博士論文

Spatiotemporal organization of whole-body rhythmic movement using self-generated information

（自己生成情報を用いた全身リズム運動の時空間的組織化）

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Contents of the thesis

Chapter 1:

Brief history of the study

Human movement results from the interaction between the body and environment. The perceptual information of the environment prompts the body to organize movement, and movement generates perceptual information. In this way, human movement is a process that circulates dynamically with perceptual information.

These facts suggest a new way of exercise support using the environmental information that promotes movement pattern formation. For instance, a rhythmic auditory stimulus is expected as the environmental information that induces pattern formation of movement. There are many studies using rhythmic auditory stimulation as a means for enhancing performance in practical settings (McIntosh et al. 1997; Arias & Cudeiro 2008; Hove et al. 2012; Thaut & Abiru 2010; Bood et al. 2013; Hoffmann et al. 2012).

Meanwhile, the environmental information derives not only from the exterior. The hallmark of living organisms is that they generate information by themselves while they perceive the environment and act on it. This self-generated information can also prompt the body to organize movement. Vocalization is one of the fundamental activities of human to make a sound with one's voice. In the example of RAS, human beings can generate a rhythmic auditory stimulus by themselves using vocalizations. This rhythmic auditory stimulus generated by vocalizations might promote pattern formation of movement.

Previous researches have investigated the interaction between vocalizations and movement. The focus of this studies is the effect of vocalizations on force production (Ikai 1961; Kijima & Choshi 2006). In this thesis, I attempted to reveal the effect of vocalizations on rhythmic movement. In this chapter, I introduce the brief history of the studies related to this thesis, dynamical system approach, and exercise support using rhythmic auditory stimulation.

1.1 Dynamical system approach

Dynamical system approach is an approach to the study of systems that evolves with time (Kelso 1995; Haken 1977). The main idea is that the spatial and temporal patterns in systems can emerge spontaneously, and this pattern formation is a collective phenomenon and results from the interaction of various constraints. Haken, Kelso, and Bunz (Haken et al. 1985) firstly used dynamical system approach to the study of human motor control. They used rhythmic bimanual coordination in the transverse plane as shown in Fig. 1-1. Participants in this task were instructed to begin either in the in-phase pattern (index fingers moving toward and away from each other) or the anti-phase pattern (the fingers moving parallel). The movements carried out in time with a metronome.

Participants could perform the task well at lower movement frequency. When the fingers start in the anti-phase pattern and driving movement frequency approaches the critical frequency from a low value, the standard deviation of the relative phase between the two fingers raised suddenly near or at the critical frequency. Then abrupt transition from the anti-phase pattern to the in-phase pattern occurred at the critical frequency. This transition is called *phase transition* and is often taken as the landmark feature of a dynamical system. If the fingers first oscillate in the in-phase pattern, phase transitions and critical fluctuation do not occur. Phase transitions have been major focus of study because it provides a special entry point for experimentally identifying the collective variables or *order parameter* characterizing states of coordination and the *control parameter* that influences the coordination dynamics. Haken, Kelso, and Bunz (Haken et al. 1985) offered an equation that described the coordination dynamics using relative phase of the left and right fingers as an order parameter, and movement frequency as a control parameter as bellow:

$$V(\phi) = -acos(\phi) - bcos(2\phi) \tag{1.1}$$

where the Greek letter ϕ denotes relative phase, *a* and *b* are real numbers, and $V(\phi)$ denotes potential energy as a function of ϕ. The ratio *b/a* is relevant to movement frequency.

Fig. 1-2 shows the potential landscape, $V(\phi)$, as a function of the ratio *b/a*. When *b/a* equals 1, the potential landscape has two local minima. These two local minima indicate that both the in-phase pattern (relative phase = 0°) and the anti-phase pattern (relative phase = 180°) are stable at low movement frequency. However as *b/a* approaches 0, the potential landscape has just one local minimum, indicating that the anti-phase pattern becomes unstable and only the in-phase pattern is stable at the corresponding movement frequency. Consequently, phase transition occurs from the anti-phase pattern to the in-phase pattern.

In addition to the bimanual coordination (Kelso 1981; Kelso 1984; Haken et al. 1985), phase transition and the same coordination dynamics have been observed in various experimental model systems, such as intra-limb coordination (Buchanan et al. 1997; Kelso et al. 1991), sensorimotor coordination (Kelso et al. 1990; Miura et al. 2011; Miura et al. 2013), and social coordination between two people (Richardson et al. 2007; Schmidt et al. 1990). These findings suggest that rhythmic coordination of human movement is governed by general dynamical principles. In this way, dynamical system approach has offered a theoretical framework for analyzing human rhythmic coordination. It is also powerful tool for the study of the coordination between self-generated information (vocalizations) and movement.

1.2 Exercise support using rhythmic auditory stimulation

The perspective that movement results from the interaction between the body and the environment leads an idea that objective movement can be organized by manipulating the environmental information. Previous studies have reported that rhythmic auditory stimulation (RAS) enhances performances in practical settings, particularly gait rehabilitation and sports.

With respect to gait rehabilitation, there are many studies reporting the effectiveness of RAS on parkinsonian gait (McIntosh et al. 1997; Arias & Cudeiro 2008; Hove et al. 2012; Thaut & Abiru 2010). McIntosh et al. (McIntosh et al. 1997) have investigated the effect of RAS on gait velocity, cadence, stride length, and symmetry in 21 patients with Parkinson's disease (PD) on medication, 10 PD patients off medication, and 10 healthy age matched participants as a control group. Patients and participants were instructed to walk in four conditions: their own maximal speed without RAS, with RAS frequency matched to the baseline cadence, with RAS 10 % faster than the baseline cadence, and without RAS to test for short-term carry-over effects. Faster RAS produced significant improvement in mean gait velocity, cadence, and stride length in all groups. These facilitating effects of RAS on gait performance have also been reported in patients with hemiparetic stroke (Muto et al. 2012) and traumatic brain injury (Thaut & Abiru 2010).

In terms of sports, previous research demonstrated that RAS enhances performance in sports that are cyclic in nature, such as running and cycling. In the study of Bood et al. (Bood et al. 2013), participants were asked to run as long as they could in three conditions; a control condition without RAS, a metronome condition with a sequence of metronome beats matched to participants' cadence, and a music condition with synchronous motivational music matching participants' cadence. As a result, time to exhaustion was significantly longer with RAS than without. There was no difference between metronome and motivational music conditions, despite differences in motivational quality. Hoffmann et al. (Hoffmann et al. 2012) have investigated the effect of metronome beats on Locomotor-Respiratory Coupling that is a universal phenomenon underlying the production and supply of energy. When participants were instructed to cycle in cadence with rhythmic auditory stimulus, an increase in Locomotor-Respiratory Coupling and a corresponding decrease in energy consumption were observed.

One of the reasons for these performance enhancements due to RAS relates to movement stabilization. Movement stabilization occurs probably because a coordination pattern is generated with external acoustic stimuli that are more stable than human movement. Then, increments in movement stability might reduce energy loss accompanied with accelerations and decelerations in rhythm.

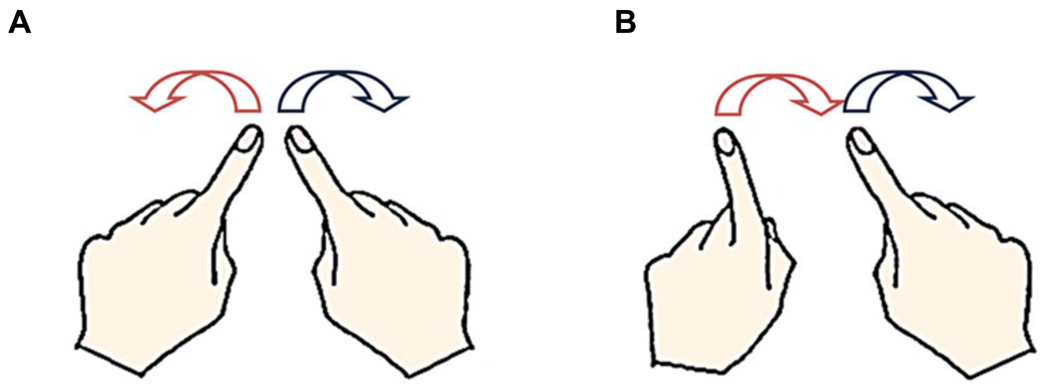

Fig. 1-1 In-phase coordination pattern (A) and anti-phase coordination pattern (b).
From Sleimen-Malkoun, R., Temprado, JJ., & Hond, L. (Sleimen-Malkoun et al. 2014).

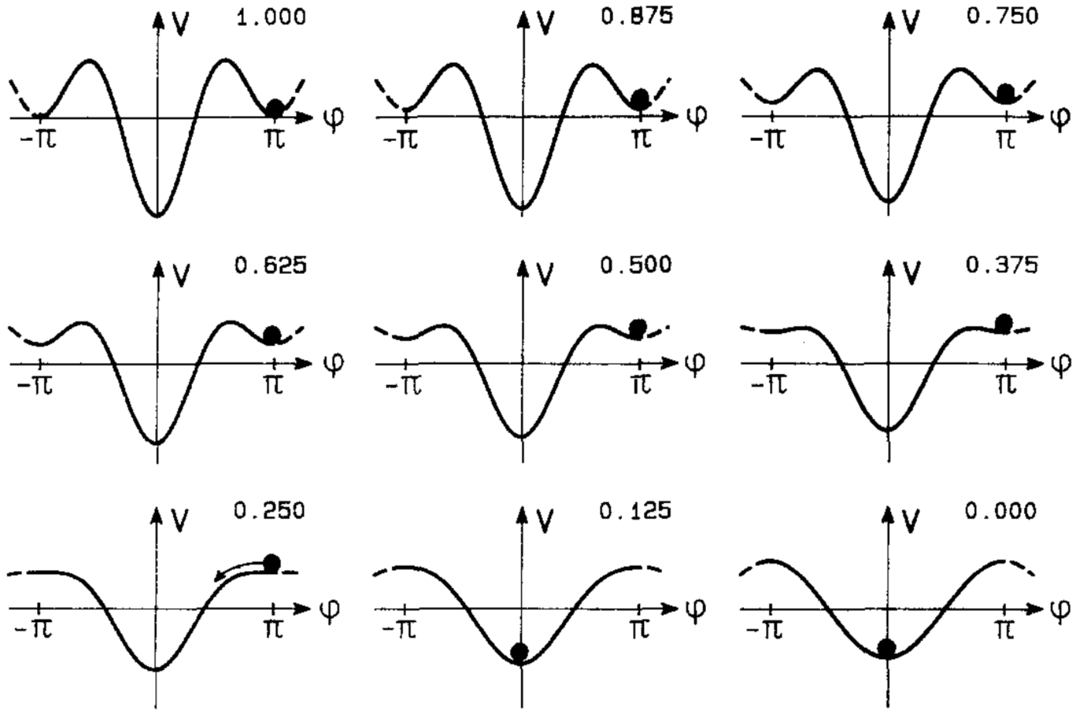

Fig. 1-2 The potential, *V*, as a function of relative phase, ϕ, depending on the ratio *b*/*a*.
From Haken, H., Kelso, J.A.S., & Bunz, H. (Haken et al. 1985).

Chapter 2:

The purpose and outline of this thesis

As mentioned in *the brief history of the study* (Chapter 1), a self-organized pattern formation has been reported in inter-limb, intra-limb and auditory-motor coordination (Haken et al. 1985; Kelso 1981; Kelso 1984; Buchanan et al. 1997; Kelso et al. 1991; Miura et al. 2011; Miura et al. 2013; Kelso 1995). Furthermore, previous studies have reported that RAS stabilizes human movement (Arias & Cudeiro 2008; Hausdorff et al. 2007; Thaut & Abiru 2010; Muto et al. 2012). This movement stabilization might be due to self-organizing pattern formation between human movement and rhythmic auditory stimuli. These rhythmic auditory stimuli are generated by not only external devices but also one's own movement, such as vocalization.

The general purpose of this thesis is to explore whether self-generated information through vocalizations can organize stable whole-body movement. To achieve this end, four experiments were conducted.

The focus of Experiment 1 (Chapter 3) is coordination dynamics between vocalizations and whole-body movement. Phase transition and a stable coordination pattern indicate the formation of coordination pattern (Haken et al. 1985; Kelso 1981; Kelso 1984; Buchanan et al. 1997; Kelso et al. 1991; Miura et al. 2011; Miura et al. 2013). Therefore, I investigated whether there is a stable coordination pattern between vocalizations and whole-body movement.

The focus of Experiment 2 (Chapter 3) is the effect of coordination between vocalizations and whole-body movement on the stability of two movements. I investigated movement stabilization through comparisons of temporal variability between movements performed independently and in a stable coordination pattern.

A vocalization has two aspects, a vocalization as movement and a voice as an acoustic stimulus. In Experiment 3 (Chapter 4), the focus is the effect of vocalizations as movement on a stable coordination pattern and stabilization effect of vocalizations on whole-body movement. I explored this effect by interfering auditory feedback using white noise masking.

Practical motor performances are often required to be in accordance with the environment that changes with time. The ability of coordination with external events has been investigated mainly by rhythmic coordination task of perception and action. Auditory-motor coordination is one of the action-perception coordination, in which participants coordinate rhythmic movement with external auditory stimuli (Repp 2005). The focus of Experiment 4 (Chapter 5) is the effect of vocalizations on the stability of auditory-motor coordination. The stability of coordination was evaluated by the SD of relative phase between metronome beats and joint movement.

Chapter 6 contains a general discussion of all experiments. The coordination dynamics between vocalizations and whole-body movement, and the stabilization effect of vocalizations on whole-body movement and auditory-motor coordination are discussed. Based on the present findings, I attempt to provide some practical implications.

Chapter 3: Experiment 1 and 2

Mutual Stabilization of

Rhythmic Vocalization and Whole-Body Movement

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3.1 Introduction

Rhythmic auditory stimulation (RAS) is expected to be a means for enhancing performance in practical settings, particularly gait rehabilitation and sports. With respect to gait rehabilitation, extensive clinical studies have shown that RAS improves several aspects of gait timing among patients with Parkinson's disease, such as gait tempo, stride length, and the magnitude of stride-time variability (Arias & Cudeiro 2008; Hausdorff et al. 2007; McIntosh et al. 1997; Thaut & Abiru 2010; Rubinstein et al. 2002; Lim I, van Wegen E, de Goede C, Deutekom M, Nieuwboer A 2005). These facilitating effects of RAS on gait performance have also been reported in patients with hemiparetic stroke (Muto et al. 2012) and traumatic brain injury (Thaut & Abiru 2010). In terms of sports, previous research demonstrated that RAS enhances performance in sports that are cyclic in nature such as running and cycling (Bood et al. 2013; Hoffmann et al. 2012). In regard to running, Bood et al. (Bood et al. 2013) reported that time to exhaustion was longer with metronome beats than without. RAS also reduced energy costs during cycling (Hoffmann et al. 2012). One of the reasons for enhancing performance due to RAS relates to movement stabilization. Rhythmic acoustic stimuli generated by external devices are more stable than human movement so that movement stabilization occurs when accompanied with external acoustic stimuli, such as metronome beats.

Meanwhile, not only external devices but also vocalizations can generate rhythmic acoustic stimuli. One question is whether vocalizations that generate rhythmic acoustic stimuli could be a possible alternative to metronome beats for enhancing performance through movement stabilization. Concerning interactions between concurrent vocalizations and movements, several studies have suggested an interfering effect of vocalizations on motor performance (Hicks 1975; Hiscock & Chipuer 1986; Inhoff & Bisiacchi 1990; Pashler 1994; Hiscock & Inch 1995; Kinsbourne & Hicks 1978). For example, Hiscock and Chipuer (Hiscock & Chipuer 1986) asked participants to rhythmically tap a telegraph key while reciting verbal sentences that had an irregular rhythm; they found that variability in the tapping interval increased due to the concurrent vocalization. This suggested there was interference between speech and manual tapping. Inhoff and Bisiacchi (Inhoff & Bisiacchi 1990) also reported that vocalizations with relatively complex articulation increase tapping variability. These studies suggest that dual-task interference occurs between vocalizations and manual task performance. However, more recent studies on coordination dynamics indicate that an interaction between vocalizations and other active effectors can be understood as being coupled and coordinated systems (Kelso et al. 1983; Kelso 1995; Treffner & Peter 2002). In this dynamical view, while coupled systems can behave with large fluctuations in terms of relative timing as reported by studies on dual-task interference (Hiscock & Chipuer 1986; Pashler 1994), they can also act as a single functional unit or coordinative structure through functional coupling or mutual constraint between the systems (Kugler et al. 1980). Previous studies have suggested that behaving as a coordinative structure can decrease temporal variability (Helmuth & Ivry 1996; Drewing & Aschersleben 2003). For example, Helmuth and Ivry (Helmuth & Ivry

1996) reported reduced variance during bimanual as compared to unimanual finger tapping, referred to as the bimanual advantage. They also demonstrated that this bimanual advantage was obtained during tapping movements with non-homologous effectors such as the finger and forearm. Therefore, it can be hypothesized that concurrent vocalizations that are well coupled with rhythmic movement can decrease the variability of that rhythmic movement, and vocalization as well.

Human rhythmic coordination, such as auditory-motor, inter-limb, and intra-limb coordination, has often been investigated in the context of the phase transition paradigm. In this paradigm, increasing movement frequency plays a critical role in the organization of human coordination patterns (Kelso et al. 1990; Miura et al. 2011; Miura et al. 2013). At low movement frequencies, there are no significant differences in the stability of two distinct coordination patterns, such as in-phase vs. anti-phase, synchronization vs. syncopation, or flexion-on-the-beat vs. extension-on-the-beat, during human rhythmic movements. However, as movement frequency increases, a spontaneous transition occurs from a less stable coordination pattern to a more stable one. This transition is called *phase transition*. Miura et al. (Miura et al. 2011; Miura et al. 2013) investigated metronome beats and whole-body movement coordination involving flexing and extending one’s knees repeatedly in a standing posture with metronome beats. They demonstrated that increased movement frequency induced phase transition from an extension-on-the-beat to a flexion-on-the-beat coordination pattern. This can be understood as there being two *attractors* during both coordination patterns at a low movement frequency. From there, the extension-on-the-beat *attractor* was lost due to incremental movement frequency, and a transition to the flexion-on-the-beat occurred. This also indicates that the flexion-on-the-beat is a stable coordination pattern. This phenomenon have also been observed during inter-limb (Haken et al. 1985; Kelso 1981; Kelso 1984) and intra-limb coordination (Buchanan et al. 1997; Kelso et al. 1991). These findings suggest that rhythmic movement coordination is governed by general dynamical principles.

In the example of the bimanual advantage (Helmuth & Ivry 1996), the phase relation of bimanual tapping is in-phase (i.e., a stable coordination pattern during inter-limb coordination). When investigating movement stabilization due to rhythmic vocalization, it is necessary to investigate the property of coordination between vocalizations and rhythmic movement to reveal a stable coordination pattern. Previous studies have reported a stable coordination pattern during auditory-motor (Kelso et al. 1990; Miura et al. 2013; Miura et al. 2011), inter-limb (Haken et al. 1985; Kelso 1981; Kelso 1984), and intra-limb coordination (Buchanan et al. 1997; Kelso et al. 1991). Therefore, it can be hypothesized that there is also a stable coordination pattern between vocalizations and movement. Indeed, Treffner and Peter (Treffner & Peter 2002) demonstrated that transition from anti-phase coordination (syncopated or alternated speech-tapping) to in-phase coordination (synchronized speech-taping) occurred during a speech-hand coordination task when a metronome frequency as a pacing signal increased. Since they used metronome beats to manipulate movement frequency, a stable coordination pattern was induced by the external pacing signal.

The central goal for Experiment 1 and 2 was to investigate whether variability in rhythmic movement is reduced through coordination with vocalizations within a stable coordination pattern. The aim of the first experiment was to examine whether there is a stable coordination pattern between vocalizations and movement without metronome beats. I used similar methods from a previous studies by Miura et al. (Miura et al. 2013; Miura et al. 2011), including a whole-body movement task, pace manipulation, and analyses. I used two kinds of coordination patterns between whole-body movement and vocalizations in a standing posture: flexion-on-the-voice condition (hip, knee, and ankle joint flexion with vocalization) and extension-on-the-voice condition (joint extension with vocalization). I expected that when movement frequency is increased, relatively unstable coordination pattern is replaced by a stable coordination pattern. The aim of the second experiment was to investigate whether variability in whole-body movement and vocalizations decreases through coordination during a stable coordination pattern. I focused on temporal stability and regarded decreases in movement variability as increases in movement stability. The variability of vocalizations and whole-body movement was assessed by the standard deviation (SD) of the interval and compared between two conditions; one condition included the tasks performed in a stable coordination pattern (coordination condition), and the other included tasks being performed independently (control condition). I expected that variability of the two movements would be smaller in the coordination condition than in the control condition.

3.2 Experiment 1

3.2.1 Methods

Participants

Fourteen healthy volunteers (14 males; aged 23–36 years) participated in this experiment. All had no known neurological or movement deficits and were non-dancers recruited from the University of Tokyo community. All participants signed an informed consent document before participating. The Ethics Committee of the Graduate School of Arts and Sciences, the University of Tokyo, approved this experiment.

Experimental task

The task included a whole-body movement of flexing and extending one's hip, knee, and ankle joints repeatedly to go up and down one's center of mass while maintaining a standing posture. The task also included the vocalization "ta" at a 1:1 frequency locking with the whole-body movement. Participants were instructed to stand with their feet roughly at shoulder width and look at a fixation point on a wall at a distance of 1 m. The repetitive flexing and extending movement was the same as in previous studies (Miura et al. 2013; Miura et al. 2011). Participants were asked to flex and extend their hip, knee, and ankle joints in a comfortable angular range without their feet leaving the ground. The repetitive vocalization was performed at each participant's usual speech volume. Although participants were asked to continue to vocalize as much as they could, they were allowed to temporarily stop the vocalization if they wanted to breathe. Two different coordination patterns were investigated: flexion-on-the-voice and extension-on-the-voice (Fig. 3-1). In the flexion-on-the-voice condition, participants flexed their hip, knee, and ankle joints in line with a vocalization (Fig. 3-1A). In the extension-on-the-voice condition, participants extended their joints in line with a vocalization (Fig. 3-1B). The phase transition paradigm needs to manipulate movement frequency continuously within a trial. Since it is difficult for participants to control movement frequency systematically without metronome beats, I aimed at capturing a stable coordination pattern and manipulated movement frequency in separate trials. The movement frequency was set at 80, 130, and 180 beats per minute (bpm), and task duration was approximately 35, 25, and 20 seconds, respectively. There were approximately 40 cycles for each flexion and extension trial. Before each recording, participants listened to metronome beats as a reference for movement frequency. Then participants performed the tasks at the memorized frequency without auditory signals to help with pacing. Trials where the average frequency was within ±20 bpm of the assigned frequency were defined as successful trials. As a result, approximately 4 % of all trials were removed and re-recorded. During task performance, participants were instructed not to move any other parts of their body other than the hip, knee, and ankle joints.

Design and procedure

Participants went through 18 trials (2 coordination patterns × 3 movement frequencies × 3 repetitions). The first 3 cycles were discarded to remove unstable coordination, and subsequent 30 cycles were analyzed for each participant. I also conducted the analysis with the inclusion of all cycles and checked the consistent results. Trial order was randomized. Before the experimental session, participants practiced the tasks for a few minutes. Participants were instructed to keep a one-to-one correspondence between their whole-body movement and vocalizations and not resist any pattern change; additionally, they were asked to establish the most comfortable pattern. Participants had brief breaks between trials in order to limit fatigue.

Data collection and analysis

Knee angular displacement as a representative of joint motion of the extension-flexion movement was measured using an electro goniometer (Biometrics Ltd, SG150, Newport, United Kingdom) attached to the right knee joint. Vocalization was measured using a headset microphone (SHURE, WH20XLR, Chicago, USA) and amplified (audio-technica, AT-MA2, Tokyo, Japan). All data were digitized at 1 kHz using an analog-digital converter (ADI Instrument, PowerLab 4/25 s, NSW, Australia). Angular displacement data were filtered using a low-pass filter (cutoff frequency = 7 Hz). The cutoff frequency was determined from a residual analysis of the difference between the filtered (at cutoff frequencies in the range 1-20 Hz) and the unfiltered data (Winter 2009). Angular velocities were obtained by differential calculus of angular displacement data. Angular displacement and angular velocity were normalized and plotted on the phase plane (Fig. 3-2A). The vocal onset times were defined when voice amplitude exceeded a threshold set at approximately 20% of the average peak value and superimposed on the phase plane trajectory. Vocal onsets in the flexion-on-the-voice (Fig. 3-2B) and extension-on-the-voice (Fig. 3-2C) conditions were expressed in solid and open dots, respectively. The relative phase angle between the knee movement and voice, and its SD, were calculated using circular statistics (Batschelet 1981). In the flexion-on-the-voice condition, the phase angle was calculated from the peak knee flexion point (Fig. 3-2B); in the extension-on-the-voice condition, the angle was calculated from the peak knee extension point (Fig. 3-2C).

Statistical analysis

Two-way analyses of variance (ANOVAs) with two within-subject factors, coordination pattern (flexion on the voice and extension on the voice) and movement frequency (80, 130, and 180 bpm), were performed on mean voice frequency, mean SD of the voice frequency, and mean SD of the phase angle. Since the phase angle of voice time in the extension-on-the-voice condition did not have a normal distribution at 130 bpm, a Wilcoxon matched-pairs signed rank test was performed at 130 bpm to compare the coordination patterns. Separate ANOVAs were performed on phase angle of voice time at 80 and 180 bpm. If Mauchly's test of sphericity was significant, then the Greenhouse-Geisser corrections were used to identify the significance of the main effects and interactions. The statistical significance level was set at $p < .05$.

3.2.2 Results

Voice Frequency

Voice frequency mean and SD were measured in order to determine whether participants performed tasks at the appropriate frequency. Fig. 3-3A shows mean voice frequency. A two-way ANOVA revealed a significant main effect of movement frequency, $F(2, 26) = 2862.1$, $p < .001$, but the main effect of coordination pattern was not significant, $F(1, 13) = .39$, $p = .54$. The two-way interaction was also not significant, $F(2, 26) = .92$, $p = .41$. The mean voice frequency was approximately the same for the specified voice frequency and was not significantly different between the flexion-on-the-voice and extension-on-the-voice conditions.

Fig. 3-3B shows the SD of voice frequency. A two-way ANOVA revealed a significant main effect of movement frequency, $F(1.11, 14.42) = 113.98$, $p < .001$, and coordination pattern, $F(1, 13) = 6.55$, $p = .02$. However, the two-way interaction was not significant, $F(1.31, 16.99) = 1.19$, $p = .31$. The SD of voice frequency in the extension-on-the-voice condition was significantly larger than that in the flexion-on-the-voice condition.

