An Experimental and Computational Approach to the Dynamic Body Boundary Problem

Yuki Sato[1], Hiroyuki Iizuka[2] and Takashi Ikegami[1]

[1] General Systems Sciences, The Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan

[2] