPERIMENT 2

3.1 Method

3.1.1 Participants

Written informed consent was obtained from 12 paid participants (average age, 23.2 years: ten males and two females). All participants had an appropriate auditory threshold and normal touch and exhibited no problems in moving their right arms. They all were right-handed.

3.1.2 Apparatus and stimuli

The apparatus and stimuli were same as those in experiment 1.

3.1.3 Task and Conditions

The tasks were auditory-tactile TOJs under two movement conditions and three duration conditions. In this experiment, we did not use no-movement condition because in experiment 1, there were no differences of PSSs and JNDs between involuntary and no-movement condition. In experiment 1, the duration from the onset of arm movement to the presentation of tactile stimulus was fixed at 900 ms. In this experiment, the duration was selected from 600, 900 or 1,500 ms for each trial so that participants could not predict the timing of presentation of the auditory and tactile stimuli. Eight SOAs (-200, -90, -60, -30, +30, +60, +90 and +200) between auditory and tactile stimuli were prepared. The negative values indicate that the tactile stimulus preceded the auditory stimulus.

3.1.4 Design

This experiment had two movement conditions (voluntary and involuntary) × three duration conditions (600, 900 and 1,500 ms) × eight SOA conditions (-200, -90, -60, -30, +30, +60, +90 and +200).

3.1.5 Procedure

The procedures were similar to those under voluntary and involuntary conditions in experiment 1 except for the durations from the beginning of the arm movement to the tactile stimulus presentation.

This experiment consisted of some blocks. In the block, the movement condition remained the same and each block consisted of 120 trials, i.e., five trials for each SOA and duration condition. The order of blocks (movement conditions) and the order of trials (SOA and duration conditions) in one block were randomized.

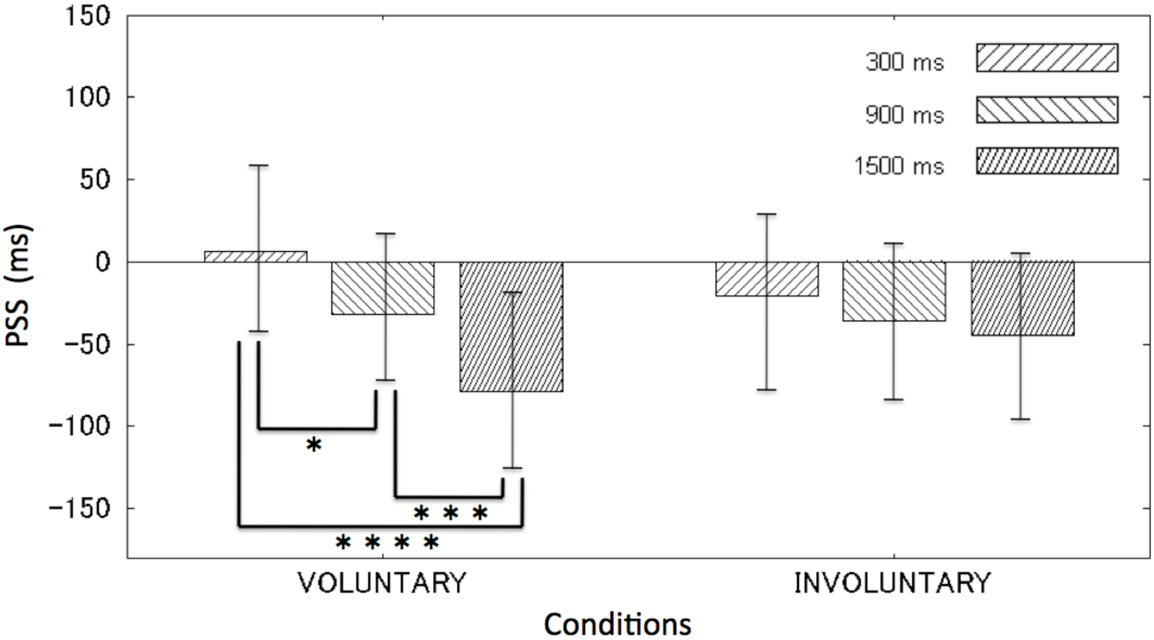

Fig. 3 Averaged PSSs in experiment 2. Error bars mean standard errors between participants.

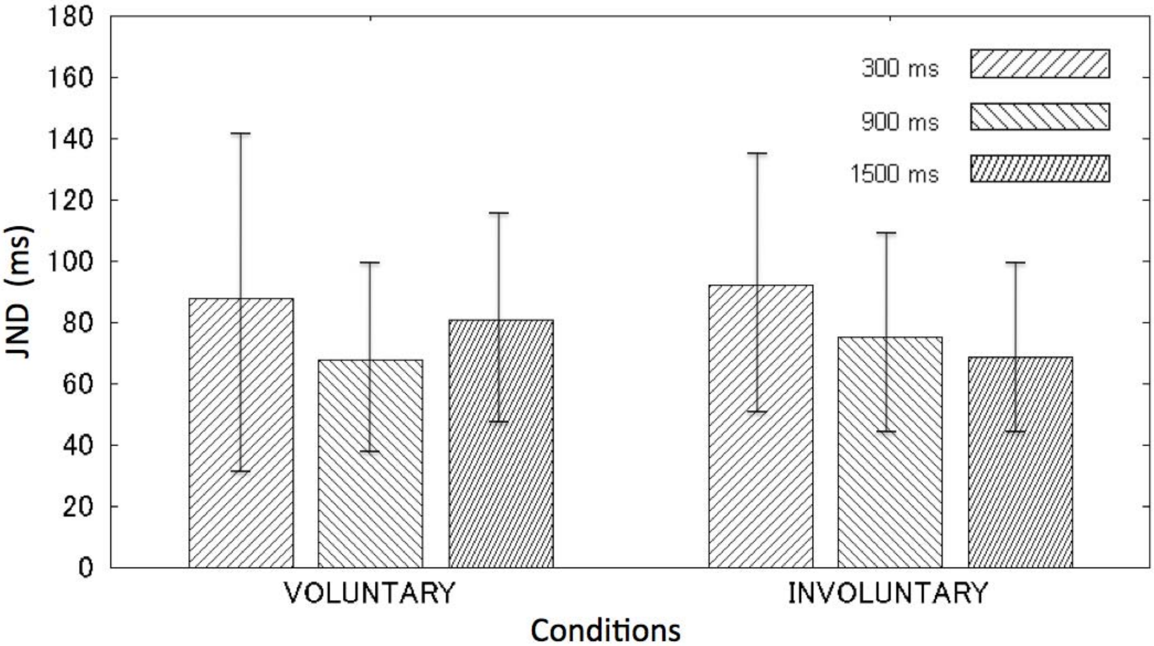

Fig. 4 Averaged JNDs in experiment 2. Error bars mean standard errors between participants.

3.2 Results

Fig. 3 and 4 respectively show the results of PSSs and JNDs under each movement and each duration condition. As shown in Fig. 3, both under voluntary condition and under involuntary conditions, the means of PSSs decreased as the movement duration increased. As shown in Fig. 4, the means of JNDs under involuntary condition decreased as the movement duration increased. On the other hand, under voluntary condition, the JND in 900 ms condition was narrower than that in the other two duration conditions.

The two-way ANOVA showed the interaction between movement and duration conditions in PSSs ($p = .039$) and the simple main effect of the voluntary condition ($p < .001$). In the voluntary condition, significant differences were found between 300 and 1,500 conditions ($p < .001$), between 300 and 900 conditions ($p = .014$) and between 900 and 1,500 conditions ($p = .003$). In JNDs, we found no significant effect of movement condition ($p = .994$) but the main effect of the duration conditions ($p = .025$) The multiple comparison showed the significant differences between 300 and 1,500 conditions ($p = .031$) and between 300 and 1,500 conditions ($p = .011$).