Phase angle of voice time

Fig. 3-4 shows typical examples of the phase plane trajectories and vocal onsets for one participant. In the flexion-on-the-voice condition, participants performed this task successfully for all movement frequencies (Fig. 3-4A). In contrast, in the extension-on-the-voice condition, replacement of knee extension on the voice by knee flexion on the voice occurred at a movement frequency of 180 bpm (Fig. 3-4B).

The phase angle of voice time was calculated to quantify the relationship between voice and knee movement. Fig. 3-5A shows the mean phase angle of the voice time as a function of movement frequency. The phase angle of the voice time in the extension-on-the-voice condition was significantly larger than that in the flexion-on-the-voice condition for all movement frequencies of 80, 130, and 180 bpm, $F(1,13) = 5.7$, $p = .03$; $p = .01$; $F(1,13) = 153.65$, $p < .001$, respectively.

Fig. 3-5B shows the SD of the phase angle as a function of movement frequency. A two-way ANOVA revealed a significant main effect of movement frequency, $F(1.2, 15.58) = 13.28$, $p < .01$, and coordination pattern, $F(1, 13) = 54.8$, $p < .001$. However, the two-way interaction was not significant, $F(1.12, 14.59) = 4.05$, $p = .06$. The SD of the phase angle in the flexion-on-the-voice condition was significantly smaller than in the extension-on-the-voice condition.

3.3 Experiment 2

3.3.1 Methods

Participants

The same 14 participants from Experiment 1 participated in Experiment 2.

Experimental task

Participants performed two tasks: one was flexing and extending their hip, knee, and ankle joints repeatedly without vocalization; the other task was to repeat the vocalization “ta” without any body movement. The movement frequencies were set at 80, 130, and 180 bpm, and task durations were approximately 35, 25, and 20 seconds, respectively. The number of flexing and extending cycles or vocalizations during each trial was approximately 40. Before each recording, participants listened to metronome beats as a reference frequency for the task. Then, participants performed the tasks at the memorized frequency without auditory pacing signals. Thus, trials where the average frequency was within ± 20 bpm of the assigned frequency were defined as successful trials. As a result, approximately 4 % of all trials were removed and re-recorded.

Design and procedure

Participants performed 18 trials (2 tasks × 3 movement frequencies × 3 repetitions) on a different day from Experiment 1 to preclude any memory effects of the vocalization, which could affect performance. Furthermore, the whole-body movement task was also conducted before the vocalization task. The time interval between the 2 experiments was at least 60 days. Trial order was randomized for each task. The first 3 cycles of each trial were discarded to remove unstable coordination. The subsequent 30 flexing and extending cycles or vocalizations were analyzed for each trial. I also conducted the analysis with the inclusion of all cycles and checked the consistent results.

Data collection and analysis

The apparatus and data recording were the same as in Experiment 1. For Experiment 2, I focused on temporal stability. In order to investigate whether the variability of whole-body movement and vocalizations was reduced when two movements are coordinated during a stable coordination pattern (flexion-on-the-voice), the variability of whole-body movement and vocalizations was compared between two conditions (i.e., control vs. coordination condition). Participants were asked to repeat hip, knee, and ankle joint flexion and extension in a standing position without vocalization or repeat vocalizations without any body movement in the control condition. In the coordination condition, participants were instructed to coordinate hip, knee, and ankle joint flexion with a vocalization. Variability of whole-body movement was evaluated by the SD of the peak knee flexion interval (I_{knee}) measured by calculating the time interval between knee flexion peaks. Variability in vocalizations was also compared between the two conditions, which was evaluated by the SD of the vocal onset interval (I_{voc}) measured by calculating the time interval between vocal onsets. Knee movement and vocalization data in the flexion-on-the-voice condition recorded in Experiment 1 were used for the coordination condition in Experiment 2. The data of knee movement and vocalization recorded in Experiment 2 were used as the control condition. The order of conditions was not randomized so that order and learning effects could affect results.

Statistical analysis

Two 2-way ANOVAs with one between-subject factor (condition: control and coordination) and one within-subject factor (movement frequency: 80, 130, and 180 bpm) were performed on the SD of I_{knee} and I_{voc}. If the two-way interaction was significant, I performed separate post-hoc ANOVAs for movement frequency. If Mauchly's test of sphericity was significant, then Greenhouse-Geisser corrections were used to identify the significance of the main effect and interaction.

3.3.2 Results

SD of I_{knee} and I_{voc}

In order to investigate the effect of coordination with vocalizations on the variability of whole-body movement, the SD of I_{knee} was calculated and compared among conditions (Fig. 3-6A). I also computed the SD of I_{voc} in order to explore the effect of coordination with whole-body movement on the variability of vocalizations (Fig. 3-6B).

Fig. 3-6A shows the SD of I_{knee}. A two-way ANOVA revealed significant main effects of movement frequency, $F (1.42, 36.81) = 83.64$, $p < .001$, and condition, $F (1, 26) = 5.4$, $p = .03$. However, the two-way interaction was not significant, $F (1.42, 36.81) = 2.59$, $p = .1$. The SD of I_{knee} in the coordination condition was significantly smaller than that in the control condition.

Fig. 3-6B shows the SD of I_{voc}. A two-way ANOVA revealed a significant two-way interaction, $F (2, 52) = 4.25$, $p = .02$, and separate post-hoc ANOVAs were performed to compare the control and coordination conditions at each movement frequency. The

SD of I_{voc} in the coordination condition was significantly smaller than that in the control condition at 80 bpm, $F(1, 26) = 9.92$, $p < .01$. Although it was not significant, the SD of I_{voc} in the coordination condition was also smaller than that in the control condition at 130 bpm, $F(1, 26) = 3.11$, $p = .09$.

3.4 Discussion of Experiment 1 and 2

The purpose of Experiment 1 was to examine whether there is a stable coordination pattern between vocalizations and whole-body movement. Participants conducted two types of coordination patterns between a vocalization and whole-body movement: hip, knee, and ankle joint flexion with a vocalization and joint extension with a vocalization at different movement frequencies. As movement frequency increased, the phase angle of voice time in the extension-on-the-voice condition shifted away from the required phase angle. Contrary to the extension-on-the-voice condition, the phase angle in the flexion-on-the-voice condition did not show this shift. Furthermore, the SD of the phase angle in the flexion-on-the-voice condition was smaller than that in the extension-on-the-voice condition. These results suggest that the flexion-on-the-voice coordination pattern was more stable than was the extension-on-the-voice coordination pattern.

Experiment 1 did not use metronome beats to manipulate movement frequency while participants performed the tasks. In order to verify that these results were not due to differences in movement frequency, I calculated the mean voice frequency and the SD of voice frequency. Although the SD of voice frequency in the extension-on-the-voice condition was larger than in the flexion-on-the-voice condition, the mean voice frequency was not significantly different between the conditions, suggesting that participants performed the tasks successfully and vocalized with similar frequency in both conditions.

A stable coordination pattern in vocalization and whole-body movement coordination was expected from previous studies on auditory-motor (Kelso et al. 1990; Miura et al. 2013; Miura et al. 2011), inter-limb (Haken et al. 1985; Kelso 1981; Kelso 1984), and intra-limb coordination (Buchanan et al. 1997; Kelso et al. 1991). Actually, a stable coordination pattern has been demonstrated between vocalizations and finger tapping, although metronome beats were used as a pacing signal (Treffner & Peter 2002). Thus, there remained the possibility that the stable coordination pattern was induced by the external pacing signal. My results showed a stable coordination pattern between vocalization and whole-body movement without metronome beats. This result suggests that vocalization and movement coordination obeys general dynamical principles and provides additional evidence that human movement coordination is governed by general dynamical principles.

In this experiment, participants were instructed to flex or extend their joints with a vocalization. The results showed that they synchronized vocalizations and the commencement that an angular velocity decreases. This tendency was also observed in previous research, suggesting that this is general phenomenon on auditory-motor coordination of whole-body movement. The extensor group of lower limb is activated before reaching the peak knee flexion, which is expected to be the highest muscle activity within a cycle. There might be the property of synchronization between the highest muscle activity and a vocalization or a metronome beat.

In previous studies on various forms of human coordination (Kelso et al. 1990; Miura et al. 2011; Miura et al. 2013; Haken et al. 1985; Kelso 1981; Kelso 1984; Buchanan et al. 1997; Kelso et al. 1991), movement frequency plays a critical role in the transition of coordination patterns. In the present experiment, a similar phenomenon was observed. The increased movement frequency induced the deviation of the phase angle in the extension-on-the-voice condition from the intended phase angle but not in the flexion-on-the-voice condition. In typical examples of phase plane trajectories and vocal onsets for one participant in the extension-on-the-voice condition (Fig. 3-4B), the voice onsets settled into the flexion-on-the-voice coordination pattern at 180 bpm. The group data for the phase angle of voice time also showed that the phase angle at 180 bpm in the extension-on-the-voice condition was the flexion-on-the-voice coordination pattern because the angle at 180 bpm was about 180 degrees greater than at 80 bpm (Fig. 3-5A). Although I did not use the phase transition paradigm, a phase transition from the extension-on-the-voice to the flexion-on-the-voice coordination pattern was estimated from my results and examples of phase transitions in previous studies (Kelso et al. 1990; Miura et al. 2011; Miura et al. 2013; Haken et al. 1985; Kelso 1981; Kelso 1984; Buchanan et al. 1997; Kelso et al. 1991).

The aim of Experiment 2 was to explore whether the variability of whole-body movement and vocalizations is reduced when two movements are coordinated in a stable coordination pattern (flexion-on-the-voice). In order to evaluate the variability of whole-body movement, the SD of I_{knee} was calculated and compared between two conditions: control condition (hip, knee, and ankle joint flexion without vocalization) and coordination condition (joint flexion on the voice). The SD of I_{knee} in the coordination condition was smaller than in the control condition. I also compared the SD of I_{voc} in the two conditions. The SD of I_{voc} in the coordination condition was also smaller than in the control condition at 80 and 130 bpm. At 180 bpm, the SD of I_{voc} did not differ between the two conditions. This might be because the vocalization interval was short at 180 bpm in which vocalizations could be perturbed occasionally for respiration or gas exchange.

Trials in the coordination and control conditions were not randomized to exclude any memory of vocalizations, which could affect performance. However, in studies where conditions are not randomized, order and learning effects could affect obtained results. My results showed that the SD of I_{knee} and I_{voc} in the control condition was larger than in the coordination condition. These results demonstrated that learning effects were likely negligible since performance conducted 60 days later actually diminished rather than improved.

Several studies have reported that vocalization has an interfering effect on motor performance (Hiscock & Inch 1995; Hiscock & Chipuer 1986; Kinsbourne & Hicks 1978; Hicks 1975; Inhoff & Bisiacchi 1990; Pashler 1994), suggesting that dual-task interference occurs between concurrent vocalizations and manual activity. Previous dual-task studies have reported interference, which refers to decrements in performance for one or both tasks when two activities are carried out concurrently (Pellecchia & Turvey 2001; Pellecchia 2003). Pellecchia and Turvey (Pellecchia & Turvey 2001) reported that errors on a bimanual coordination task increased when coupled with arithmetic tasks. Performing vocalizations and whole-body movement concurrently might also be a dual-task. However, results showed that each rhythmic movement was not detrimentally affected, even though each movement was performed as part of a dual-task. Pellecchia (Pellecchia 2003) reported that dual-task training, but not single-task training, reduced dual-task interference. This finding suggests that strengthening the linkage between the component tasks is important. In line with this suggestion, studies on coordination dynamics indicate that an interaction between vocalizations and other active effectors can be well understood as coupled systems (Kelso et al. 1983; Kelso 1995; Treffner & Peter 2002). Movement stabilization through acting as a coordinative structure has been reported in previous studies (Helmuth & Ivry 1996; Drewing & Aschersleben 2003). The results also showed the variability of vocalizations and whole-body movement coordination was reduced when being coordinated in a stable manner.

Vocalization and whole-body movement coordination differs from inter-limb and intra-limb coordination in that vocalization has two aspects of movement and auditory feedback. Drewing and Aschersleben (Drewing & Aschersleben 2003) have reported that the bimanual advantage is due to an increase in sensory information such as proprioceptive sensibility. That is, timing is better as more sensory information becomes available. Therefore it can be expected that vocalizations and movement coordination is more stable than inter-limb and intra-limb coordination. On the other hand, Helmuth and Ivry (Helmuth & Ivry 1996) argued that there are different timing signals associated with each limb, and the bimanual advantage is due to output integration of effector-specific timers. They explained that the unimanual and bimanual conditions can be considered as two pendulums of different mass. The smaller pendulum can represent the unimanual condition. The larger pendulum can represent the bimanual condition, where two small pendulums have been strictly coupled (and thus have larger mass). The larger pendulum is less subject to a perturbation than is the smaller one, indicating that the bimanual condition has reduced variability. In case of that, there would be no advantage of vocalizations and movement coordination. Future research I should address these two possibilities, increased sensory information and the integration of effector-specific timer output.

There might be stabilization mechanisms specific to the interaction between vocalizations and motor performance based on neurophysiological evidence. For instance, increases in excitability of corticospinal pathways toward dominant hand muscles due to vocalizations has been reported in previous studies (Tokimura et al. 1996; Seyal et al. 1999), suggesting that vocalizations facilitate hand movement. On the other hand, Broca's area, the cortical area for speech production and articulation, is also activated by hand movement (Gallese et al. 1996). These neurophysiological results indicate mutual facilitation between vocalizations and hand movement. Although motor task in this experiment was more global than simply hand movements, mutual facilitation between vocalizations and whole-body movement might appear as mutual stabilization.

