矛盾を内包するシステムの両義性

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博士論文

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1. Introduction

We are usually unaware of how to walk during walking. Both of our legs are skillfully coordinated and both of upper and lower bodies and so on, even where the stairs, slope or escalator. However, this scenario is rewritten dramatically with a slightest thing. Imagine that an escalator is not working. It is just a stairs, should be no longer an escalator. Since the stairs consists of larger steps than normal, it is easy to imagine the difficulty to go up stairs. But something further happens actually. The skilled coordination among each part of body is lost, and we cannot help making conscious effort to walk [1]. It is considered that walking, namely coordination of one's body, is usually applicable to any place, although there is difference in physical difficulties. In the case of an escalator without working, walking is, however, altered to conscious walking. If we continue to use walking in such situation, then we will stumble over the steps.

A program is usually separated from the objects, and the program is not changed by each object [2]. But a living thing can change its own behavioral rule, and this contributes to resolving problems such as mentioned above. The robustness of living things may be caused by intrinsic discrepancies of the open-ended rule.

An animal aggregation is a system consisting of individuals that interact one another. Many models of a collective behavior employed interaction rules that an agent determines its own movements by observing movements of the other neighboring agents [3, 4]. Then an agent and its neighboring agents are discriminated, and the system does not include discrepancies. Recently, a model based on a mutual anticipation was introduced [5]. Each agent has multiple potential transitions except a principal vector. An agent and its neighboring agents are connected via popular sites. Then there is indiscernibility between part and whole. This model implemented two interesting collective behaviors, namely hourglass and logical gate [5, 6]. To estimate feasibility of them, we implemented them by real soldier crabs.

For human beings, a sense that I own my body seems most fundamental. Such sense is regarded as a precondition to act freely. So it is considered that one never lost one's own body, even if external object is incorporated into one's body image [7-11]. But we are usually unaware of an ownership of our own bodies like example of above walking. Thus we demonstrate that a sense of ownership about a hand can be lost. Then a sense of moving a hand is not lost. This implies that the intrinsic discrepancy is exposed as the ambiguity, namely the hand is I but not mine.

2. Behavioral Experiments of Soldier Crabs

2.1. Introduction

Collective behaviors are often regarded as self-organized phenomena generated through local interactions among individuals, such as pheromone trails in ants, bird flocks, fish schools and human audience applause [3, 12-14]. The mode of collective behaviors is different from that of an individual [15-18]. Some animals show a unity of group as if they act as one organism.

BOID [3] and self-propelled particle model (SPPs) [4, 19] have been proposed to imitate collective animal behaviors like a flock, herd and school. In the case of BOID, an individual determines its own velocity based on three rules dependent on neighborhood, namely, velocity matching, collision avoidance and flock centering, in the case of SPPs, only velocity matching. The velocity matching is implemented as averaging individual velocities in the neighborhood, the collision avoidance is avoiding collision with nearby individuals and flock centering is staying close to nearby individuals. These mechanisms are based on a clear discrimination an individual implementing the transition rule from other individuals. SPPs predicted an occurence of rapidly transition from disordered movement of individuals in a group to ordered collective behavior with increase of a density of individuals in the group [4].

Actually Buhl and his colleagues varied the number of locust nymphs on a homogeneous ring-shaped experimental arena without external perturbation and quantitatively demonstrated a phase transition from disordered to ordered as the population density increases [20]. Additional studies showed that coherent behaviors, marching locust bands, arose since locusts were motivated to align neighboring locusts by the risk of cannibalism [21]. When we pay attention to a locust of migrating band, the locust has to escape from predation by the other neighboring locusts, and then he or she would be discriminated from others. Animal aggregation is an environment for the individuals of it. Primarily it is difficult to separate individuals from their environment.

There is a similar problem about a relationship between computation and computational objects. Interaction of natural entities can implement logical operations. Collision-based computing is gives us the most illustrative examples of computing devices where interactions between natural entities plays a key role. Thus in the billiard ball model (BBM) [22, 23] the non-dissipative and reversible computation is implemented by colliding elastic balls, the logical gate is implemented at a site of collision. In the case of BBM, any perturbation of the system directly influences the trajectory of balls. In reaction-diffusive systems, a computation is implemented by collision of traveling waves and wave-fragments in the Belousov-Zhabotinsky (BZ) medium [24-28]. To implement a collision-based computing with a living organism or organisms we must used propagating domains as carriers of information. For example, the plasmodium of ***Physarum polycephalum*** that can be regarded as an encapsulated reaction-diffusive system by viscoelastic membrane controls all the parts of the cell by synchronous oscillation of cytoplasm and provides computational capacity such as maze solving [29, 30] and calculation of efficient networks [31-33]. We can implement logical gates with ***P. polycephalum*** by encoding logical variables in the plasmodium's active growing zones, which exhibit gradient-dependent growth and collide as elastic bodies or fuse [34-36].

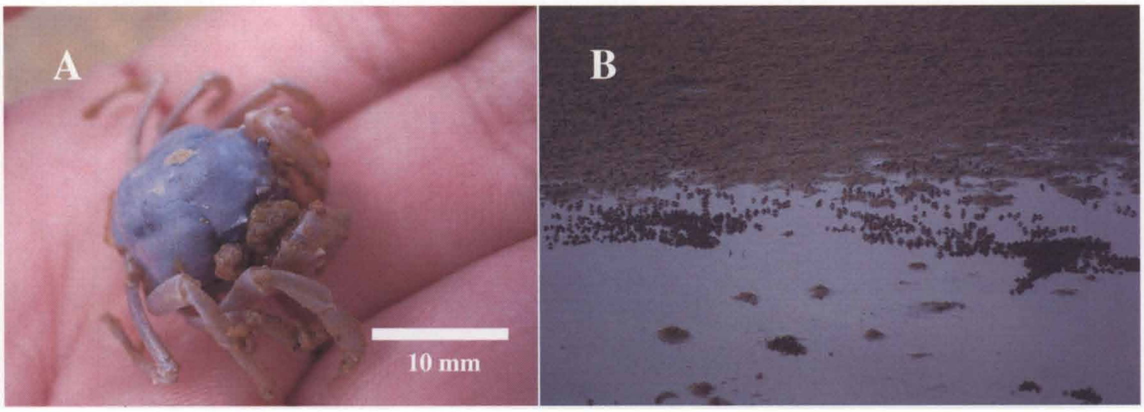


Figure1. A, *Mictyris guinotae*, at Okukubi River, Okinawa I., Japan; B, Swarms of soldier crabs, at Funaura Bay, Okinawa I., Japan

Soldier crabs of family ***Myctyridae*** are common on tropical and subtropical sea shores and with specific traits of forward walking and mass wandering on tidal flats, influencing other benthic fauna through their feeding, burrowing and mass wandering. They play an important ecological role as preventers of the overgrowth of dense microbial mats and as prey animals of shore birds [37-43]. Individuals of ***Mictyris guinotae***, one species of them, inhabit sandy-mud intertidal flats including estuaries in the Ryukyu Islands, southern Japan, north to Tanega-shima I. and south to Iriomote-jima I. [44]. Their bodies are small (less than 16 mm in carapace length) and have pale blue color (Fig. 1A). They feed on deposited matter in two ways during the daytime low tide [45, 46]. One is to feed inside the tunnel made by them. Another is on a flat surface for one and a half to three hours. For the latter, large crabs (the carapace length > 7 mm) which appear over the surface of a tidal flat approach the shoreline through alternating between walking and feeding, in time they form great conspicuous swarms and wander en masse, eventually burrow again into subsurface above the shoreline before the flood [45, 47]. Such mass wandering involves a few dozen to thousands of individuals, extends their feeding area on tidal flats and increases a chance of getting food sources near the shoreline [48]. It was discussed the relationship with the energy requirements [46]. Crabs who have appeared on the surface firstly head for shorelines. Since the predecessors do not wade deeper and the successors catch up them in sequence, the great swarms are formed near shorelines. More tide goes out, the swarms begin to wander en masse. Moreover previous studies reported observations of aligning with neighbors and no fighting between individual crabs during mass wandering [45, 49].

From our field observations, a swarm of crabs is constituted by the ever-changing arrangement of individuals but maintains a coherent and dense unity (Fig. 1B). Moreover we observed intriguing collective behaviors that a number of crabs often get across puddle of water in serried ranks. Each crabs usually prevents water and minimizes wading when his or her ambulatory leg is in water. Nevertheless they can march into a puddle of water in serried ranks, namely water-crossing behavior. When there is water in the direction crabs are traveling, they go back and forth along the perimeter of water. If a highly concentrated front part of a swarm is formed, they eventually got across it in serried ranks. This is an example that a case (a concentrated front) causes to change a universal rule (avoiding water crossing), like a proverb "When everybody is crossing on a red, it is not so scary." Then it is suggested that a crab and the others affect one another through the medium of water, and the discriminations between individuals of the swarm are vague. We predicted that crabs between opposite impasse repeated to move from end to end. In the Section 2.2, we demonstrate that the crabs generate regular oscillations and discuss about the relationship between an individual and swarm.

Recently, from observations of their behaviors, a model based on mutual anticipation has been proposed, in which collective behaviors with intrinsic turbulence are generated and maintained without external noise when individuals detect multiple potential transitions that each of them has except their own velocity vector [5]. According to this model, when cohesive and definite bounded swarms fuse together, the velocity of united swarm is summation of the velocities of each swarm. Moreover swarms are robust because individuals generate the swarm without discrimination of external perturbation from inherent noise, namely potential transitions. By utilizing those characteristics, collision computing by crabs has been implemented in simulation model [6]. To demonstrate feasibility of the swarm collision gate by real soldier crabs we conducted laboratory experiments. The crab swarms represent quanta of information, values of Boolean variables. In the Section 2.3, we introduce a crabs' logic gate that produce logical conjunction and negation and discuss a possibility of robust computing.