4. DISCUSSION

We have investigated the effect of voluntary movement on an auditory-tactile TOJ. In experiment 1, to examine separately the effect of voluntary movement and proprioceptive information on simultaneous perception, we compared with three TOJ tasks; TOJ with voluntary movement, TOJ with involuntary movement and TOJ without any movement. From the results, we found no significant differences of PSSs and JNDs between the involuntary and the no-movement conditions. These results mean that proprioceptive information does not affect cross-modal simultaneous perception. On the other hand, a smaller JND value was observed in the voluntary condition compared with the involuntary and no-movement conditions. Thus, we conclude that in addition to visual-tactile TOJs [13], the effect of voluntary movement on simultaneous perception was observed in auditory-tactile TOJs and that not proprioceptive information but voluntary movement improves the temporal resolution of TOJ tasks.

Our results regarding the difference in JND between the voluntary and no-movement conditions corroborate the results of the preceding study on visual-tactile TOJ performed by Shi et al. [13], despite our study yielding a smaller difference. The quantitative discrepancy between these studies could be attributed to two causes. First, the difference in modality combination could lead to this discrepancy. According to previous studies, however, TOJ is less affected by modality combination [9]. Therefore, the difference in modality combination is unlikely to explain the discrepancy. Second, the discrepancy could be attributed to the different degrees of predictability under the voluntary condition. In the study by Shi et al. [13], participants were able to make precise predictions via the combination of visual information, proprioceptive information, and motor command signals such as the efference copy. Similarly, Tanaka et al. [19] showed that the prediction of dynamic target positions was more accurate under a condition of active tracking rather than one of passive observation and that, even under the active condition, lack of visual feedback caused larger errors. In contrast, participants in our study predicted motion based only on proprioceptive information and motor command signals. Thus, the smaller JND difference between the voluntary and no-movement conditions observed in experiment 1 may be a consequence of the poorer predictive performance in our experimental setting.

In experiment 2, the difference of JNDs between voluntary and involuntary conditions was not found. It is known that selective temporal attention [15] or temporal preparation [20] could increase under the voluntary condition and could narrow JNDs compared with the other conditions. Correa et al. [15] presented the words "early" or "late" as a cue before the TOJ task of two visual stimuli, and found that when the cues corresponded to the actual cue–target interval, the JND was smaller than when they did not. This result shows that if the temporal point when the stimuli come is predictable, attending to a specific moment improves temporal resolution. Although the previous study used a unimodal TOJ task and thus differs from ours, compared between the JND results of experiment 1 and 2, the voluntary movement could increase temporal attention to the time point of the target stimuli. That is, the voluntary movement could increase the temporal predictability of the stimuli presentation, and attending to the predicted timing could enhance temporal resolution.

In experiment 1, the differences of PSSs between all three movement conditions were not found but in experiment 2, the difference of PSSs between voluntary and involuntary condition were found. As shown in Fig. 3, the value of voluntary-900 and that of involuntary-900 conditions were close and under voluntary condition, as the duration increased, the PSS decreased. That is, near the duration, 900 ms, which we used in experiment 1, the PSS of voluntary condition was in agreement with that of involuntary condition. Therefore, in experiment 1, we did not found the differences of PSSs between movement conditions.

The results of PSSs in experiment 2 could be attribute to attention to tactile sensation. Previous studies revealed an attentional bias known as prior entry ([3, 4, 17]; see also [16], for a review), in timing judgment tasks. Although we instructed participants to attend to tactile sensation in all conditions of our experiment, participants may have paid more attention to the tactile information under the voluntary-300 condition than under the involuntary-300 condition. Therefore, the processing speed of tactile information under the voluntary-300 condition could be faster compared with the involuntary-300 condition, and the PSS of voluntary-300 condition could shift to the point when auditory stimulus was presented earlier compared with the involuntary-300 condition. On the other hand, participants may have paid less attention to tactile information in the voluntary-1,500 condition more than in the involuntary-1,500 conditions. Therefore, the processing speed of tactile information slowed down under the voluntary-1,500 condition and the PSSs shift to the point when the tactile stimulus was presented earlier. Despite these hypotheses, the relation between the attention to the stimuli and the movement duration is still unclear. This is an interesting topic for future research.

5. CONCLUSION

Not proprioceptive information but voluntary movement affects simultaneous perception. Voluntary movements enhanced the temporal resolution of simultaneous perception when the prediction of timing of stimuli presentation is available. PSS shifts from auditory-first presentation to tactile-first presentation according to increasing of the voluntary movement duration. Our results of PSSs suggest that the longer the duration of voluntary movement, the less attention tactile signals are paid to.