A stable coordination pattern between vocalizations and whole-body movement indicates coordination between voices as acoustic stimuli and/or vocalizations as movement and whole-body movement. A stable coordination pattern between external acoustic stimuli and rhythmic movement has been reported in previous studies on auditory-motor coordination (Kelso et al. 1990; Miura et al. 2013; Miura et al. 2011). Thus, a stable coordination pattern between voices as acoustic stimuli and whole-body movement should occur. The possibility of a stable coordination pattern between vocalizations as movement and whole-body movement is also suggested by previous studies on inter-limb (Haken et al. 1985; Kelso 1981; Kelso 1984) and intra-limb coordination (Buchanan et al. 1997; Kelso et al. 1991). Furthermore, mutual stabilization between vocalizations and whole-body movement, also indicate voices as acoustic stimuli and/or vocalizations as movement stabilize whole-body movement. In the future, I plan to investigate whether there is a stable coordination pattern and mutual stabilization between vocalizations as movement and whole-body movement. This will be done by obstructing or manipulating auditory feedback to reveal each effect of vocalizations as acoustic stimuli and movement.

Previous studies have reported that various types of motor performance are enhanced by RAS (Thaut & Abiru 2010; Rubinstein et al. 2002; Lim I, van Wegen E, de Goede C, Deutekom M, Nieuwboer A 2005; McIntosh et al. 1997; Arias & Cudeiro 2008; Hausdorff et al. 2007; Muto et al. 2012; Bood et al. 2013; Hoffmann et al. 2012). The present results are relevant for practical exercise support without the aid of an external device. My results suggest the possibility that motor performance could be enhanced through vocalizations. Exercise support using vocalizations has been conducted, and performance enhancement on certain motor tasks has been reported in previous studies (Maitra et al. 2003; Park et al. 2009). However, this past research was conducted with older adults and patients with hemiparetic stroke while examining discrete and partial movement. My results showed an effect of vocalizations among healthy young men while performing continuous and whole-body movement. In the future, I will investigate the usability of vocalizations for motor learning and clinical settings such as gait rehabilitation.

In summary, I revealed that the flexion-on-the-voice coordination pattern was stable, and the SD of I_{knee} and I_{voc} in the coordination condition was smaller than that in the control condition. This suggests that vocalization and whole-body movement strengthened each other's companion stability.

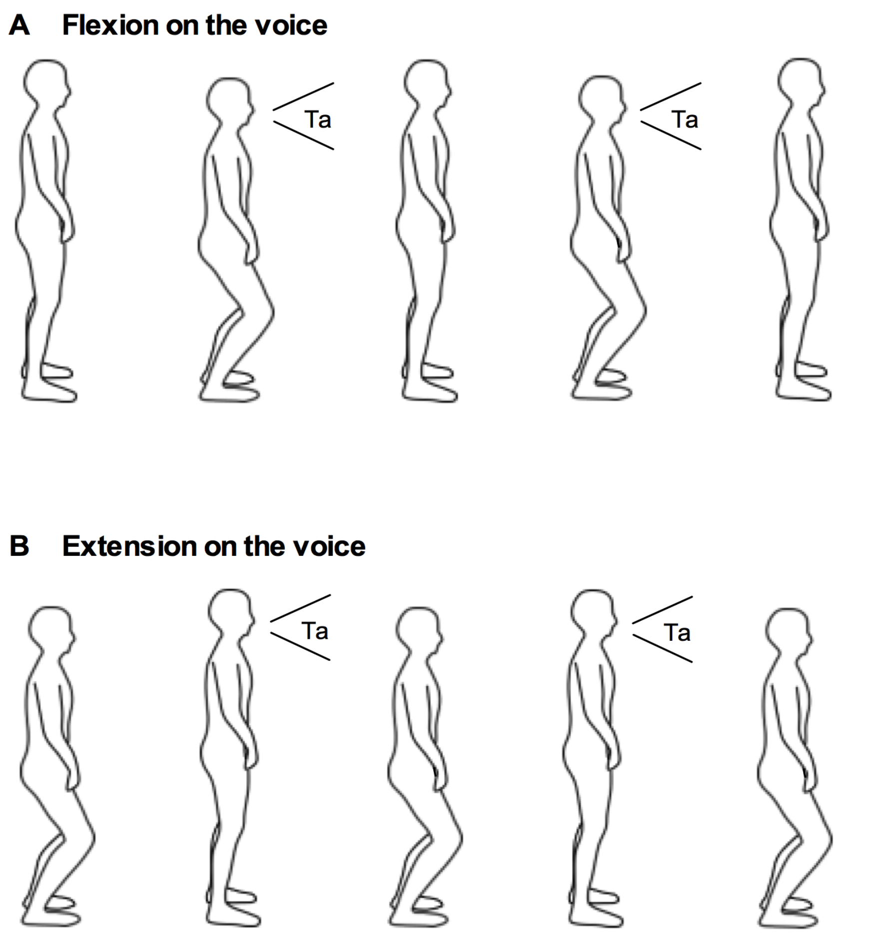

Fig. 3-1 Flexion on the voice condition (A) and extension on the voice condition (B). In the flexion-on-the-voice condition, participants flexed their hip, knee, and ankle joints in line with a vocalization (A). In the extension-on-the-voice condition, participants extended their joints in line with a vocalization (B).

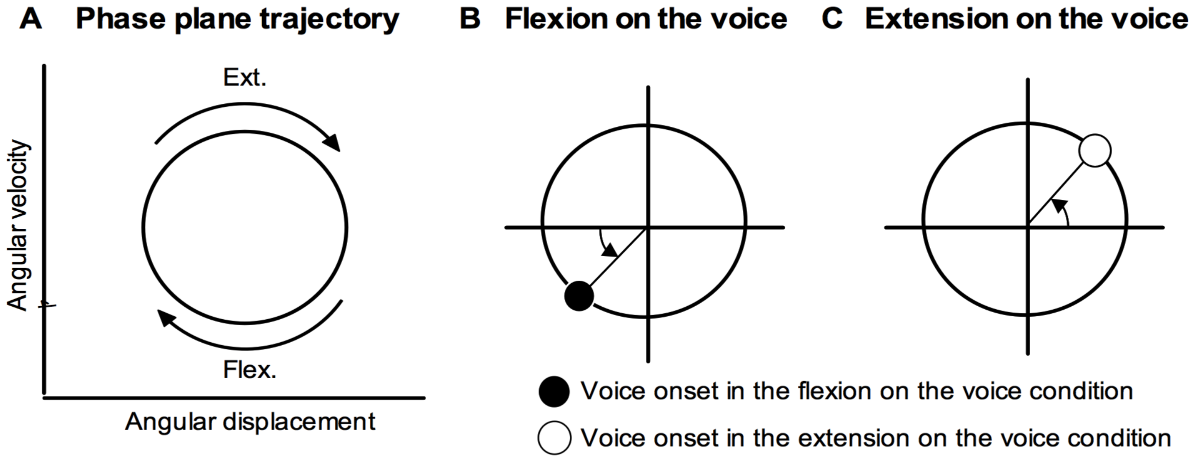

Fig. 3-2 Knee movement trajectory and voice time on the phase plane.
Knee movement trajectory on the phase plane (A). The phase angle is expressed as the difference from the peak knee position. In the flexion-on-the-voice condition, difference between voice time and the peak knee-flexion point is calculated (B), and in the extension-on-the-voice condition, difference between voice time and the peak knee-extension point is calculated (C).

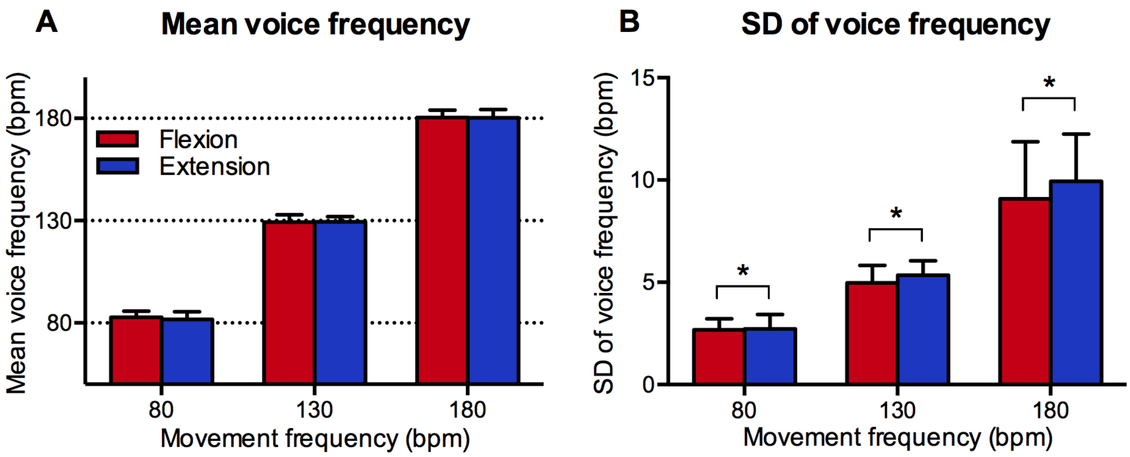

Fig. 3-3 Mean voice frequency (A) and SD of voice frequency (B).
Vertical bars represent between-participant standard deviations.

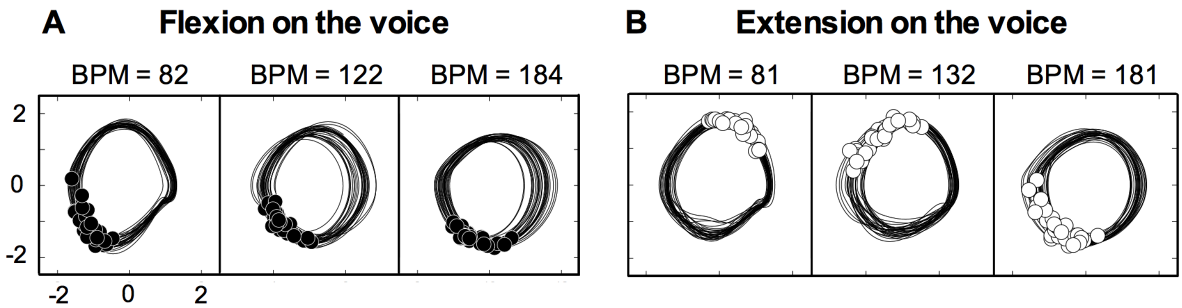

Fig. 3-4 Typical examples of the phase angle of voice time for one participant. The value at the top of each trajectory is the average voice frequency in each trial. In the extension-on-the-voice condition (B), the replacement of joint extension on the voice by joint flexion on the voice occurred at 180 bpm. This replacement did not occur in the flexion-on-the-voice condition.

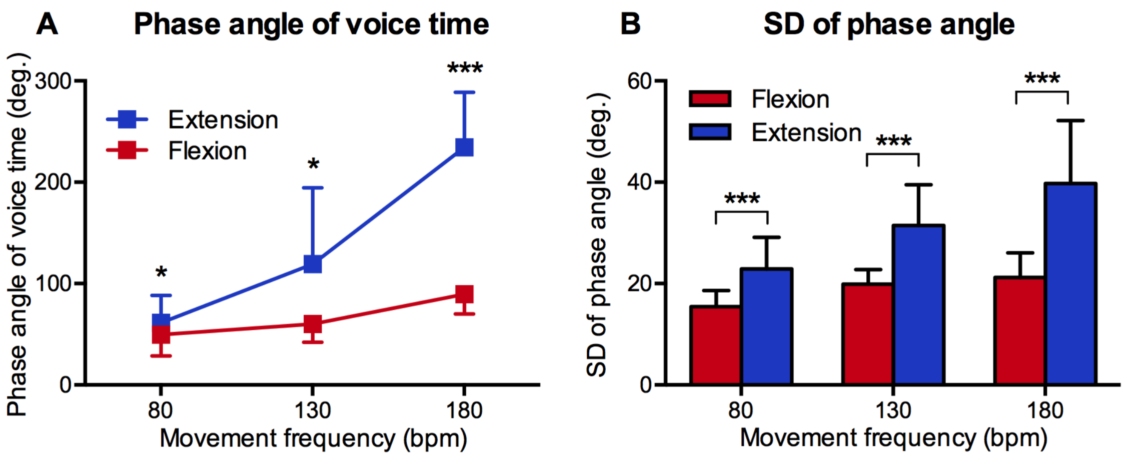

Fig. 3-5 Phase angle of voice time (A) and SD of phase angle (B).
Vertical bars represent between-participant standard deviations.

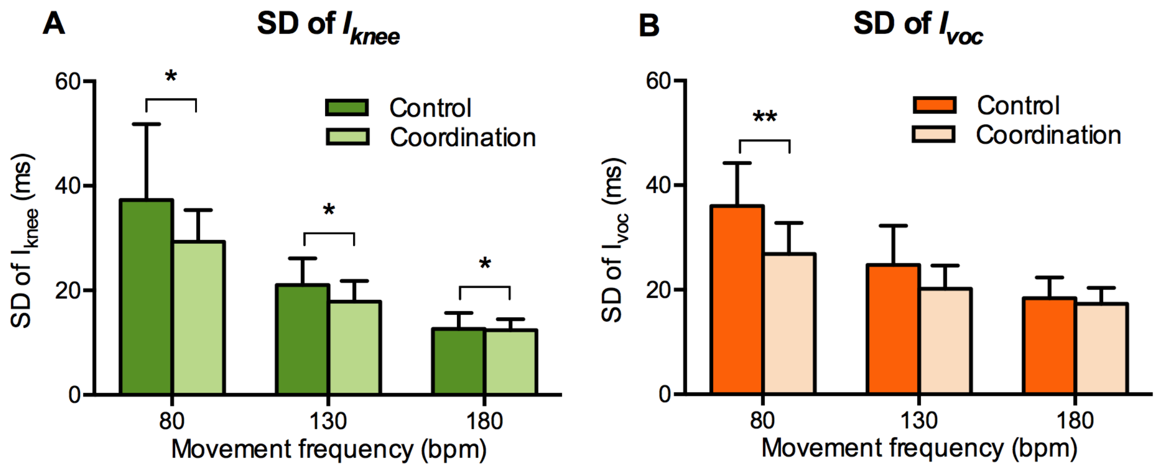

Fig. 3-6 SD of I_{knee} (A) and I_{voc} (B).
Vertical bars represent between-participant standard deviations.