2.2. Crabs' hourglass

2.2.1. Architecture and settings

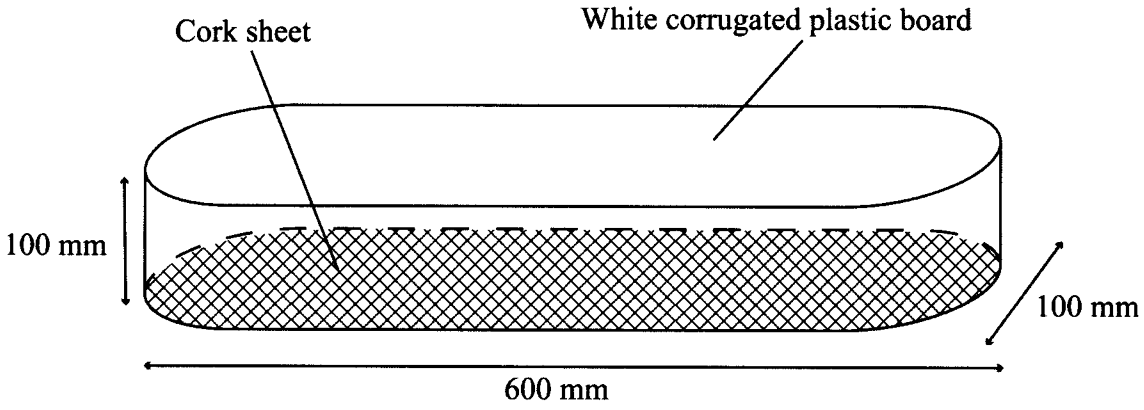


Figure2. The scheme of experimental arena.

An experimental arena is a closed corridor, six hundred millimeters long and a hundred millimeters width (Fig. 2). The corridor is consisted of cardboard wall (100 mm high) and cork floor (to prevent burrowing and provide friction).

Soldier crabs were collected on an intertidal flat including estuaries of Funaura Bay, Iriomote Island, Japan (123°48′ E; 24°24′ N) about an hour before daytime low tide. After caught, they were immediately brought to the laboratory at Iriomote Marin Station, Tropical Biosphere Research Center, Ryukyu University. Crabs that were eleven to fifteen millimeters in the carapace length with good physical appearances were selected as subjects and placed in a plastic container until beginning of experiments.

Experiments were conducted using the arena placed in the laboratory in a low tide period (the twentieth July and the second to fifth October in 2010). Their breeding seasons (from December to earlier March) were avoided because of sexual differences of individual behaviors [47, 50].

To estimate difference of behaviors with a population, we used various numbers of crabs (N=1(5), 2(5), 4(5), 8(5), 16(2), 40(2); the digits in brackets represent number of trials.). Crabs were placed gently into a coop on the arena within thirty minutes after caught. The coop was taken down a few minutes later and crabs were left on the arena in the desolate laboratory about 2 hours. The movements of crabs were filmed using digital video camera from above. Crabs were used only once and released after each experiments.

We found that crabs moved from end to end again and again regardless of population.

2.2.2. Oscillations generated by crabs

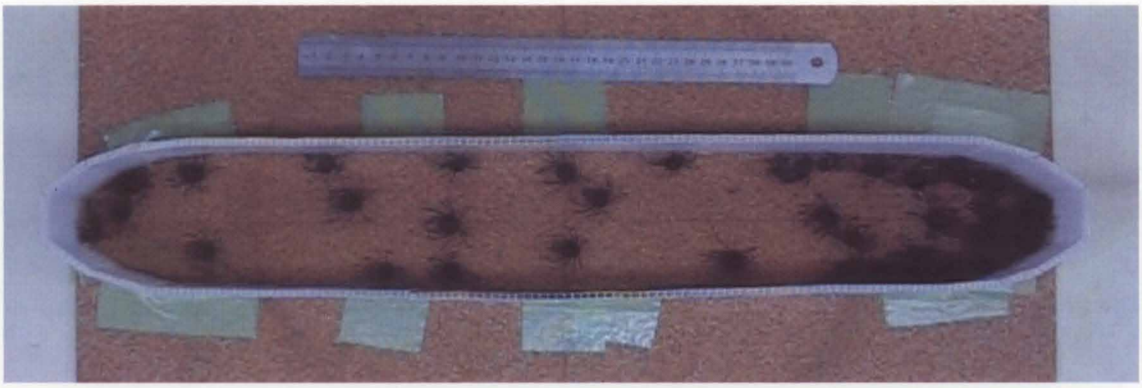


Figure3. A snap shot of crabs' hourglass.

We captured five hundred twelve still images from each video file. The analyzed period was about an hour from the onset of each trial because an interval between two successive images was seven seconds. To analyze movements of crabs, distributions of individuals at given times were given manually as Cartesian coordinates of which the origin was one end of the arena (Fig. 3).

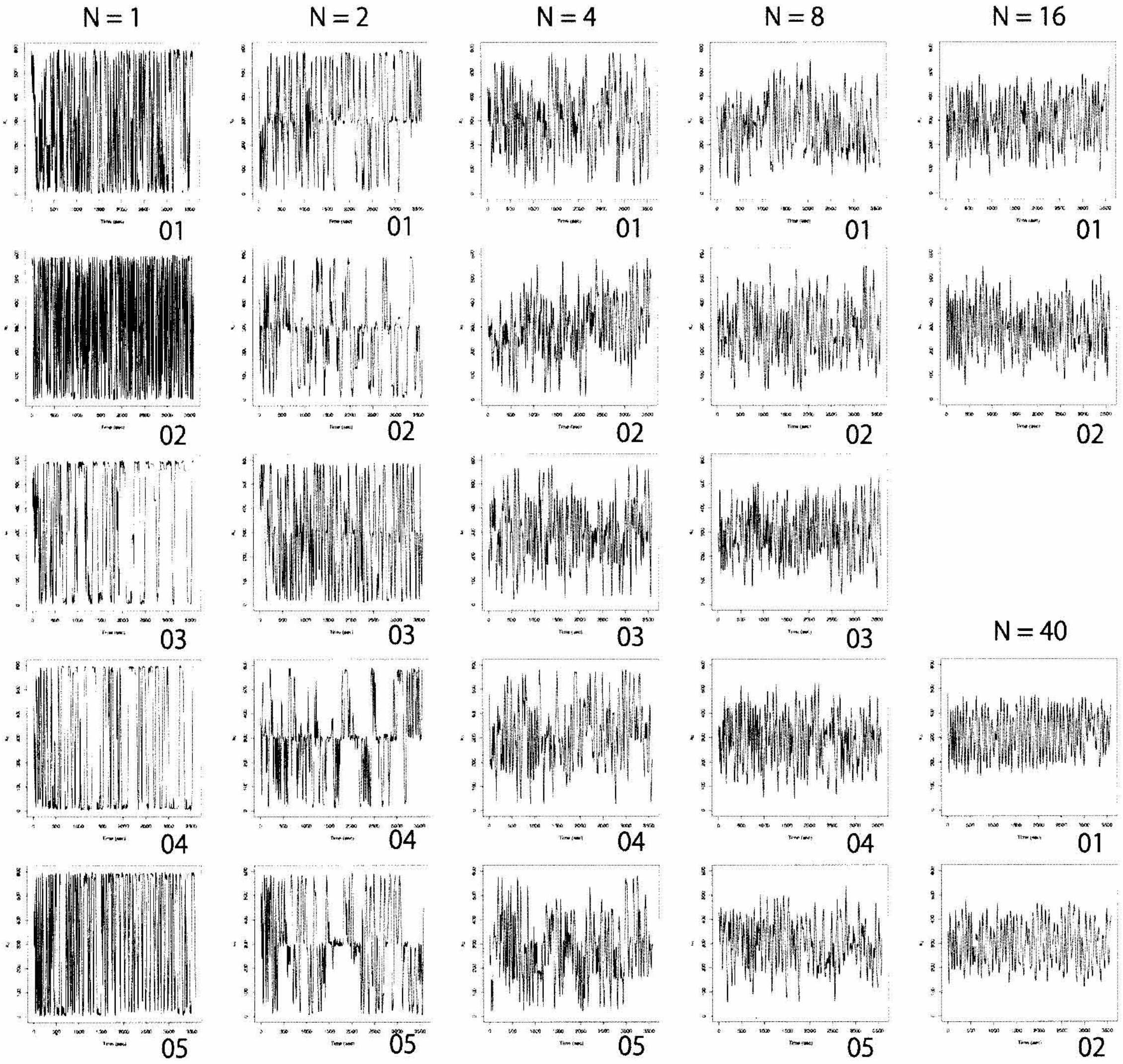


Figure 4. Fluctuations of center of swarm or a crab (N=1). The number at the bottom of each figure represents trial ID.

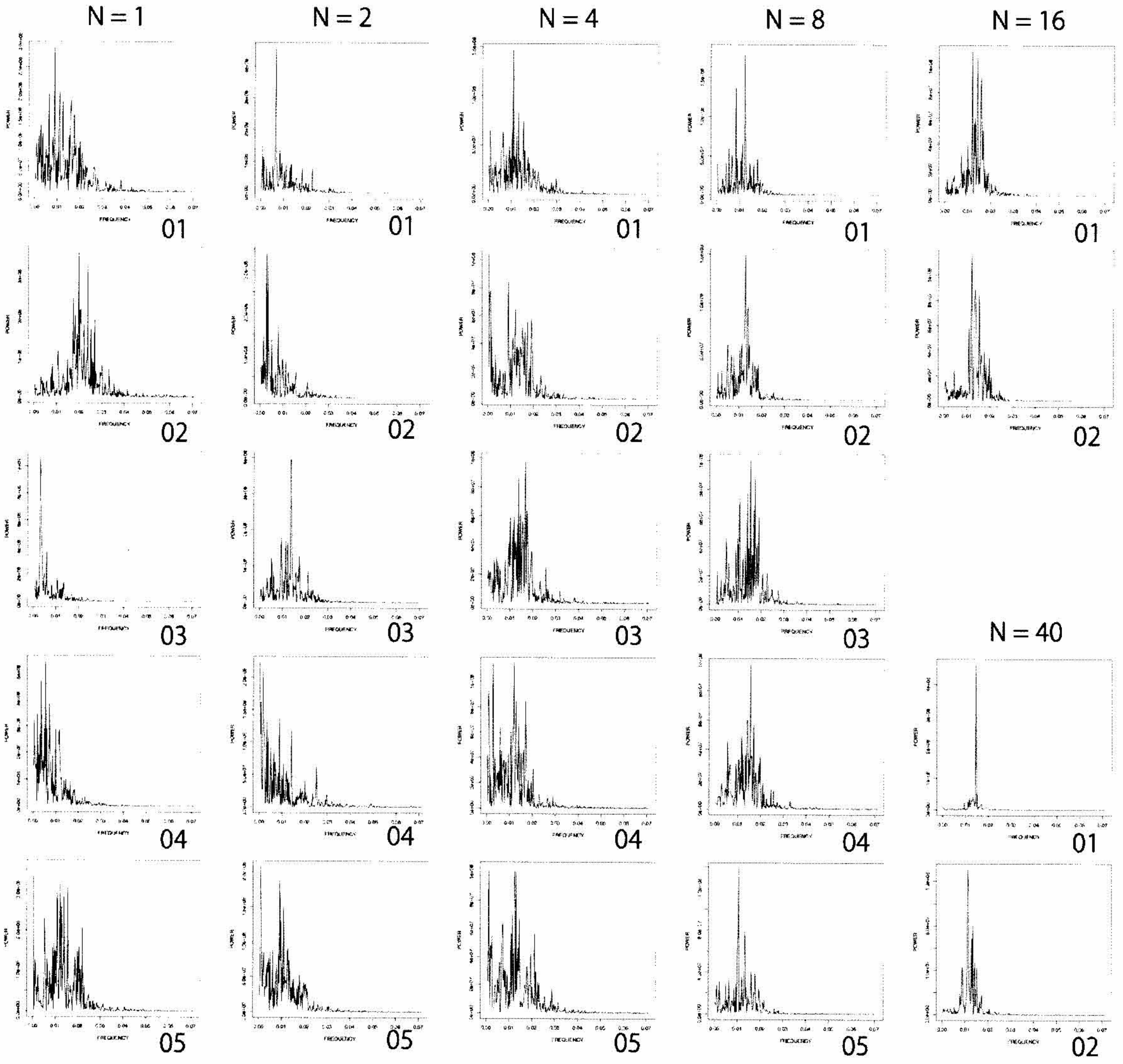


Figure 5. Power spectrum correspondent to each fluctuation of figure 4.

Figure 4 illustrates that center of distributions continues to fluctuate between both ends for all trials. Do these fluctuations have a significant period that indicates ordered collective behavior? If only large swarm had a certain characteristic period, otherwise not, then it means phase transition from disordered to ordered collective behavior with density, namely like marching locust bands. So Fast Fourier Transform (FFT) was applied to the time series of center of distributions. Figure 5 shows power spectrums for all trials. Every fluctuation has at most one or two peaks, even if shapes of hills are steeper about large swarms (N=16, 40). The both behaviors of individuals and swarms indicate more or less ordered oscillations. Are individual and collective oscillations only different in degree? What differences are there in addition to distinctness of the peaks? Then we focus on the location of peaks that is given as the frequency. It seems that large swarms have similar frequencies. In order to be intuitive clear, the reciprocal of frequencies, namely periods, are compared. Figure 6 show that the diversity of periods of the first ten about the power decreases at large population. There is a duality that the oscillator is an individual itself and a swarm. Next we confirm the global behavior of a swarm during oscillation.

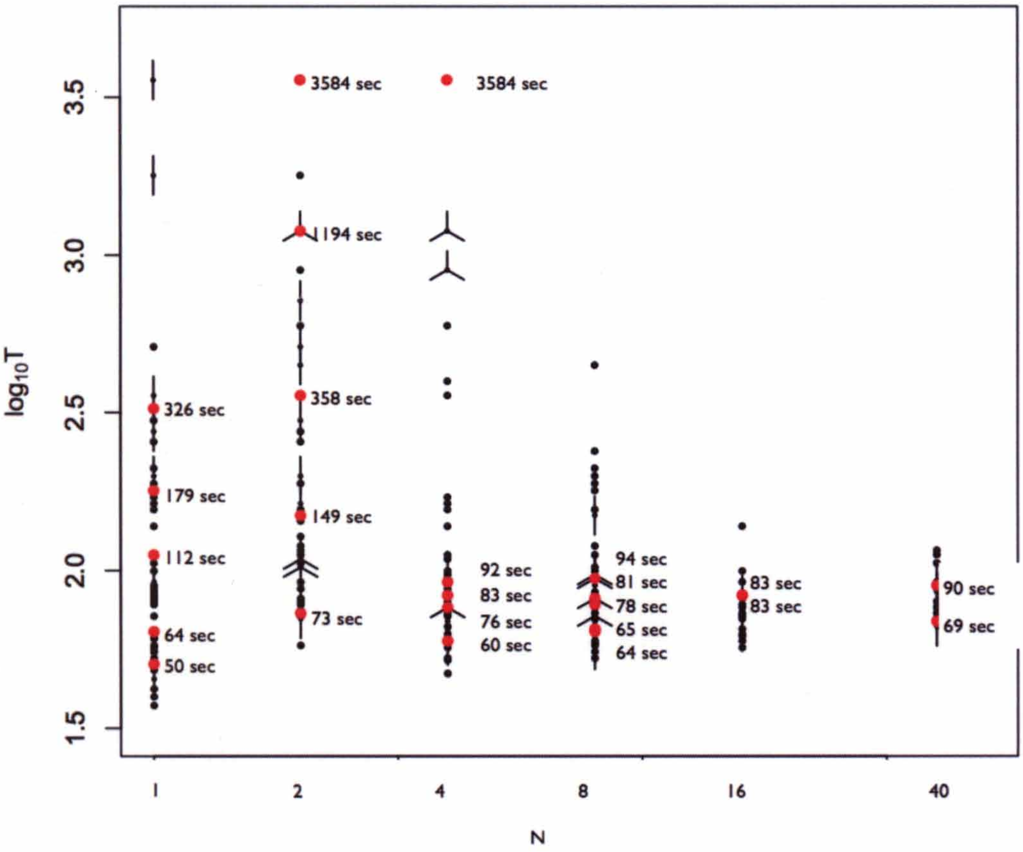


Figure6. Oscillation periods of each condition. The periods were obtained first ten of strong power about each trial (The first period is represented by red dots and lateral numbers.). Petals represent number of overlapping.

2.2.3. Flexible swarm

How does a swarm move from end to end? Does it maintain aggregation or repeat expansion and contraction? To confirm such global behavior of swarm, we analyze the swarm including forty crabs (correspondence with Fig. 5 N=40-1). A dependency between location and density of a swarm will express the global behavior of it because the location corresponds to the above-mentioned oscillation, where the location is represented by median of the X coordinates of all crabs and the density is number of neighboring individuals. When we determine the neighborhood of which radius is thirty millimeters that is the distance just touching each other, the density is strongly dependent on the location (Fig. 7). The swarm is dense near the both ends and sparse near the center of arena.

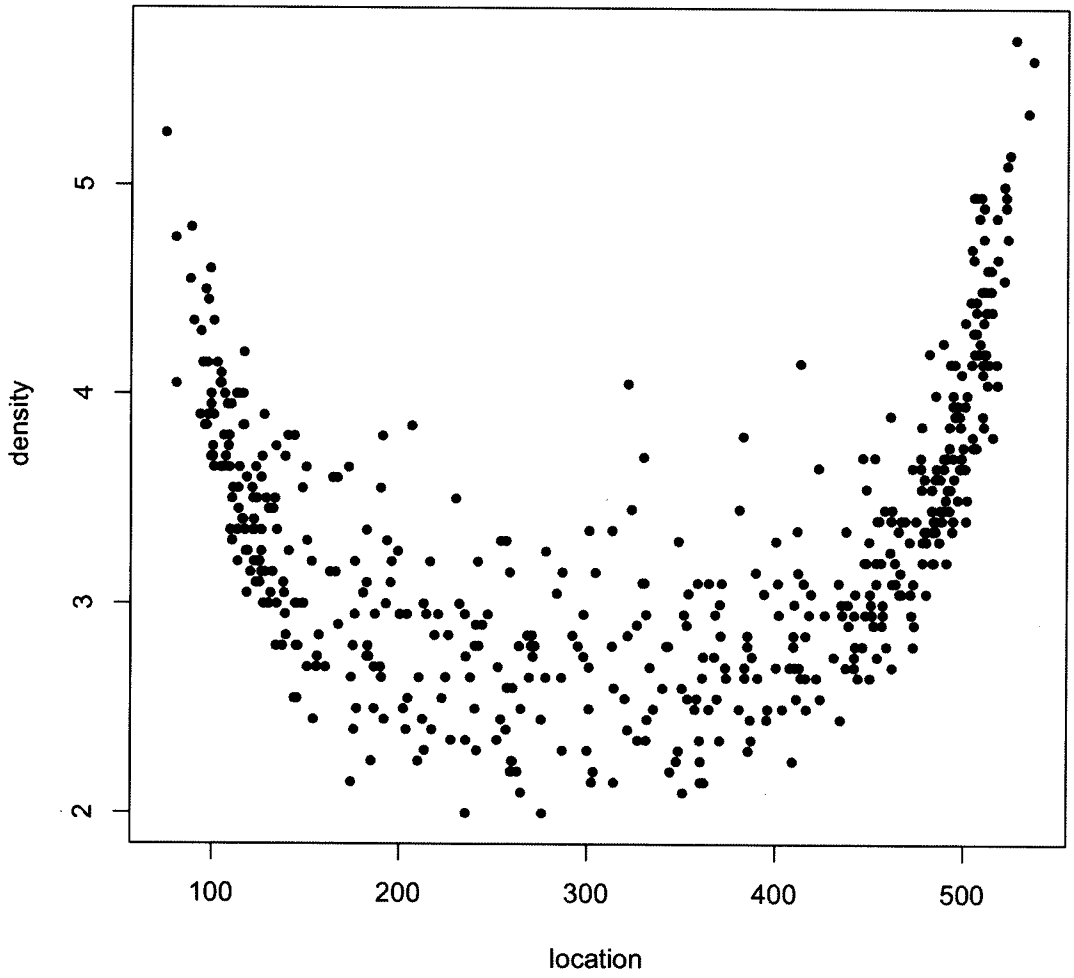


Figure 7. Location-density plots about N=40-01. The location is median of X coordinates of crabs and the density is averaging population of neighboring crabs.

The radius of neighborhood is 30 mm.

Addition to this fact, to also confirm the transition of population, we obtained population in three domains that evenly divided the arena (Fig. 8). The swarm oscillates in the arena as mentioned in previous section, and moves with repeating expansion and contraction because there is little color indicating large number in the middle domain unlike in the other two domains. Moreover it seems that the time of moving from end to end is shorter than that of staying at either end. Figure 9 illustrates the frequency of a period of time that the median of swarm spends staying in each domain at a time, where three domains are classified into a middle domain and an end domain. The frequent short time spent in the middle domain and the frequent long time spent in the end domain suggests that the most individuals of swarm move to another end about the same time as a part of them start to do so and the predecessors stay at the end for a while.

2.2.4. Discussion

When a property of animal group differ from that of individuals, we can regard it as the emergent property that self-organization underlies [51]. Both of a solitary crab and swarm oscillated in our experimental arena. But the periods of oscillation of large swarm obey the law of large number unlike those of solitary individuals or small swarm. So the oscillation of swarm would be emergent property. Recent model based on a mutual anticipation satisfied the property of oscillation [5]. This mechanism differs from a marching locust band based on escape-and-pursuit behavior regarding cannibalism and inherent noise of swarm contributes to generate collective behavior. The long term staying in either end of arena implies the presence of reservoir for concentration.

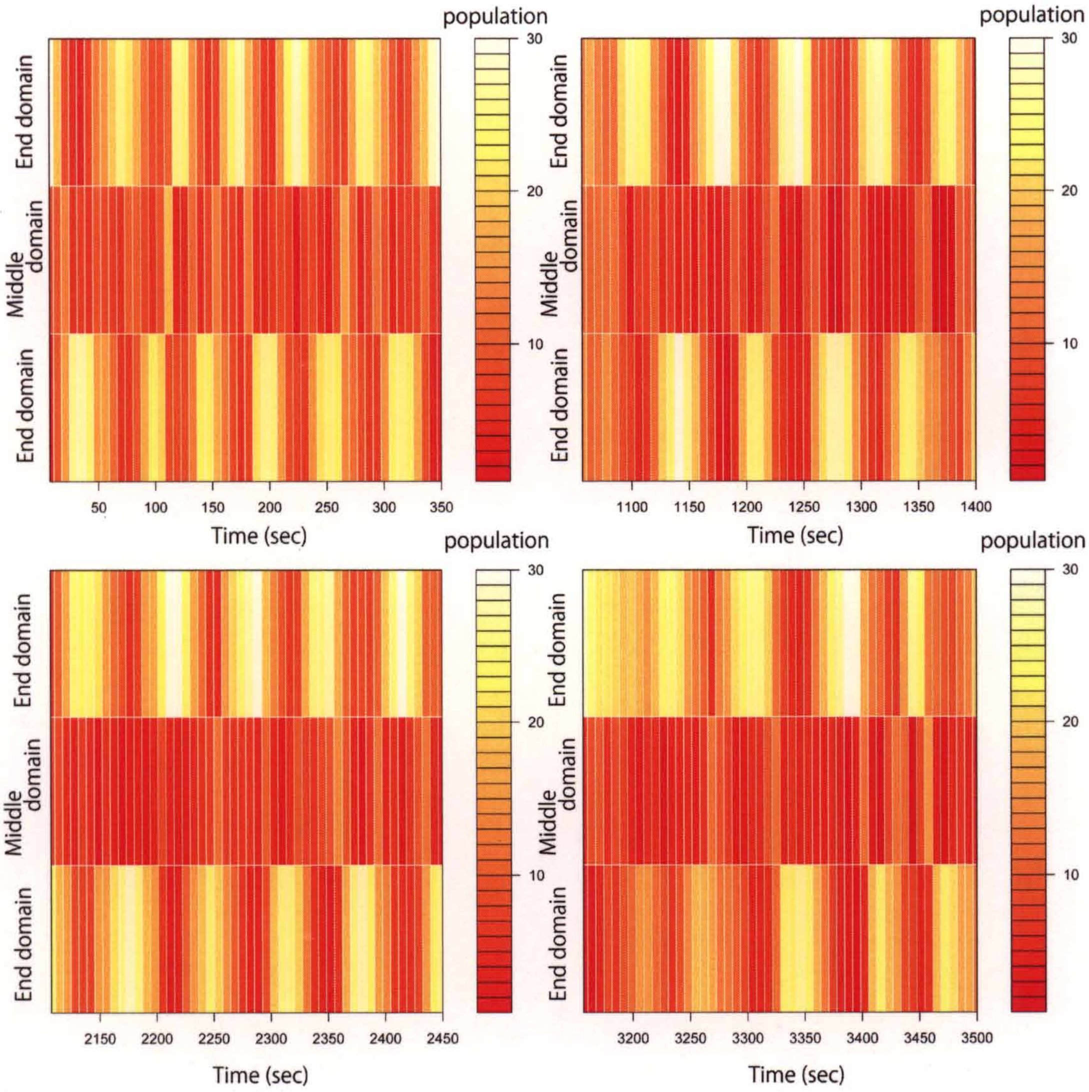


Figure 8. The distribution of population. The arena was divided into three even domains.

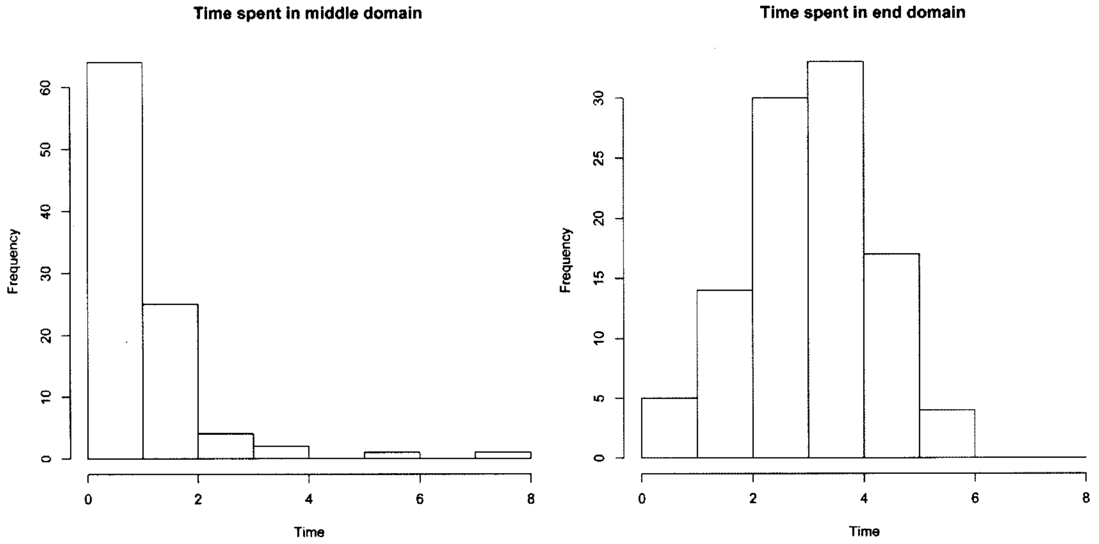


Figure 9. The frequency of successive time spent by median of crabs' distribution (A) in middle domain, (B) in end domain.

2.3. Crabs' logic gate

2.3.1. Architecture and settings

The logical gate discussed here has two input channels X and Y (representing, input variables (x, y)) and three output channels P, Q, and R (output variables, (p, q, r)) (Fig. 10). The channels are made as cardboard corridors (to direction motion of crabs) with cork floors (to provide friction to crabs). The channel X joins R-channel in a straight line, and Q-channel at 45° and P-channel at 90°. Y connects to outputs P, Q and R in a similar way.

We impose on crabs two gradients in each channel. One gradient is implemented by utilizing escaping behavior by intimidation plate placed just behind each starting gate. Crabs are sensitive to sudden standing or moving large objects because such objects could be signs of predators. Thus the intimidation plate popped up can causes the crabs to move away from the plate. Another gradient is implemented by physical gravitational stimulus produced by a slope towards exists of output channels. The slope facilitates straightforward movement of swarms and prevents individuals returning to input channels.

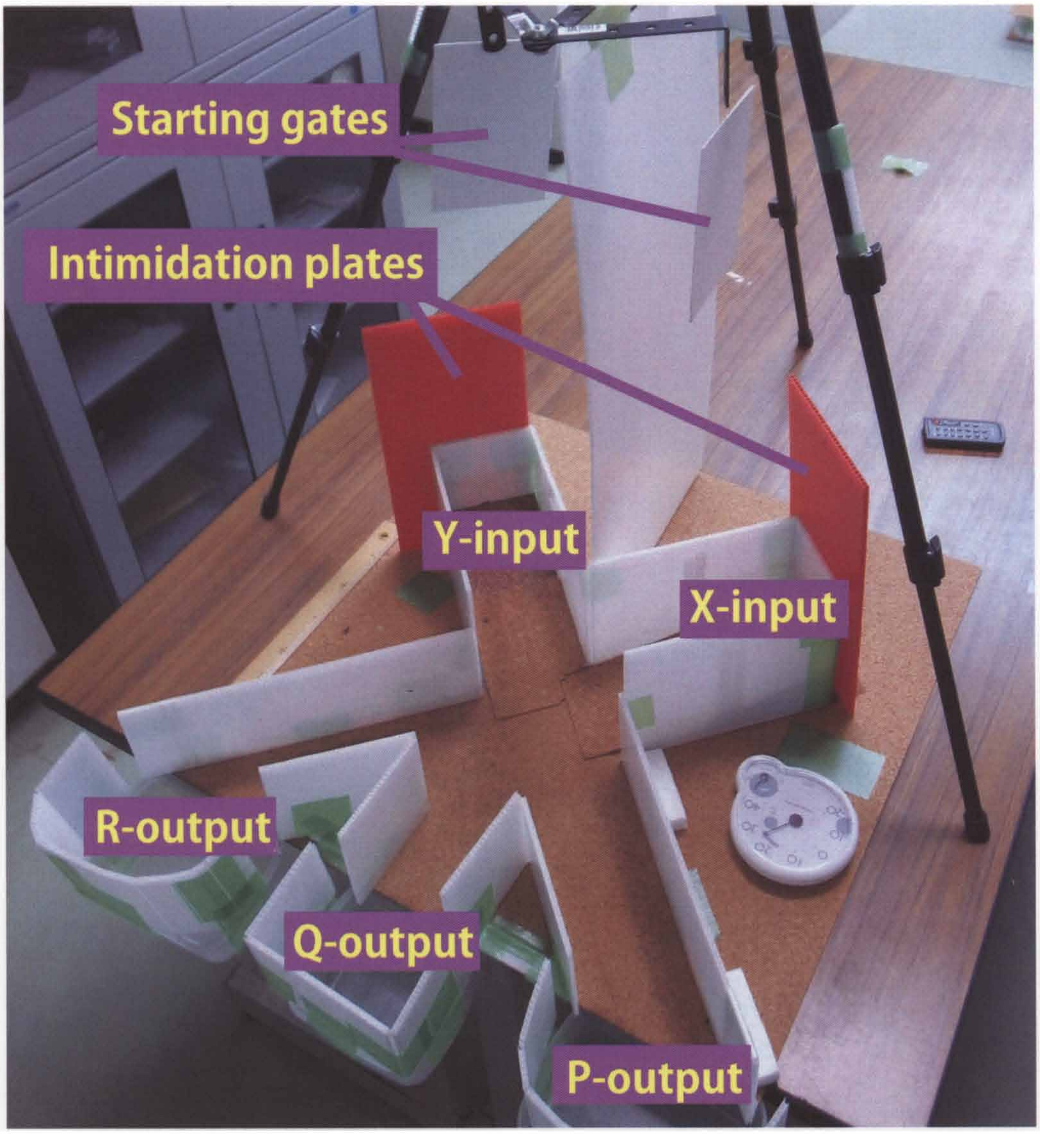
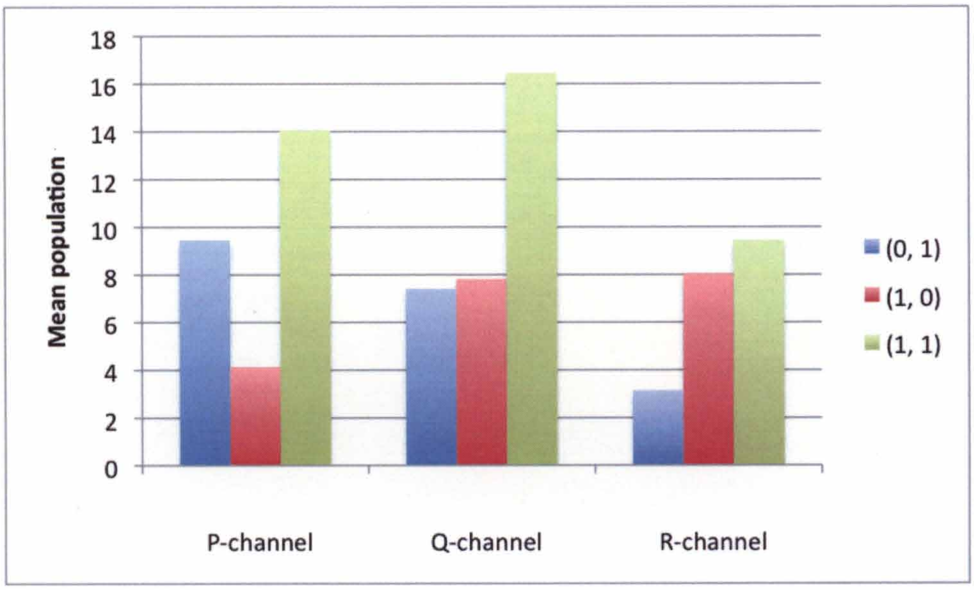


Figure 10. An apparatus for implementation of Boolean logic gate by using soldier crabs. Swarm consisted of twenty crabs is located in X- and/or Y-input. After relaxation, starting gates are opened and intimidation plates are popped up simultaneously.

Soldier crabs were collected on an intertidal flat including estuaries of Funaura Bay, Iriomote Island, Japan (123°48'E; 24°24'N), about an hour before daytime low tide. After being caught, they were immediately brought to the room. Then we selected individuals that were more than 11 mm in the carapace and agile. The experiments were conducted in a room during the daytime low tide between 20th and 22nd October in 2010, room temperature 26 °C and humidity 80 %.

We placed a swarm of 20 crabs in input channels X and/or Y at the beginning of each trial. A swarm in a channel X or Y represents x=True, y=True respectively.



(Fig11) Probabilities Pxy, Qxy and Rxy that proportion (A) or population (B) of crabs in each output channel is above threshold for each state of inputs. The indices represent a pair of inputs.

Crabs were left about two minutes for relaxation. After the relaxation, starting gates were opened and intimidation plates were simultaneously popped up, and then crabs moved ahead to the P, Q or R. Intimidation plates were moved up and down in a few seconds every minute. A trial was finished when all crabs arrived at output channels. Twenty-two trials were conducted for each state of inputs (1, 0), (0, 1) or (1, 1). When all crabs got out the channels, we found that many crabs arrived at Q and R if a swarm was set in X, and similarly many subjects at P and Q if Y (Fig. 11).

2.3.2. Swarm collision computing

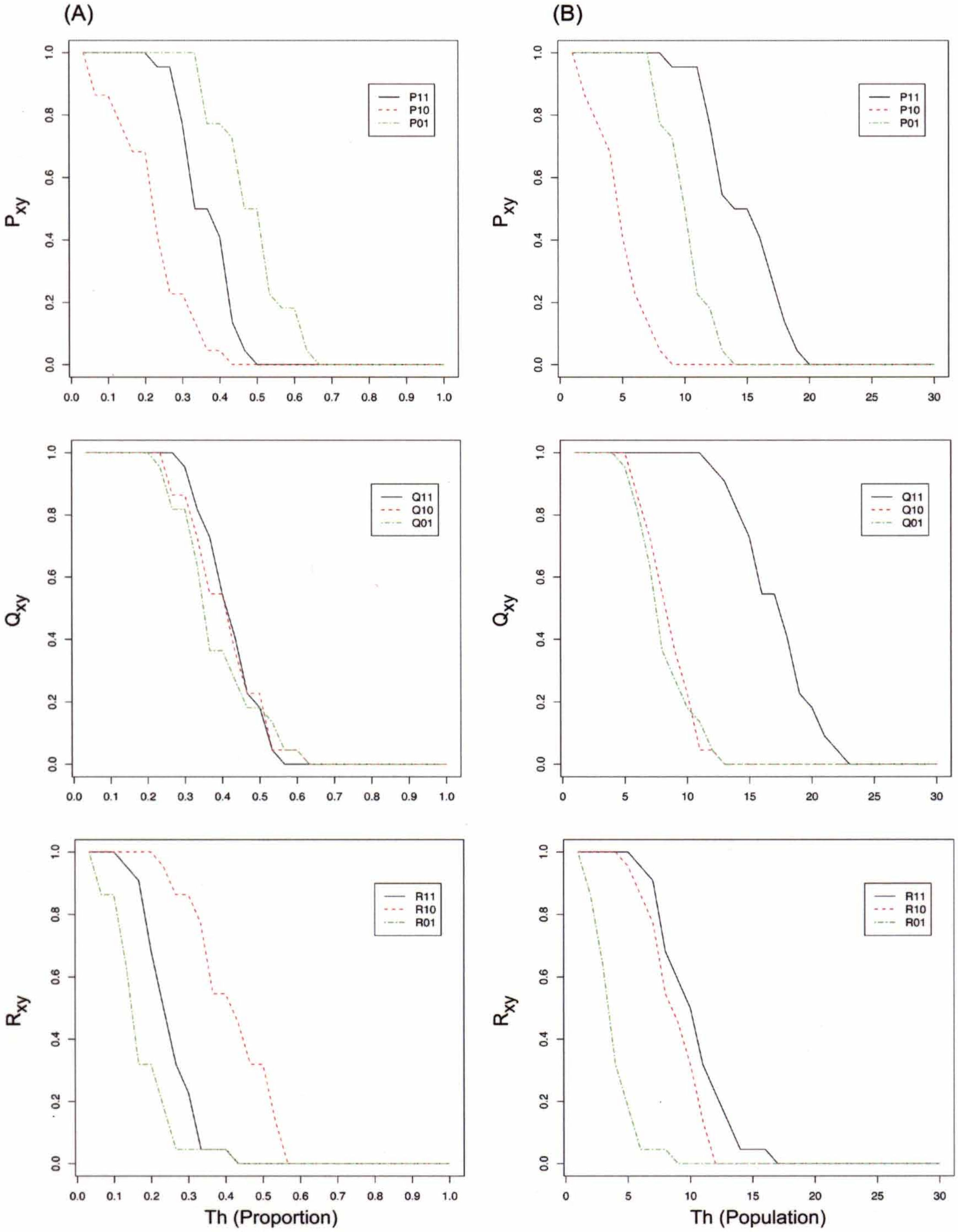


Figure 12. Probabilities Pxy, Qxy and Rxy that proportion (A) or population (B) of crabs in each output channel is above threshold for each state of inputs. The indices represent a pair of inputs.

Presence or absence of entities utilized as signals represented True or False values of Boolean variables respectively about previous collision gates. In our swarm gate, we had to define threshold values of population in an output channel for obtaining a logical value because not all crabs within a swarm arrive at one exit. That is, presence of more individuals than the threshold value in an output channel means True value, otherwise False. If the threshold value is too low then the swarm collision gate with inputs (0, 1), (1, 0) or (1, 1) is almost certain to output 1 in all output channels, conversely too high output 0. This implies that appropriate threshold values make our gate function some kind of logical operations.

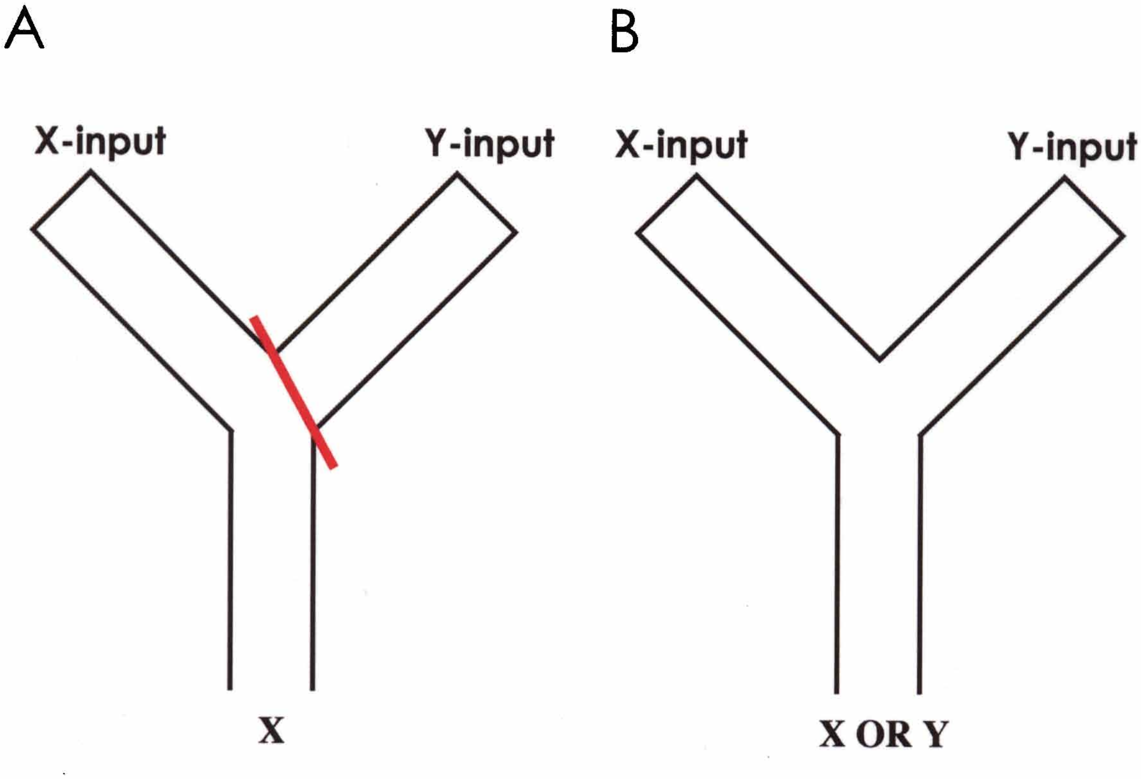


Figure 13. Scheme examples of gates without threshold. A, A gate producing X. A solid line nearby a junction represents impasse.; B, A gate producing X OR Y.

We estimated output value in each output channel by a proportion, in which output values p, q, or r are 1 if the proportion of population in P-, Q-, or R-channels to all crabs exceeds a threshold respectively, otherwise 0. Figure

12A illustrates performances Pxy, Qxy and Rxy of each output channel for a pair of inputs (x, y) that represent the probabilities of each output channel producing output 1 for each state of inputs under a given threshold value respectively. P01 and P11 could be discriminated from P00 and P10 at a lower threshold value (e.g. Th= 4/15, P01= 22/22, P10= 5/22, P11= 21/22) then the swarm gate about P-channel implemented logical operation Y (Fig. 12A top). Moreover P01 could be discriminated from the others at a higher threshold value (e.g. Th= 13/30, P01= 16/22, P10= 0/22, P11= 3/22) then logical operation NOT X AND Y was implemented (Fig. 12A top). Similarly R10 and R11 could be discriminated from R00 and R01 at a lower threshold (e.g. Th= 1/6, R01= 7/22, R10= 22/22, R11= 20/22) then swarm gate about R-channel implemented logical operation X, R10 could be discriminated from the others at a higher threshold (e.g. Th= 3/10, R01= 1/22, R10= 19/22, R11= 5/22) then logical operation X AND NOT Y was implemented. We can, however, construct a simpler gate implementing operation X or Y without threshold, which has two input channels and one output channel but one input channel is impasse (Fig. 13A). So we must employ the higher threshold. Unlike in the case of Pxy and Rxy, Qxy for each state of inputs was irreducible except for a pair of input (0, 0) and the gate about Q-channel implemented the logical operation X OR Y until a certain threshold value (Th= 1/5, R01= 22/22, R10= 22/22, R11= 22/22; Fig. 12A bottom). But we can again construct a simpler swarm OR gate without a threshold, which produces output 1 if and only if crabs are put in the apparatus because it has only a single output channel (Fig. 13B). We should find another operation that our swarm gate about Q-channel could implement only by defining a threshold. To achieve the purpose, the output value in each output channel was estimated about the population of crabs. The illustration of performances Qxy with respect to populations showed that Q11 could be discriminated from the others when the threshold is 12 (Q01= 1/22, Q10= 1/22, Q11= 21/22; Fig. 12B middle). So the gate could function as AND gate in Q-channel. Then what does the gate implement in P- and R-channel? The gate about P-channel had abilities of implementation of two operations, Y or X AND Y, because P01 and P11 were discriminated from P00 and P10 at a lower threshold (e.g. Th= 7, P01= 22/22, P10= 3/22, P11= 22/22) and P11 were discriminated from the others at a higher threshold (e.g. Th= 11, P01= 5/22, P10= 0/22, P11= 21/22; Fig. 12B top). About the R-channel, the gate implemented a logical operation X because R10 and R11 were discriminated from R00 and R01 (e.g. Th= 5, R01= 4/22, R10= 21/22, R11= 22/22; Fig. 12B bottom). It has already shown that the simpler gate implemented logical operations X or Y (Fig. 13A). We want the swarm logic gate that has simpler architecture and variety of computation. Thus we adopted a proportion about P- and R-channels and a population about Q-channel as criteria to obtain logical value in each output channel respectively. Hereafter the threshold values could be chosen in such a way that the P-, Q- and R-channels perform logical operations NOT X AND Y, X AND Y and X AND NOT Y respectively. Remarkably, We can produce NOT gate by selecting only Y-input and R-output when there is a swarm in X-channel.

2.3.3. Discussion

This study demonstrated that the apparatus with two gradients and the appropriate threshold values enabled swarms of soldier crabs to implement basic logical gates. In such swarm collision gate, two swarms departing from a pair of input channels turned out to be increase of population within a center of three output channels because the apparatus made the individuals within each swarm escape in the anterior direction.

A logical gate utilizing plasmodium of ***P. polycephalum*** as a signal is likely to be robust against external perturbation. Tsuda and his colleagues demonstrated that the ***Physarum*** gate performed logical conjunction with some degrees of precision, even if a part of apparatus was broken, the plasmodium maintained the performance of the gate by an unconventional behavior [36]. This suggested that altered local behavioral principles of organisms entailed the global robustness against environments. Does our swarm collision gate also have the potential to perform robust computation? Even if some of individuals within the group fell into impossible to perform normally owing to any disturbances, the remaining ones might be possible because the swarm was organized by a few dozens of individuals. But such scenario would be based not on a robust computation but only a redundant one. For a long time, it was well known that animal swarm, for example flock of starlings and school of sardines, acted with unity as if it was one living organism [15, 17, 18, 52]. Nevertheless the internal structures within a group might hold inherent turbulence that positively contributed to robust collective motion [5, 53, 54, 55]. In the case of soldier crabs, it has reported that a few dozen neighboring crabs simultaneously and synchronously behave when a soldier crab move [45]. In addition, from our field survey, soldier crabs formed swarms of which boundaries were amorphous but definitely sharp though individuals moved toward various directions. Thus a swarm might not discriminate internal perturbations resulting from turbulence and external ones, if some kind of perturbations were given to it during the gate working then global behaviors could be maintained. The swarm gate in simulation model showed the shifts of velocities of two swarms after colliding [6]. In our swarm gate, it, however, seemed that two swarms, the case of a pair of inputs (x, y) = (1, 1), did not influence one another so that there was little difference between predicted and actual populations in each output channel (Fig. 14). It may prevent the manifestation of interaction that escape time is short because of high motivations with gradients. Though a friction of swarms at a junction, in case of (x, y) = (1, 1), might delay the escape time, there was little difference between mean experimental periods for states of inputs (1, 1) and those for states of inputs (0, 1) and (1, 0) (118 sec and 116 sec, respectively). We observed that the motions of swarms of soldier crabs were changed with fusion and segregation on a tidal flat in some situations. Such dynamical behaviors of swarms might be one representation of robustness.