REFERENCES

[1] J. V. Hanson, J. Heron and D. Whitaker, "Recalibration of perceived time across sensory modalities",

Experimental Brain Research, Vol. 185, pp. 347–352, 2008.
[2] M. Zampini, S. Guest, D. I. Shore and C. Spence, "Audio-visual simultaneity judgments", *Perception & Psychophysics*, Vol. 67, pp. 531–544, 2005.
[3] C. Spence, C. I. Shore and R. M. Klein, "Multisensory prior entry", *Journal of Experimental Psychology*, Vol. 130, pp. 799–832, 2001.
[4] M. Zampini, D. I. Shore and C. Spence, "Audiovisual prior entry", *Neuroscience Letter*, Vol. 381, pp. 217–222, 2005.
[5] P. A. Lewis and R. C. Miall, "Distinct systems for automatic and cognitively controlled time measurement: Evidence from neuroimaging", *Current Opinion in Neurobiology* Vol. 13, pp. 250–255, 2003.
[6] V. Santangelo and C. Spence, "Crossmodal exogenous orienting improves the accuracy of temporal order judgments", *Experimental Brain Research*, Vol. 194, pp. 577–586, 2009.
[7] Y. Sugita and Y Suzuki, "Audiovisual perception: Implicit estimation of sound-arrival time", *Nature*, Vol. 421, pp. 911, 2003.
[8] M. Zampini, D. I. Shore and C. Spence, "Audiovisual temporal order judgments", *Experimental Brain Research*, Vol 152, pp. 198–210, 2003.
[9] W. Fujisaki and S. Nishida, "Audiotactile superiority over visuo-tactile and audio-visual combinations in the temporal resolution of synchrony perception", *Experimental Brain Research*, Vol. 198, pp. 245–259, 2009.
[10] W. Fujisaki, S. Shimojo, M. Kashino and S. Nishida, "Recalibration of audiovisual simultaneity", *Nature Neuroscience*, Vol. 7, pp. 773–778, 2004.
[11] C. Stetson, X. Cui, P. R. Montague and D. M. Eagleman, "Motor-sensory recalibration leads to an illusory reversal of action and sensation", *Neuron* Vol. 51, pp. 651–659, 2006.
[12] Y, Sugano, M. Keetels, and J. Vroomen, "Adaptation to motor-visual and motor-auditory temporal lags transfer across modalities", *Experimental Brain Research*, Vol. 201, pp. 393–399, 2010.
[13] Z. Shi, S. Hirche, W. X. Schneider and H. Muller, "Influence of visuomotor action on visual-haptic simultaneous perception: A psychophysical study", *In Proceedings of 2008 Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, Reno, USA, March, pp. 65–70, 2008.
[14] D. Wenke, and P. Haggard, "How voluntary actions modulate time perception", *Experimental Brain Research*, Vol. 196, pp. 311–318, 2009.
[15] A. Correa, D. Sanabria, C. Spence, P. Tudela and J. Lupianez, "Selective temporal attention enhances the temporal resolution of perception: Evidence from a temporal order judgment task", *Brain Research*, Vol. 1070, pp. 202–205, 2006.
[16] C. Spence, and C. Parise, "Prior-entry: A review", *Consciousness & Cognition*, Vol. 19, pp. 364–379, 2010.
[17] E. B. Titchener, "Lectures on the elementary psychology of feeling and attention", Macmillan, New York, 1908.
[18] D. J. Finney, "Probit analysis: a statistical treatment of the sigmoid response curve", Cambridge University Press, Cambridge, 1952.
[19] H. Tanaka, C. Worringham and G. Kerr, "Contributions of vision-proprioception interactions to the estimation of time-varying hand and target locations", *Experimental Brain Research*, Vol. 195, pp. 371–382, 2009.
[20] K. M. Bausenhart, B. Rolke and R. Ulrich, "Temporal preparation improves temporal resolution: Evidence from constant foreperiods", *Perception & Psychophysics*, Vol. 70, pp. 1504–1514, 2008.