Chapter 4: Experiment 3

Stabilization Effect of Vocalization on Whole-Body Movement under Interference with Auditory Feedback

4.1 Introduction

In Experiment 1 and 2 (Chapter 3), it was revealed that there was a stable coordination pattern between vocalizations and whole-body movement, and the variability of both movements was reduced when two movements were coordinated in a stable coordination pattern.

A vocalization has two aspects, a vocalization as movement and a voice as an acoustic stimulus. Therefore, a stable coordination pattern between vocalizations and whole-body movement indicates the coordination between voices as acoustic stimuli and/or vocalizations as movement and whole-body movement. A stable coordination pattern between external acoustic stimuli and rhythmic movement has been reported in previous studies on auditory-motor coordination (Kelso et al. 1990; Miura et al. 2011; Miura et al. 2013). Miura et al. (Miura et al. 2011) have reported that there is a stable coordination pattern between metronome beats and whole-body movement that doesn't change even though movement frequency increases. Thus, a stable coordination pattern between voices as acoustic stimuli and whole-body movement is expected to emerge.

The possibility of a stable coordination pattern between movement of vocalizations and whole-body movement is also suggested by previous studies on inter-limb (Haken et al. 1985; Kelso 1981; Kelso 1984) and intra-limb coordination (Buchanan et al. 1997; Kelso et al. 1991). Kelso (Kelso 1984) has reported phase transition in inter-limb coordination with index fingers. When movement frequency increased, an anti-phase pattern in which homologous muscle groups contracting alternatively was suddenly changed to an in-phase pattern in which homologous muscle groups contracting concurrently at a critical frequency. This transition indicates that the in-phase coordination pattern is more stable than anti-phase pattern. Phase transition is also observed in intra-limb coordination (Buchanan et al. 1997; Kelso et al. 1991). These findings suggest that human rhythmic movement is governed by general dynamical principles regardless of what body parts are involved, leading a hypothesis that a stable coordination pattern may also be observed between movement of vocalizations and whole-body movement.

Furthermore, mutual stabilization between vocalizations and whole-body movement also indicates that voices (acoustic stimuli) and/or vocalizations (movement) stabilize whole-body movement. Movement stabilization by rhythmic auditory stimuli has been reported by previous studies (Arias & Cudeiro 2008; Hausdorff et al. 2007; Thaut & Abiru 2010; Muto et al. 2012). For instance, Muto et al. (Muto et al. 2012) have reported that the gait of hemiparetic stroke patients is stabilized by an walking-supporting apparatus called Walk-Mate that generates rhythmic auditory stimuli in response to a patient's gait in real time.

In regard to movement stabilization by coordinating two movements, Helmuth and Ivry (Helmuth & Ivry 1996) have reported bimanual advantage, reduced variance during bimanual as compared to unimanual finger tapping. The bimanual advantage was obtained with non-homologous effectors, finger and forearm tapping. These findings lead a hypothesis that vocalizations as movement reduce the variability of rhythmic movement.

The purpose of Experiment 3 was twofold: first, to investigate whether there is a stable coordination pattern between movement of vocalizations and whole-body movement, second, to explore whether the variability of whole-body movement is reduced by movement of vocalizations by interfering with auditory feedback. Auditory feedback was interfered by white noise masking. A stable coordination between vocalizations and whole-body movement even under the auditory feedback interference is suggested by previous studies on inter-limb and intra-limb coordination (Haken et al. 1985; Kelso 1981; Kelso 1984; Buchanan et al. 1997; Kelso et al. 1991). Furthermore, previous studies reporting bimanual advantage (Helmuth & Ivry 1996; Drewing & Aschersleben 2003) suggest that movement of vocalizations can stabilize whole-body movement. Therefore it can be hypothesized that the variability of whole-body movement is reduced by vocalizations even under interference with auditory feedback.

4.2 Methods

Participants

Fourteen males (23-36 years) from the University of Tokyo community participated in this experiment. They received compensation for participation in the experiment. None reported any health problem. This experiment conformed to the Declaration of Helsinki, and informed written consent was obtained from all participants. This experiment was approved by the Ethics Committee of the Graduate School of Arts and

Sciences, the University of Tokyo.

Experimental task

Participants were instructed to perform whole-body movement of flexing and extending one's hip, knee, and ankle joints in a comfortable angular range repeatedly while keeping a standing posture. The task also included the vocalization "ta" at a 1:1 frequency locking with the whole-body movement. Although participants were asked to continue to vocalize as long as they could, they were allowed to temporarily stop the vocalization if they wanted to breathe. Auditory feedback was masked by white noise through a noise-canceling headphone (Bose, Quiet Comfort 15, Massachusetts, USA). All participants but one reported they could not hear their own voice due to white noise masking. Therefore one participant was excluded from this experiment.

Two different coordination patterns were investigated: flexion-on-the-voice and extension-on-the-voice. In the flexion-on-the-voice condition, participants flexed their hip, knee, and ankle joints in line with a vocalization. In the extension-on-the-voice condition, participants extended their joints in line with a vocalization. The phase transition paradigm needs to manipulate movement frequency continuously within a trial so that pacing signals are often used, such as metronome beats. However these pacing signals can affect coordination dynamics. At the same time, it is difficult for participants to control movement frequency systematically without pacing signals. Therefore, I aimed at capturing a stable coordination pattern and manipulated movement frequency in separate trials. The movement frequency was set at 80, 130, and

180 beats per minute (bpm), and task duration was approximately 35, 25, and 20 seconds, respectively. There were approximately 40 cycles for each flexion and extension trial. Before each recording, participants listened to metronome beats as a reference for movement frequency. Then participants performed the tasks at the memorized frequency without auditory signals to help with pacing. Trials where the average frequency was within ±20 bpm of the assigned frequency were judged as successful trials. As a result, approximately 3 % of all trials were removed and re-recorded.

Design and procedure

Participants went through 18 trials (2 coordination patterns × 3 movement frequencies × 3 repetitions). The first 3 cycles of each trial were discarded to remove unstable coordination, and subsequent 30 flexion and extension cycles were analyzed for each participant. Trial order was randomized. Before the experimental session, participants practiced the tasks for a few minutes. Participants were instructed to keep a one-to-one correspondence between their whole-body movement and a vocalization and not resist any pattern change; additionally, they were asked to establish the most comfortable pattern.

Moreover I investigated whether the variability of whole-body movement was reduced by stable coordination with vocalizations (flexion-on-the-voice) even under white noise masking. The variability of whole-body movement was compared between three conditions; control, coordination without white noise masking (No-MSK), and coordination with white noise masking (MSK). In the control condition, participants were asked to repeat hip, knee, and ankle joint flexion and extension in a standing position without vocalizations. In the No-MSK condition, participants were instructed to coordinate hip, knee, and ankle joint flexion with a vocalization with auditory feedback. For these two conditions, the data recorded in Experiment 1 and 2 were appropriated. For the MSK condition, the data of knee movement in the flexion-on-the-voice condition was recorded anew. The order of conditions was not randomized so that order and learning effects could affect results.

Data collection and analysis

Knee angular displacement as a representative of joint motion of the extension-flexion movement was measured using an electro goniometer (Biometrics Ltd, SG150, Newport, United Kingdom) attached to the right knee joint. Vocalizations were measured using a headset microphone (SHURE, WH20XLR, Chicago, USA) and amplified (audio-technica, AT-MA2, Tokyo, Japan). All data were digitized at 1 kHz using an analog-digital converter (ADI Instrument, Power Lab 4/25 s, NSW, Australia). Angular displacement data were filtered using a low-pass filter (cutoff frequency = 7 Hz). Angular velocities were obtained by differential calculus of angular displacement data. Angular displacement and angular velocity were normalized and plotted on the phase plane. The vocal onset times were defined when voice amplitude exceeded a threshold set at approximately 20% of the average peak value and superimposed on the phase plane trajectory. The relative phase angle between the knee movement and voice, and its SD, were calculated using circular statistics (Batschelet 1981). In the flexion-on-the-voice condition, the phase angle was calculated from the peak knee flexion point; in the extension-on-the-voice condition, the angle was calculated from the peak knee extension point. The variability of whole-body movement was evaluated by the SD of the peak knee flexion interval (I_{knee}) measured by calculating the time interval between knee flexion peaks.

Statistical analysis

Three, 2-way analyses of variance (ANOVAs) with two within-subject factors, coordination pattern (flexion on the voice and extension on the voice) and movement frequency (80, 130, and 180 bpm), were performed on (1) the mean voice frequency, (2) the mean SD of the voice frequency, and (3) the mean SD of the phase angle. Since the phase angle of voice time in the extension-on-the-voice condition did not have a normal distribution at 130 bpm, a Wilcoxon matched-pairs signed rank test was performed at 130 bpm to compare the coordination patterns. Separate ANOVAs were performed on the phase angle of voice time at 80 and 180 bpm. A two-way ANOVA with one between-subject factor (condition: control, No-MSK, and MSK) and one within-subject factor (movement frequency: 80, 130, and 180 bpm) were performed on the SD of I_{knee}. If the two-way interaction was significant, separate post-hoc ANOVAs were performed for each movement frequency. If Mauchly's test of sphericity was significant, then the Greenhouse-Geisser corrections were used to identify the significance of the main effects and interactions. The statistical significance level was set at $p < .05$.

4.3 Results

Voice Frequency

The mean and SD of voice frequency were measured in order to determine whether participants performed the tasks at the appropriate frequency. Fig. 4-1A shows the mean voice frequency. A two-way ANOVA for mean voice frequency revealed a significant main effect of movement frequency, F (2, 24) = 2982.25, p < .001, but the main effect of coordination pattern was not significant, F (1, 12) = .01, p = .91. The two-way interaction was also not significant, F (2, 24) = .37, p = .70. The mean voice frequency was approximately the same for the specified voice frequency and was not significantly different between the coordination conditions.

Fig. 4-1B shows the SD of voice frequency. A two-way ANOVA for the SD of voice frequency revealed a significant main effect of movement frequency, F (1.1, 13.23) = 49.76, p < .001, and coordination pattern, F (1, 12) = 6.47, p = .03. On the other hand, the two-way interaction was not significant, F (1.12, 13.39) = .27, p = .64. The SD of voice frequency in the extension-on-the-voice condition was significantly larger than that in the flexion-on-the-voice condition.

Phase angle of voice time

The phase angle of voice time was calculated to quantify the relationship between voices and knee movement. Fig. 4-2A shows the mean phase angle of the voice time as a function of movement frequency. The phase angle of the voice time in the extension-on-the-voice condition was significantly larger than that in the flexion-on-the-voice condition for all movement frequencies of 80, 130, and 180 bpm, F (1, 12) = 12.46, $p < .01$; $p < .01$; F (1, 12) = 174.1, $p < .001$, respectively.

Fig. 4-2B shows the SD of the phase angle as a function of movement frequency. A two-way ANOVA revealed a significant main effect of movement frequency, F (2, 24) = 4.25, $p = .03$, and coordination pattern, F (1, 12) = 22.09, $p < .01$. On the other hand, the two-way interaction was not significant, F (2, 24) = 1.57, $p = .23$. The SD of the phase angle in the flexion-on-the-voice condition was significantly smaller than that in the extension-on-the-voice condition.

SD of I_{knee}

In order to investigate whether vocalizations reduce the variability of whole-body movement under interference with auditory feedback, the SD of I_{knee} was calculated and compared among conditions. Fig. 4-3 shows the SD of I_{knee}. A two-way ANOVA revealed a significant two-way interaction, F (3.1, 55.77) = 2.83, $p < .05$. Thus, separate post-hoc ANOVAs were performed to compare the coordination conditions at each movement frequency. A separate post-hoc ANOVA revealed a significant effect of coordination condition at 80 bpm, F (2, 36) = 3.72, $p = .03$. A multiple comparison with Bonferroni correction revealed marginally significant differences: The SD of I_{knee} in the No-MSK and MSK conditions were smaller than that in the control condition, $p = .06$ and .09, respectively.

4.4 Discussion

In this experiment, I did not use any pacing signal while participants performed the tasks because it can affect a stable coordination pattern. In order to verify that the results were not due to the difference in movement frequency, I calculated the mean and SD of voice frequency. Although the SD of voice frequency in the extension-on-the-voice condition was significantly larger than that in the flexion-on-the-voice condition, the mean voice frequency was not significantly different between the conditions. These results suggest that participants performed the tasks successfully and vocalized with similar frequency in both coordination conditions.

The first purpose of this experiment was to investigate whether there is a stable coordination pattern between movement of vocalizations and whole-body movement by interfering with auditory feedback. In the flexion-on-the-voice condition, the phase angle of voice time was kept even at high movement frequency. On other hand, the phase angle was deviated from the intended phase angle in the extension-on-the-voice condition. In the extension-on-the-voice condition, the degree of phase angle at 180 bpm was approximately 180 degrees more than that at 80 bpm, suggesting that coordination pattern was changed from the extension-on-the-voice pattern to the flexion-on-the-voice pattern. These results imply that there was a stable coordination pattern between vocalizations as movement and whole-body movement, and that is joint flexion with vocalizations.