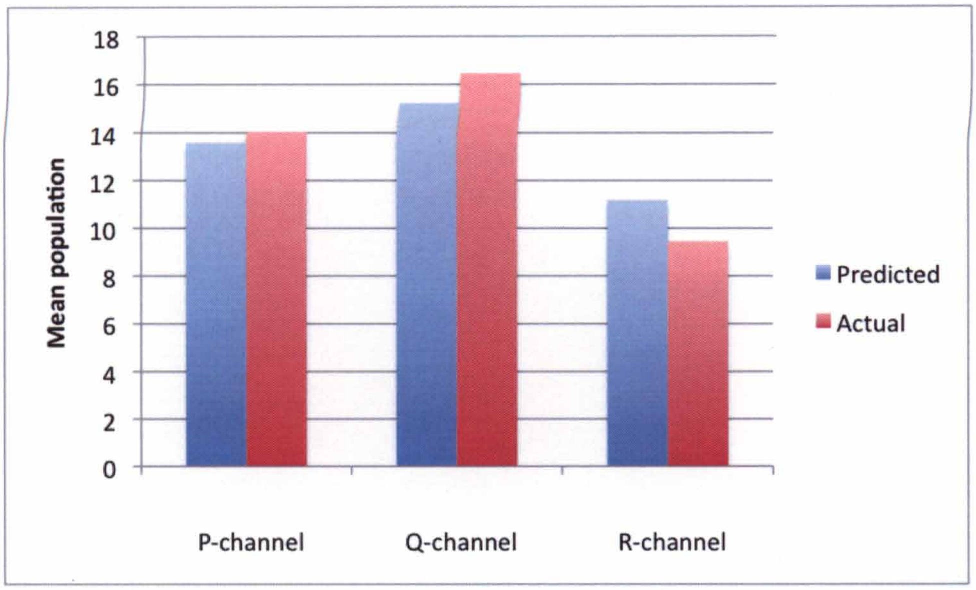


Figure 14. Predicted populations and mean populations for states of input (1, 1), namely actual populations. Predicted populations are summation of populations in each output channel for each state of inputs (0, 1) and (1, 0).

3. Indefinite Arm Illusion (IAI)

3.1. Introduction

Synchronous visuo-tactile stimulation of the type in the rubber hand illusion (RHI) [7-9] and in out of body experience (OBE) [10, 11] can induce the brain to incorporate external objects or images into a part or whole of body image. In the context of RHI or OBE, since the participant passively receives visuo-tactile stimulations, body image appears only with the sense of ownership (SoO), not with the sense of agency (the registration that we are the initiators of our actions; SoA) [56,57]. Insofar as self-consciousness as a body image is a united acting in its environments, body image has to be investigated in the relationship between SoO and SoA [58,59]. It requires an experimental condition in which SoO and SoA can be independently separated in an active condition. However, no experimental condition that is opposite to RHI and OBE in which a subject can feel SoA but not SoO has been proposed to date [60]. Here, we estimate whether a person loses SoO for his own hand that he can freely move by his own will when he sees himself in a lateral view through a head mounted display. It was previously thought that SoO can be represented by synchronous inter-modal stimulations [60], and that SoO appears to be complemented by SoA [61]. SoO and SoA are two aspects of body representation, and similar dissociations have been proposed in various contexts, such as body image and body schema [62,63], and 'Mine' and 'Acting I' [64].

Under a passive condition revealing RHI and OBE, only SoO is explicitly acquired. By contrast, in an active condition such as the phantom limb experiment [65,66], pantomime task [67], and synchronous virtual hand task [57], SoA is explicitly acquired and SoO seems to accompany SoA. These experiments are conducted so that the participant incorporates external objects into body image. Thus, it is difficult to see the loss of SoO. We therefore conducted an experiment in which a participant can lose SoO for his own hand (Section 3.2).

3.2. Altered states of bodily consciousness

3.2.1. Experimental settings

We recruited Kobe university students as volunteer participants for experiments. All comers (a total of 28 people whose sexes, ages and specialties did not matter.) participated in experiments. Any authors in this manuscript did not participate in the experiment. For all experiments, we used the following equipment (Fig. 15): Head mounted display (HMD): i-visor FX605 (DAEYANG), Video cameras: DCR-VX 1000 (SONY) 2 for experiments 1, GZ-MG 740 (Victor) 2 for experiment 2, Up-scan converters: TVBOXes (I-O DATA) 2, and Monitor splitter: VGA-HR2K (Sanwa Supply).

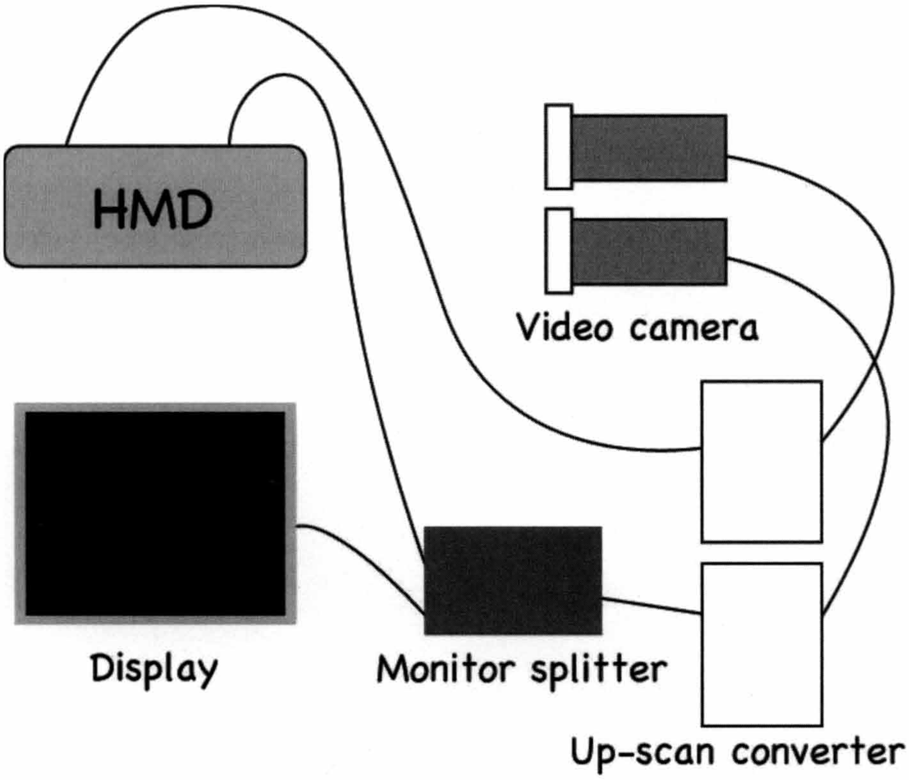


Figure15. Experimental setting for all three experiments. A display was used for the experimenter to confirm the image viewed by the participant.

During wearing of the HMD by the participant, the experimenter continuously monitored the motion images viewed by the participant on the HMD via the display. It was confirmed that changing the model of the video cameras and trials with or without a monitor splitter did not affect the motion images viewed by the participant.

3.2.2. Experiment 1: Questionnaire

Participants (n= 28) were seated while wearing a head mounted display (HMD) onto which was projected real-time motion images of one side of their own upper body filmed by two video cameras placed side by side. The video cameras were placed 130 cm away from the participant, with a 10 cm distance between the two video cameras. The images from the left video camera were presented via the left eye display and that from the right camera via the right display. The participant could see his or her own lateral view stereoscopically. The participant was shown four kinds of counterbalanced images for 30 seconds: the right or left side of his body and in a hide or display condition. In the hide condition, the participant could not see his upper arm since he was instructed to hide it behind his own body. In the display condition, he was instructed to keep it on view in front of his body, thereby serving as a control experiment (Fig. 16). During each trial, the participant could move his arm behind his body freely under the hide or display condition, and he was requested to orally provide an open-ended description of his experiences. All participants reported that they could move their own hands freely as they intended to move them, regardless of the hide and display conditions. Such a finding reveals they had SoA.

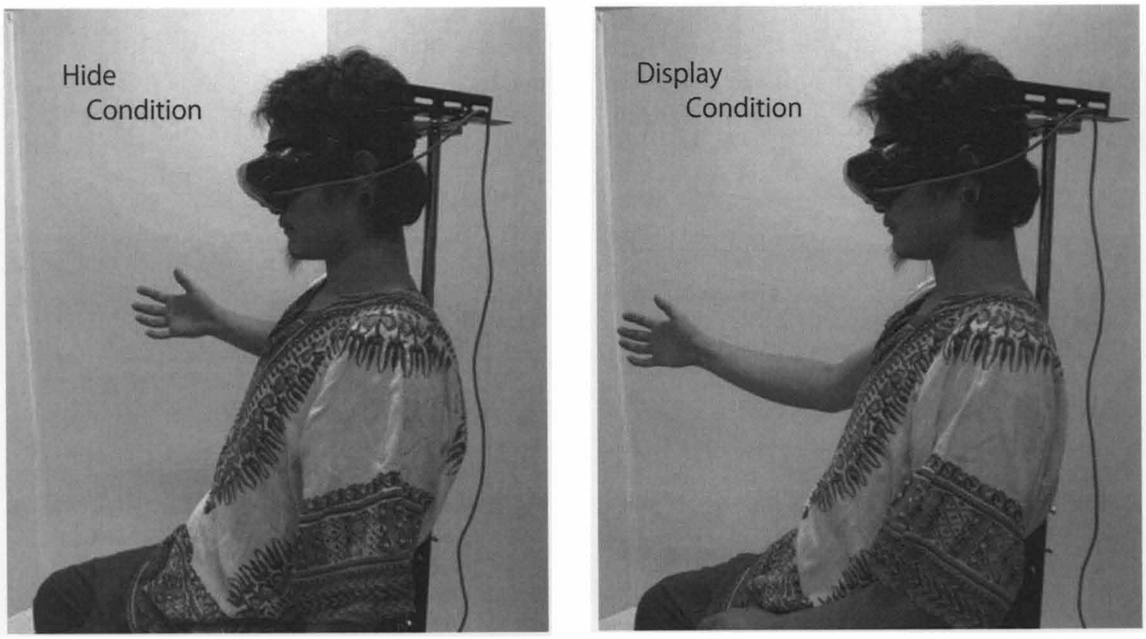


Figure16. Experimental images viewed by the participant. They viewed these motion images during each trial on a head mounted display.

After 30 seconds viewing each motion image, participants were asked to complete a questionnaire in which they had to affirm or deny the occurrence of seven specific perceptual effects using a seven-point visual analog scale. The completed questionnaire indicated that participants experienced strong loss of SoO under the hide condition (Fig. 17) and the side of participant's body did not influence (maximum F(1,108)=2.30 then P=0.13). The first three questionnaire items were important to estimate the loss of SoO, and the results for items 1 and 2 showed significant differences between the display and hide conditions (item 1: $P < 0.001$, $t = 4.91$, item 2: $P < 0.001$, $t = 4.60$). The particularly highly positive score for item 1 indicates that the participant felt as if the hand were not his own despite moving it by his own will.