In Experiment 1, a stable coordination pattern was also joint flexion with a vocalization. Similarly, Miura et al. (Miura et al. 2011) have reported a stable coordination pattern between metronome beats and whole-body movement is joint flexion on the beat. What factors decide a stable coordination pattern? The stability of rhythmic coordination pattern can be affected by a number of factors, for example, neuromuscular-skeletal properties (Carson 1996), and environmental constrains such as gravity (Carson et al. 2009) or coupling to task-specific environmental events (Fink et al. 2000; Kudo et al. 2006). In particular, Carson et al. (Carson et al. 2009) demonstrated that the effect of gravity on hand auditory-motor coordination using a robotic system that generates artificial gravity. They reported a reverse phenomenon that the upward phase of rhythmic movement coincided with the beat was more stable than that in which downward movement was made on the beat when the effect of gravity was reversed. This reverse phenomenon of a stable coordination pattern can be explained by the economy of action that derived from the exploitation of gravity. My results showed that flexion-on-the-voice coordination pattern (synchronization of knee movement along the gravity with the vocalization) was more stable than extension-on-the-voice (synchronization of knee movement in the opposite direction of gravity with the vocalization). Therefore, one of the reasons for consistent results in this experiment is probably due to the gravitational effect.

The second purpose of this experiment was to examine whether vocalizations reduce the variability of whole-body movement under interference with auditory feedback. The SD of I_{knee} was compared between three conditions, control, No-MSK, and MSK. The data recorded in Experiment 1 and 2 was used as that in the control and No-MSK conditions. In this experiment, the data in the MSK condition was recorded anew.

The result showed the SD of I_{knee} in the MSK condition was smaller than that in the control condition, suggesting that vocalizations as movement reduces the variability of whole-body movement. A stable coordination pattern between movements indicates that they can act as a single functional unit or coordinative structure through functional coupling or mutual constraint between the systems (Kugler et al. 1980). Previous studies have suggested that behaving as a coordinative structure can decrease temporal variability (Helmuth & Ivry 1996; Drewing & Aschersleben 2003). The results of this experiment suggest a stable coordination pattern between movement of vocalizations and whole-body movement. Therefore, vocalizations reduced the variability of whole-body movement probably due to acting as a coordinative structure with that.

In summary, I demonstrated a stable coordination pattern between vocalizations and whole-body movement, and the reduced variability of whole-body movement due to vocalizations under interference with auditory feedback. These results suggest that the coordination between vocalizations as movement and whole-body movement obeys general dynamical principles, and movement of vocalizations reduces the variability of whole-body movement.

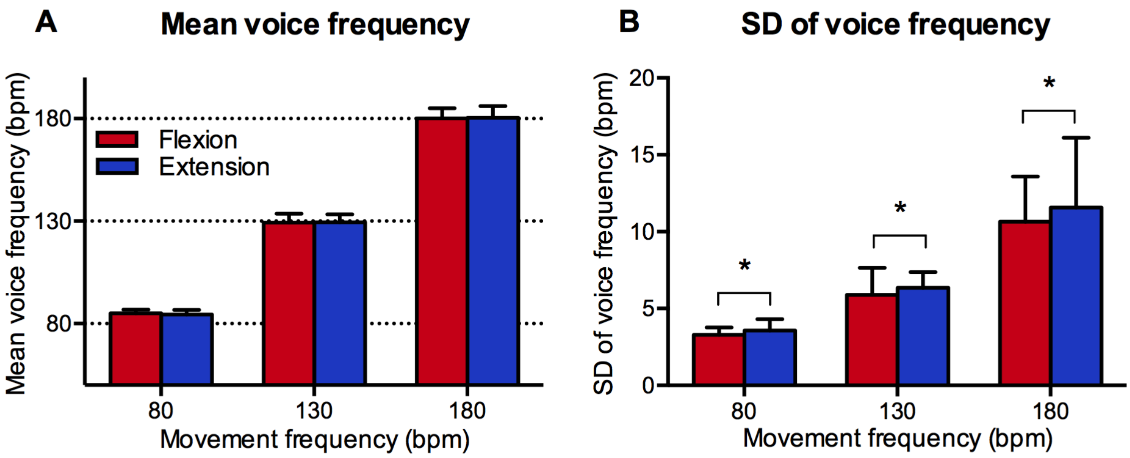

Fig. 4-1 Mean voice frequency (A) and SD of voice frequency (B).
Vertical bars represent between-participant standard deviations.

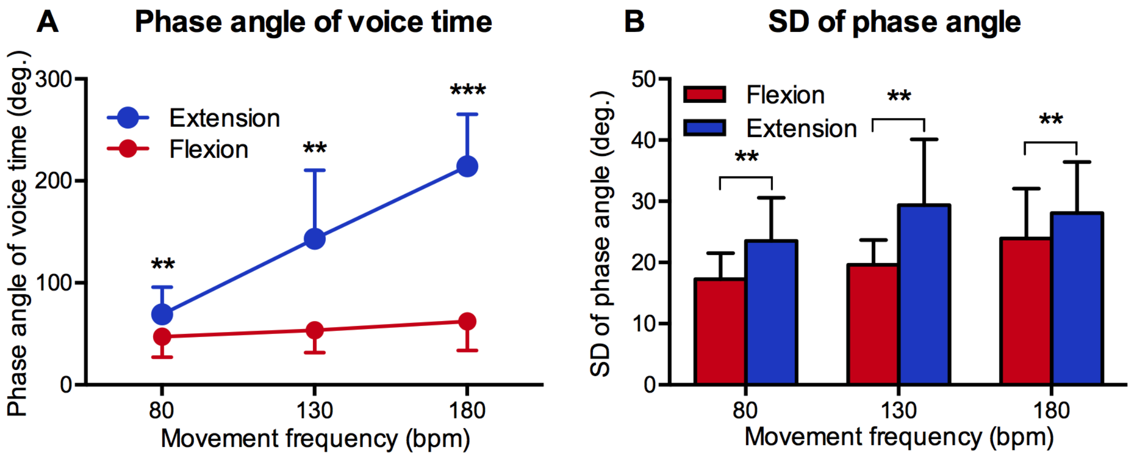

Fig. 4-2 Phase angle of voice time (A) and SD of phase angle (B).
Vertical bars represent between-participant standard deviations.

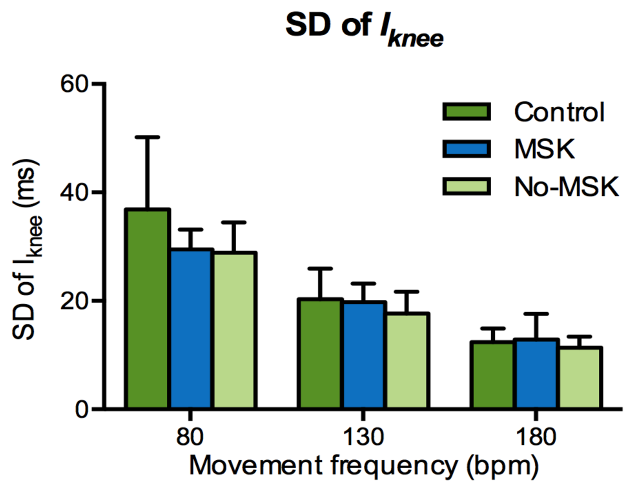

Fig. 4-3 SD of I_{knee}.
The conditions are control, coordination without white noise masking (No-MSK), and coordination with white noise masking (MSK). Vertical bars represent between-participant standard deviations.

Chapter 5: Experiment 4

Effect of Vocalizations on the Stability of Rhythmic Auditory-Motor Coordination

5.1 Introduction

Experiment 1 and 2 (Chapter 3) revealed that concurrent vocalizations temporally stabilize whole-body movement, that is, flexing and extending one's hip, knee, and ankle joints repeatedly.

When actually conduct some kind of movement, we percept the environmental surrounding us and move in accordance with that. The environment changes with time. Therefore, practical motor performance is often required to be temporally coordinated with the surrounding environment. This coordination has been investigated mainly by rhythmic coordination task of perception and action.

Auditory-motor coordination is one of the action-perception coordination, in which participants coordinate rhythmic movement with external auditory stimuli. This coordination ability is important for dance and music performance (Repp 2005; Repp & Su 2013). Previous studies have reported that experts at music and street dance performed more stable auditory-motor coordination than non-experts (Miura et al. 2011; Miura et al. 2013; Repp & Doggett Rebecca 2007; Repp 2010). In the study of Repp et al. (Repp 2010), the variability of the coordination between finger tapping and metronome beats was compared between highly trained musicians and non-musicians. The variability of coordination was evaluated by the SD of asynchrony (SD_{asy}) that calculated from the difference between the time of a finger tap and that of the corresponding beat onset. They have reported that the SD_{asy} for highly trained musicians was lower than that for non-musicians. In the study of Miura et al. (Miura et al. 2011;

Miura et al. 2013), street dancers and non-dancers performed rhythmic whole-body movement in two modes of coordination with metronome beats, flexion-on-the-beat and extension-on-the-beat. In the flexion-on-the-beat condition, participants were required to synchronize knee flexion with each beat of a metronome while keeping a standing posture. In the extension-on-the-beat condition participants were required to synchronize knee extension with each beat of the metronome. As a result, the dancers performed both flexion-on-the-beat and extension-on-the-beat tasks more stably than did the non-dancers. Although phase transition from the flexion-on-the-beat mode to extension-on-the-beat mode occurred as beat frequency increased for both groups, dancers could keep extension-on-the-beat mode at higher movement frequencies than non-dancers. These findings suggest that stable auditory-motor coordination is essential for skilled dance and music performance.

Previous studies have reported that the stability of auditory-motor coordination is affected by several factors, such as haptic information (Kelso et al. 2001), neuromuscular-skeletal properties (Carson 1996; Carson & Riek 1998), and gravitational force (Carson et al. 2009). Among these factors, Kelso et al. (Kelso et al. 2001) investigated the effect of haptic information on the dynamics of finger auditory-motor coordination. When participants started in extension on a metronome beat, there was a tendency to change to flexion at higher frequencies, but not vice versa. However when participants were instructed to touch a physical stop actively that was coincident with the beat, the coordination was stabilized, regardless of whether finger flexion or extension was synchronized with the beat. That is, transitions were not occurred. On the other hand, when haptic contact was counter-phase to the beat, transitions occurred from the extension to flexion on the beat, and from the flexion to extension on the beat. These results suggest that haptic information arising as a result of active touch contributes to the stable coordination. One of the factors for this stabilization effect might be related to perceptual saliency of haptic information. The importance of salient perceptual information for stable coordination has also been suggested in visual information during bimanual coordination. Kovacs et al. (Kovacs et al. 2010) have demonstrated that when participants were provided a Lissajous display with cursor indicating the position of the limbs and a template illustrating the desired movement pattern, participants could perform a difficult 5:3 bimanual coordination pattern after 10 minutes of practice. This result suggests salient perceptual information provided via the Lissajous feedback enabled participants to stably perform less stable coordination pattern. These findings indicate that salient perceptual information is one of the key factors underlying the stable coordination.

The purpose of current experiment is to explore whether vocalizations can stabilize auditory-motor coordination of whole-body. Vocalizations also generate perceptual saliency by repeating syllables, leading a hypothesis that vocalizations stabilize auditory-motor coordination. Furthermore, it has been reported that loss of stability in coordination is one of the key factors underlying pattern change (Schöner & Kelso 1988; Kelso 1995). Fink et al. (Fink et al. 2000) have demonstrated that the stability of coordination carries the global stability of the coordinative patterns. That is, pattern changing occurred less often or at higher movement frequencies when the variability of anti-phase bimanual coordination was reduced. Therefore, it can be hypothesized that pattern change occurs less often or at higher movement frequencies if vocalizations can stabilize the less-stable coordination mode.

On the other hand, Experiment 1 revealed that there was a stable and less-stable coordination relation between vocalizations and whole-body movement, which is similar with the coordination between metronome beats and whole-body movement. These facts suggest that vocalizations stabilized a stable coordination pattern but not less stable one. Therefore, I investigated whether vocalizations reduce the variability of two coordination modes between metronome beats and whole-body movement.

5.2 Methods

Participants

Seven males (23-32 years) from the University of Tokyo community participated in this experiment. None had the experience of the task and reported any health problem. This experiment conformed to the Declaration of Helsinki, and informed written consent was obtained from all participants. This experiment was approved by the Ethics Committee of the Graduate School of Arts and Sciences, the University of Tokyo.

Experimental task

Participants were instructed to perform auditory-motor coordination of whole-body, that is, flexing and extending one's hip, knee, and ankle joints to a metronome beat repeatedly. Two different coordination modes were investigated: flexion-on-the-beat and extension-on-the-beat. In the flexion-on-the-beat condition, participants flexed their hip, knee, and ankle joints to a metronome beat. In the extension-on-the-beat condition, participants extended their joints to a metronome beat. In order to investigate the effect of vocalizations on the auditory-motor coordination of whole-body, two vocalization conditions were investigated; Vocalization and Non-vocalization. In the Vocalization condition, the task also included a vocalization "ta" at a 1:1 frequency locking with a metronome beat. Therefore, participants were instructed to flex their hip, knee, and ankle joints with a vocalization in the flexion-on-the-beat condition, and extend their joints with a vocalization in the extension-on-the-voice condition. Although participants were asked to continue to vocalize as long as they could, they were allowed to temporarily stop the vocalizations if they wanted to breathe. As the Non-vocalization condition, they just perform flexing and extending one's hip, knee, and ankle joints to metronome beats. The beat frequency increased from 80 to 160 beats per minute (bpm) in steps of 20 bpm within one trial. There were 16 beats for each beat frequency. The task duration was 47 seconds.

Design and procedure

Participants went through 12 trials (2 coordination modes × 2 vocalization conditions × 3 repetitions). The first 3 cycles of each beat frequency were discarded to remove unstable coordination, and subsequent 10 flexion and extension cycles were analyzed.

Trial order was randomized between- and within-participants. Before the experimental session, participants practiced the tasks for a few minutes. Participants were instructed to keep a one-to-one correspondence between their whole-body movement and a metronome beat. They were asked not to resist any pattern change, but to establish the most comfortable pattern.

Data collection and analysis

Knee angular displacement as a representative of joint motion of the extension-flexion movement was measured using an electro goniometer (Biometrics Ltd, SG150, Newport, United Kingdom) attached to the right knee joint. All data were digitized at 1 kHz using an analog-digital converter (ADI Instrument, PowerLab 4/25 s, NSW, Australia). Angular displacement data were filtered using a low-pass filter (cutoff frequency = 7 Hz). Angular velocities were obtained by differential calculus of angular displacement data. Angular displacement and angular velocity were normalized and plotted on the phase plane. The beat onset times were defined when beat amplitude exceeded a threshold set at approximately 20% of the average peak beat and superimposed on the phase plane trajectory. The relative phase angle between the knee movement and the beat, and its SD, were calculated using circular statistics (Batschelet 1981). In the flexion-on-the-beat condition, the phase angle was calculated from the peak knee flexion point; in the extension-on-the-beat condition, the angle was calculated from the peak knee extension point.

Statistical analysis

Two, 3-way analyses of variance (ANOVAs) with three within-subject factors, coordination mode (flexion on the beat and extension on the beat), vocalization condition (Vocalization and Non-vocalization), and beat frequency (80, 100, 120, 140, and 160 bpm), were performed on (1) the SD of the phase angle, and (2) the phase angle of the beat time. If the two-way interaction was significant, separate post-hoc ANOVAs were performed. If Mauchly's test of sphericity was significant, then the Greenhouse-Geisser corrections were used to identify the significance of the main effects and interactions. The statistical significance level was set at $p < .05$. Before analyzing the phase angle of voice time on the phase plane, each value was transformed into a value that was closer to the group average, calculated using circular statistics (Batschelet 1981).

5.3 Results

SD of phase angle

Fig. 5-1 shows the SD of the phase angle as a function of beat frequency. The three-way interaction was not significant, F (4, 24) = 2.27, p = .09. The main effect of coordination was significant, F (1, 6) = 9.69, p = .02. On the other hand, two two-way ANOVA (coordination mode × vocalization condition, and coordination mode × beat frequency) were not significant, F (1, 6) = 1.62, p = .25; F (4, 24) = .79, p = .54.

These results indicate that the SD of phase angle in the flexion-on-the-beat condition was significantly smaller than that in the extension-on-the-beat condition in both vocalization conditions.

Since the three-way ANOVA revealed that the beat frequency by vocalization condition interaction was significant, F (4, 24) = 2.91, p = .04, separate post-hoc ANOVAs were performed for comparison between the Non-vocalization and Vocalization conditions at each beat frequency and coordination mode. In the flexion-on-the-beat condition, the SD of phase angle in the Vocalization condition was smaller than that in the Non-vocalization condition, and there was a significant difference at 120 bpm, F (1, 6) = 6.47, p = .04. In the extension-on-the-beat condition, the SD of phase angle in the Vocalization condition was significantly more positive than that in the Non-vocalization condition at 160 bpm, F (1, 6) = 7.96, p = .03. These results imply that vocalizations stabilize auditory-motor coordination in the flexion-on-the-beat condition, but not in the extension-on-the-beat condition.

Phase angle of beat time

Fig. 5-2 shows the mean phase angle of the beat time as a function of beat frequency. A three-way ANOVA was performed on the phase angle of the beat time. The three-way interaction was not significant, F (1.41, 8.44) = 1.01, p = .37. Because the beat frequency by coordination interaction was significant, F (1.67, 9.99) = 13.7, p < .01, separate post-hoc ANOVAs were performed for comparison between the flexion-on-the-beat and extension-on-the-beat conditions at each beat frequency and vocalization condition. In the Non-vocalization condition, the phase angle of the beat time in the extension-on-the-beat condition was significantly larger than that in the flexion-on-the-beat condition at 120, 140, and 160 bpm, $F\ (1, 6) = 6.38$, $p = .05$; $F\ (1, 6) = 10.71$, $p = .02$; $F\ (1, 6) = 13.04$, $p = .01$, respectively. In the Vocalization condition, the phase angle of the beat time in the extension-on-the-beat condition was significantly more positive than that in the flexion-on-the-beat condition for all beat frequencies of 80, 100, 120, 140, and 160 bpm, $F\ (1, 6) = 28.34$, $p < .01$; $F\ (1, 6) = 7.02$, $p = .04$; $F\ (1, 6) = 9.8$, $p = .02$; $F\ (1, 6) = 11.83$, $p = .01$; $F\ (1, 6) = 12.38$, $p = .01$, respectively. These results indicate that at higher beat frequencies under the extension-on-the-beat condition, the phase angle deviated from the intended phase angle in both vocalization conditions.

In the three-way ANOVA on the phase angle of the beat time, the main effect of vocalization condition was not significant, $F\ (1, 6) = .33$, $p = .59$. Two two-way interactions (vocalization condition × coordination mode, and vocalization condition × beat frequency) were also not significant, $F\ (1, 6) = 3.51$, $p = .11$; $F\ (4, 24) = 1.05$, $p = .40$. These results indicate that there was no effect of vocalizations on the mean phase angle of the beat time.

5.4 Discussion

The purpose of this experiment was to explore whether vocalizations can stabilize auditory-motor coordination of whole-body. Participants conducted two types of auditory-motor coordination (flexion-on-the-beat and extension-on-the-beat conditions) under two vocalization conditions (Vocalization and Non-vocalization) at different beat frequencies (80, 100, 120, 140, and 160). In the present experiment, the variability of the coordination was measured using the SD of phase angle. As a result, vocalizations reduced the variability of coordination in the flexion-on-the-beat condition but not in the extension-on-the-beat condition, and did not affect the phase angle of beat time.

Previous studies have reported that the SD of phase angle in the flexion-on-the-beat condition was smaller than that in the extension-on-the-beat condition (Miura et al. 2011; Miura et al. 2013). In this experiment, the similar results with previous study were obtained in both vocalization conditions. Therefore, my results are highly consistent with the previous study.

Comparison between the Vocalization and Non-vocalization conditions revealed that vocalizations significantly reduced the SD of phase angle in the flexion-on-the-beat condition at 120 bpm. Although it was not significant, the SD of phase angle in the flexion-on-the-beat condition was also smaller than that in the extension-on-the-beat condition at another frequencies of 80, 100, 140, and 160 bpm. In the extension-on-the-beat condition, there was no significant difference between the SD of phase angle under the Non-vocalization and Vocalization conditions at from 80 to 140 bpm. At 160 bpm, the SD of phase angle under the Vocalization condition was significantly larger than that under the Non-vocalization condition. This may be because participants tried to restore coordination of joint extension with the voice at 160 bpm where the phase angle settled in the flexion-on-the-beat mode. These findings indicate that vocalizations reduced the variability of coordination in the flexion-on-the-beat condition but not in the extension-on-the-beat condition.

Experiment 1 revealed that the flexion-on-the-voice coordination pattern was more stable than the extension-on-the-voice one. In the flexion-on-the-beat condition where the coordination between vocalizations and whole-body movement is stable, vocalizations reduced the variability of auditory-motor coordination. On the other hand, vocalizations did not reduce the variability of auditory-motor coordination in the extension-on-the-beat condition where the coordination between vocalizations and whole-body movement is less stable. These results suggest that whether vocalizations reduce or not the variability of auditory-motor coordination depends on the stability of coordination between vocalizations and whole-body movement.

Kelso et al. (Kelso et al. 2001) have demonstrated that haptic information stabilized auditory-motor coordination of finger tapping, suggesting that perceptual saliency stabilizes the auditory-motor coordination. Vocalizations also generate the salient sensory information. One of the factors for coordination stabilization might be the salient sensory information generated by vocalizations. However, the results of Experiment 4 also suggest that the stabilization effect of vocalizations on auditory-motor coordination is affected by the stability of coordination between motor and vocalizations.

Miura et al. (Miura et al. 2011; Miura et al. 2013) have reported that the phase angle of the beat time was deviated from the intended phase angle in the extension-on-the-beat condition but not in the flexion-on-the-beat condition. In the results of Experiment 4, similar deviation was observed in the extension-on-the-beat condition under both vocalization conditions. Because beat frequency was changed discretely, phase transition could not be confirmed directly. However, the change of coordination mode credibly indicates that phase transition occurs. In the phase transition phenomena, loss of stability is one of the key factors underlying pattern change (Schöner & Kelso 1988; Kelso 1995). In Experiment 4, I hypothesized that phase transition (i.e. deviation from intended phase angle) does not occur if vocalizations stabilize the coordination in the extension-on-the-beat condition. As a result, however, in the extension-on-the-beat condition, vocalizations did not stabilize the coordination. Therefore, the deviation from the intended phase angle was occurred even under the Vocalization condition.

In summary, I demonstrated that vocalizations reduced the variability of auditory-motor coordination of whole-body in the flexion-on-the-beat condition but not in the extension-on-the-beat condition. These results suggest that vocalizations can stabilize the coordination under the specific coordination pattern, and it might depend on the stability of the coordination between vocalizations and whole-body movement.

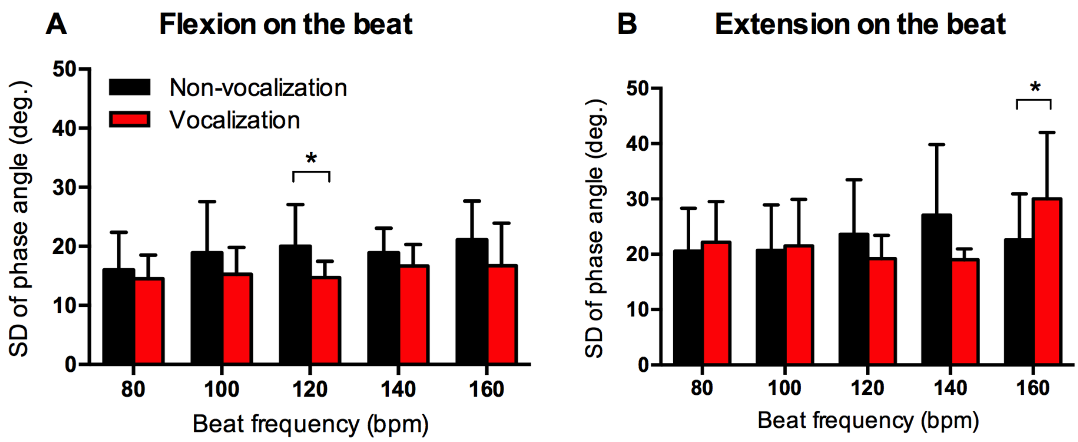

Fig. 5-1 SD of phase angle in the flexion on the voice condition (A) and in the extension on the voice condition (B).
Vertical bars represent between-participant standard deviations.

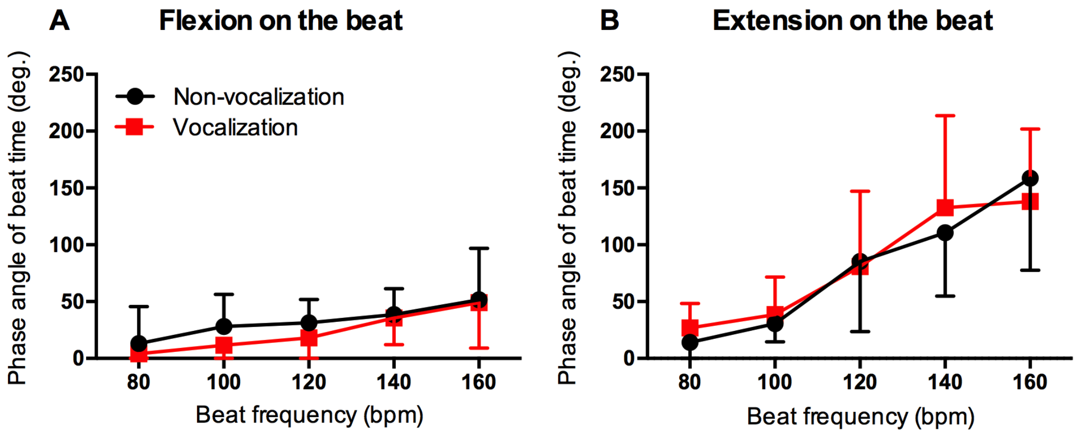

Fig. 5-2 Phase angle of beat time in the flexion on the voice condition (A) and in the extension on the voice condition (B).
Vertical bars represent between-participant standard deviations.

Chapter 6:

General discussion

6.1 Brief summary of the experiments

In this thesis, four experiments were conducted to investigate whether self-generated information through vocalizations can organize stable whole-body movement (Fig. 6-1). The following findings and suggestions were obtained from these experiments.