During the 30 seconds of viewing, there were times when:

Q1. I felt as if the arm was not mine.
Q2. I felt as if the arm was another person's.
Q3. I felt as if the arm was neither mine nor another person's.
Q4. It seemed as if the arm was not an arm.
Q5. I could not freely move by my own will.
Q6. It seemed as if the arm moved on its own.
Q7. I felt as if a stranger moved the arm.

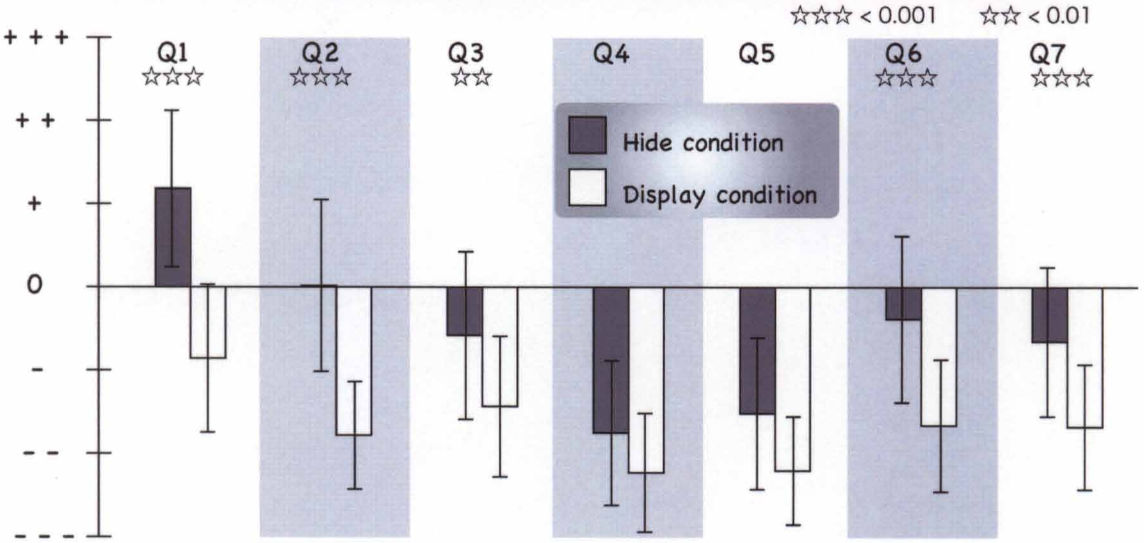


Figure 17. Questionnaire results, presenting means and standard errors of each item for the two experimental (hide and display) conditions. The double or triple asterisk indicates significant differences ($P<0.01$ or $P<0.001$ respectively).

While there was a significant difference between two conditions in the scores for items 2 and 3, the scores were not high. The questionnaire items making the person indicate the owner of the hand (which also included nobody in item 3: $P = 0.06$, $t = 1.91$) might serve as the justice of ownership [9], different from the feeling of ownership relevant to item 1. Results for items 4 and 5 showed that the hand was not recognized as anything but a hand and to be controllable, thereby confirming SoA. This result held irrespective of the hide or display condition (item 4: P =0.46, t =0.74, item 5: P =0.27, t =1.12). Items 6 and 7 were also relevant to SoA. Although participants denied the occurrence of the perceptual effect for these items, there was a significant difference between the display and hide conditions (item 6: P < 0.003, t = 3.12, item 7: P < 0.02, t = 2.45). A significant difference between the conditions reveals that the feeling that SoA is weakly lost.

3.2.3 Experiment 2: Measurement

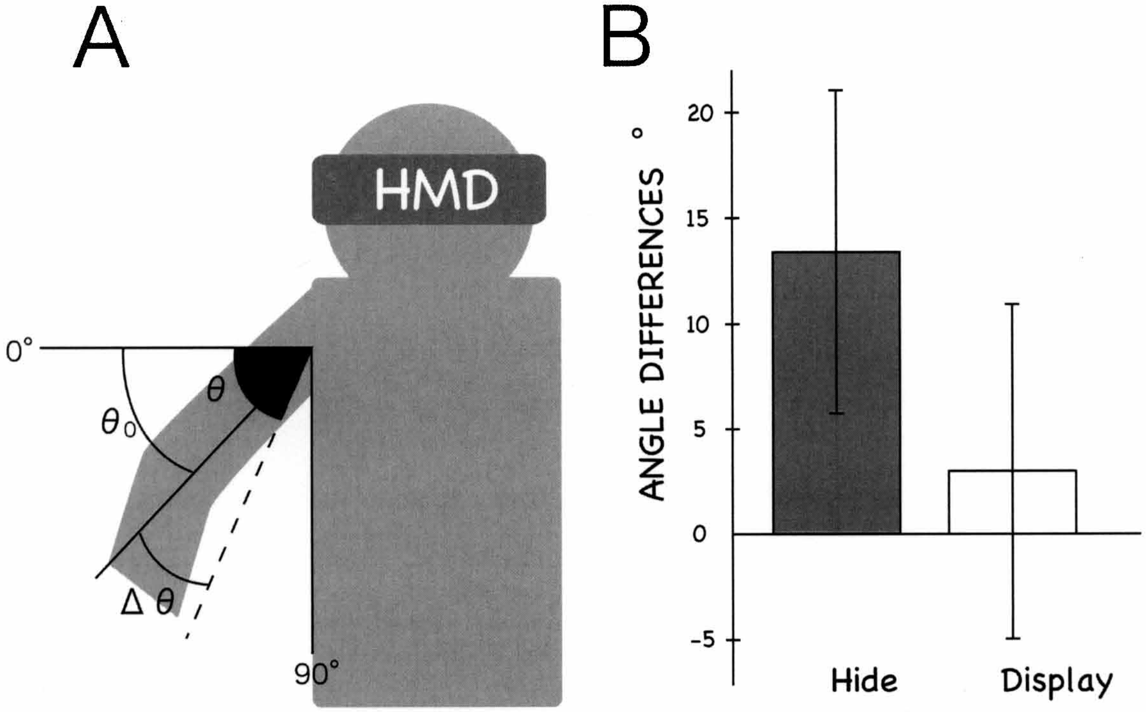


Figure 18. A. Difference of the angle (Δ θ) between the actual angle made by the upper arm and the body (θ 0) and the estimated angle (θ). Participants were exposed to the condition of our first experiment for a prolonged period, and were asked to estimate the angle between the body and the upper arm at the hidden side in the anterior view. B. The angle difference under the hide (H) and display (D) conditions.

We hypothesized that the mismatches of positional awareness regarding the upper arm between visual perception and proprioception caused the loss of SoO. The elbow and upper arm can be clearly seen by the participant in the display condition, making it is easy for him to imagine that the arm is connected with the shoulder. Under the hide condition, some participants reported feeling as if his upper arm was lost. Thus we focused on the participant's false recognition of the angle made by the body and the upper arm. This was confirmed by measuring the difference between the actual and the participant's estimated angle made by the upper arm and the body (Fig. 18A). The participant was exposed in the first experiment for prolonged periods to the hide and display conditions. The participant was instructed to move freely the hand on the hidden side (i.e. the opposite side to where the video camera was located), to stop the hand on the experimenter's cue, and to keep the same position for a short time. Thus, the participant's hand was placed in various positions. First, the experimenter measured the angle made by the body and the upper arm in the anterior view. While the participant maintained the position of the arm, he was asked to indicate the angle made by the body and the upper arm on a protractor (representing 0~90 degrees, 40 cm in size). The difference between the actual and estimated angle in the hide condition was compared to that in the display condition.

Four participants took part in this experiment. Angles were measured twenty-two trials per participant, in either the hide or display condition for each trial. The order of the conditions presented (i.e. hide or display) was randomized in advance. In each trial, after experimenters measured the actual angle, the participant reported the estimated angle by indicating the angle on the protractor. The difference of the angle in the hide condition was larger than that in the display condition (P=0.003, t=3.11) (Fig. 18B). A large positive difference in the hide condition suggests that the participant perceived the distance between his elbow and flank to be shorter than the actual distance and lost the correct positional awareness of body parts under the hide condition.

3.3. Discussion

The present illusion is fundamentally important because it provides the first experimental condition of SoA without SoO. In the passive condition, RHI and OBE reveal that multi-sensory synchronous interaction (Sense of being acted upon; So-be-A) can produce SoO [7-11]. Conversely, it is reported that SoO can produce So-be-A [68]. Thus, under the passive condition, SoO is equivalent to So-be-A. Since SoO and SoA are relevant to the distinction between you and me in terms of neuroactivity [57], investigation of the dynamical relation of SoO and SoA is necessary. The feeling of SoO or SoA alone has been noted in deafferented [69] and/or schizophrenia patients [70], and our findings relating to healthy persons' self-consciousness can contribute to expanding the knowledge about these patients.

Our experiment involving human participants was approved by the Ethics board in Nagaoka University of Technology. From all participants informed consents were written and all clinical investigations have been conducted according to the principles expressed in the Declaration of Helsinki.

4. Conclusion

Even if a system has intrinsic discrepancies, it can appear not to change any further due to humdrum simplicity of its global behavior. In implementation of crab's hourglass, the swarm revealed a simple oscillation. But a recent model [5] demonstrated that the swarm with inherent turbulent implemented the hourglass. The simulated swarm is robust because it does not separate inherent noise and external one. The hourglass and logical gate implemented by real crabs might be robust. How can a robustness of system be empirically verified? A bodily self-consciousness would provide a clue. Bestowing an assignment of extended body on an external object results from a complementary interaction between multimodalities, and we can find redundant body. Unlike this, depriving own body of the assignment co-occurs with consciousness acting, and we can find ambiguous body. Former and later conditions would lead to stability and robustness respectively.

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