Experiment 1 and 2 (Chapter 3):

In Chapter 3, Experiment 1 investigated whether there is a stable coordination pattern between vocalizations and whole-body movement, which indicates that the coordination obeys general dynamical principles. Analyses of phase relation between vocalizations and whole-body movement revealed distinct differences between the coordination conditions: At higher movement frequencies, the phase relation in the extension on the voice condition deviated from the intended phase relation. On the other hand, the phase relation of the flexion on the voice coordination was maintained even when movement frequency increased. These results suggest that there was a stable coordination pattern in the flexion on the voice coordination. In Experiment 2, in order to investigate whether a stable coordination pattern reduces the temporal variability of whole-body movement and vocalizations, the variability of whole-body movement and voice-onset intervals was compared between two conditions: one related to tasks performed in the flexion on the voice coordination (coordination condition), and the other related to tasks performed independently (control condition). The results showed that the variability of whole-body movement and voice-onset intervals was smaller in the coordination condition than in the control condition. In this chapter, I revealed mutual stabilization between rhythmic vocalizations and whole-body movement via coordination within a stable pattern.

Experiment 3 (Chapter 4):

In Chapter 4, the purpose was to reveal the effect of vocalizations as movement on a stable coordination pattern and mutual stabilization between vocalizations and whole-body movement. I examined whether there is a stable coordination pattern between vocalizations and whole-body movement under interference with auditory feedback. I also investigated whether vocalizations reduce the variability of whole-body movement under the interfered condition. As with the results of Experiment 1, the phase relation between vocalizations and whole-body movement deviated from the intended phase relation in the extension-on-the-voice condition but not in the flexion-on-the-voice condition when movement frequency increased. The variability of whole-body movement was reduced by vocalizations although auditory feedback was interfered. These results suggest that the coordination between vocalizations as movement and whole-body movement obeys general dynamical principles, and movement of vocalizations reduces the variability of whole-body movement.

Experiment 4 (Chapter 5):

In Chapter 5, I investigated whether vocalizations reduce the variability of auditory-motor coordination of whole-body. A vocalization was performed at a 1:1 frequency locking with a metronome beat. The results showed that vocalizations reduced the variability of the coordination in the flexion on the beat condition, but not in the extension on the beat condition. These results indicate that vocalizations can stabilize the coordination under the specific coordination pattern.

In the following sections, I make some arguments for the results obtained in the four experiments from the standpoint of (1) coordination dynamics between vocalizations and whole-body movement, (2) stabilization effect of vocalizations on whole-body movement and auditory-motor coordination of whole-body, and (3) practical implications.

6.2 Coordination dynamics between vocalizations and whole-body movement

Previous studies have reported that various coordination of human rhythmic movement, such as bimanual, inter-limb, intra-limb, sensorimotor, and interpersonal coordination, are governed by common and general dynamical principles (Kelso 1995). In dynamical systems approach, human coordination has been studied in terms of phase transition paradigm. The relative phase (phase angle) between two movements, or external event and movement has been identified as a collective variable or an order parameter that characterizes the emerging pattern of coordination. Movement frequency has been considered as a general control parameter that influences pattern formation of human movement coordination. Namely, as movement frequency increases, phase transition from one phase relation to another occurs spontaneously.

In this thesis, I investigated the coordination between vocalizations and whole-body movement (Experiment 1 and 3; Chapter 3 and 4). The results of Experiment 1 (Chapter 3) showed a stable coordination pattern (the flexion on the voice coordination), and suggested pattern change from extension on the voice coordination to flexion on the voice coordination at higher movement frequencies. Because a stable coordination pattern and pattern change indicate the occurrence of phase transition, these findings imply that the coordination between vocalizations and whole-body movement is governed by general dynamical principles. Furthermore, the results of Experiment 3 (Chapter 4) suggest that the coordination between movement of vocalizations and whole-body movement is also governed by dynamical organization principles.

In Experiment 1 and 3 (Chapter 3 and 4), the pattern change from less-stable coordination to stable one is induced by increased movement frequency. Therefore, movement frequency is a general control parameter for vocalizations and whole-body movement coordination.

There are several possibilities for the mechanism of stable pattern formation, flexion on the voice. It has been reported that respiration cycle is coupled with gait, Locomotion-respiratory coupling (LRC) (Hoffmann et al. 2012). Vocalizations are executed by respiratory system, and the whole-body movement task used in this study is similar with gait in terms of rhythmic movement of lower limbs. LRC has been understood as originating from neurological and mechanical interactions. The point of neurological interactions, there is a neural unit for generating rhythmic movement, central pattern generator (CPG), such as CPG for gait (Kiehn 2006; Guertin 2013) and respiration (Cohen 1979). Decerebrated animal study has shown direct interactions between CPG of respiration and gait (Viala et al. 1987). From the point of mechanical interactions, LRC has been understood as the result of the impact loading on the thorax when the limbs strike the ground (Lee & Banzett 1997). In whole-body movement task, joint flexion and extension in standing posture produce body acceleration and deceleration in vertical plane. Organs in the abdomen can push up the diaphragm during joints flexion. Then the thorax might be oppressed, and exhalation is prompted. It can be one of the mechanisms that flexion on the voice pattern is stable. On the other hand, Kelso et al. (Kelso et al. 1983) have reported that a stable coordination pattern between vocalizations and finger tapping. I also confirmed that a similar coordination property between vocalizations and an upper limb while participants sit on a chair. Therefore, a stable coordination pattern between vocalizations and whole-body movement probably due to neurological and mechanical interactions.

6.3 Stabilization effect of vocalizations on whole-body movement and auditory-motor coordination of whole-body

I explored the effect of vocalizations on whole-body movement in terms of temporal stability (Experiment 2 and 3; Chapter 3 and 4). In this thesis, the decreases in variability were regarded as increases in stability. The results of Experiment 2 showed that vocalizations increased the temporal stability of whole-body movement. At the same time, the temporal stability of vocalizations was also increased through coordination with whole-body movement. In Experiment 3, vocalizations increased the temporal stability of whole-body movement even under interference with auditory feedback, suggesting that movement of vocalizations stabilizes whole-body movement.

A stable coordination pattern between movements indicates that they can act as a single functional unit or coordinative structure through functional coupling or mutual constraint between the systems (Kugler et al. 1980). Previous studies have suggested movement stabilization through behaving as a coordinative structure (Helmuth & Ivry 1996; Drewing & Aschersleben 2003). Therefore, vocalizations might stabilize whole-body movement by behaving as a coordinative structure with that.

Furthermore, I explored the effect of vocalizations on auditory-motor coordination of whole-body in terms of coordination stability (Experiment 4; Chapter 5). As a result, vocalizations reduced the variability of coordination in the flexion on the beat coordination, but not in the extension on the beat coordination. This difference might be related to the stability of the coordination between vocalizations and whole-body movement. In this experiment, a vocalization was performed at a 1:1 frequency locking with a metronome beat. Thus, the coordination between vocalizations and whole-body movement is stable in the flexion on the beat coordination, but not in the extension on the beat coordination as shown in Experiment 1 (Chapter 3). These findings indicate that vocalizations can stabilize the coordination under the specific coordination pattern, and it probably depends on the stability of the coordination between vocalizations and whole-body movement.

I also compared the temporal variability of whole-body movement coordinated with vocalizations and metronome beats at 80 bpm. The results showed that the variability of whole-body movement was significantly smaller with metronome beats than with vocalizations, $p < .01$, $t = 3.29$. Metronome beats has equal intervals while vocalizations do not so that this difference might emerge. Although vocalizations have more temporal variability than metronome beats, vocalizations reduced the variability of auditory-motor coordination. One of the reasons for this phenomenon might be due to the increment of sensory information. Participants can get more information related to their movement in the form of auditory information or another movement information due to vocalizations. These additional sensory information might improve the accuracy of estimating a temporal state and contribute to the reduced variability of auditory-motor coordination.

6.4 Practical implications

Previous studies have reported that various types of motor performance are enhanced by RAS (Arias & Cudeiro 2008; Hausdorff et al. 2007; McIntosh et al. 1997; Thaut & Abiru 2010; Rubinstein et al. 2002; Lim I, van Wegen E, de Goede C, Deutekom M, Nieuwboer A 2005; Muto et al. 2012; Bood et al. 2013; Hoffmann et al. 2012; Hove et al. 2012). The results of this thesis are relevant for practical exercise support without the aid of an external device. The results suggest that motor performance could be enhanced through vocalizations.

Performance enhancements by vocalizations have been reported in maximum force production tasks (Ikai 1961) and reaching tasks (Maitra et al. 2003; Park et al. 2009). Ikai (Ikai 1961) has reported that increased maximum force production occurs when participants shout. Maitra et al. (Maitra et al. 2003) have demonstrated that vocalizations made older adults move faster and smoother in the reaching task. The effect of vocalizations on movement is also known through onomatopoeia. Onomatopoeia is word-formation based on the imitation of natural sound. In many contexts, onomatopoeia is used to convey the image of movement. Onomatopoeia not only helps us to imagine the movement (Osaka 2009), but also affects movement through utterance (Kijima & Choshi 2006). Kijima et al. (Kijima & Choshi 2006) have demonstrated that phonological elements of onomatopoeia change the maximum force and load duration of grasping movement. This finding suggests that exercise support using vocalizations become more extensive and effective by introducing onomatopoeia.

Vocalizations can generate various patterns of RAS more easily and flexibly than external devices do so that vocalizations are useful for extensive exercise support. In Japan, street dance became compulsory at junior high school since 2012. However there are few teachers with experience of street dance, and no educational method for street dance. The results of Experiment 4 showed that vocalizations reduced the variability in auditory-motor coordination of whole-body under a certain condition. Therefore, the use of vocalizations can be one of the effective educational methods. Furthermore, almost everyone can vocalize anytime, anywhere, and it does not any devices so that the method using vocalizations can be introduced into actual education immediately.

Meanwhile, a vocalization is carried out by respiratory system that is important for gas exchange. Thus, reckless vocalizations just put a tax on the respiratory systems and interfere with gas exchange, so that vocalizations might degrade performances. For exercise support that uses vocalizations, a harmonious relationship between vocalizations and breathing is important.

The results of Experiment 2, the temporal variability of vocalizations was reduced through coordination with whole-body movement, indicates that rhythmic whole-body movement improves the rhythm of vocalizations, such as singing a capella. That is, when sing without any accompaniment, one can sing with stable rhythm by coordinating with whole-body movement. Actually, we can see many singers sing with other movements. They often move their forehands or sway their body while they sing. These movements might stabilize their rhythm of singing.

6.5 Thesis conclusion

The present thesis investigated the coordination between vocalizations and whole-body movement. In summary, I found that the coordination between vocalizations and whole-body movement is governed by general dynamical principles, and there is mutual stabilization between two movements. Vocalizations as movement also have the stabilization effect on whole-body movement. Moreover, vocalizations stabilized auditory-motor coordination of whole-body under a certain coordination mode.

This thesis demonstrated that vocalizations could organize stable whole-body movement. That is, certain motor and coordination tasks are stabilized by vocalizations. The findings of this thesis are useful for performance improvement of sports and dance, and also can be for music performance and rehabilitation.

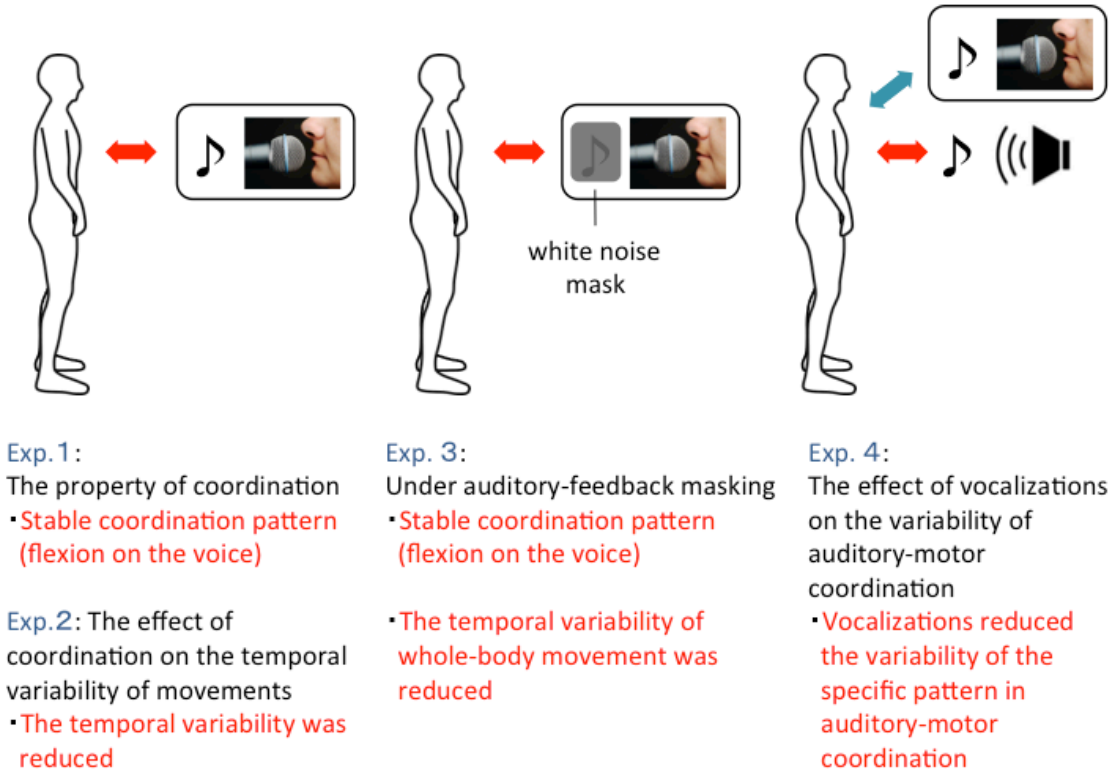

Fig. 6-1 Conceptual diagram of this study.

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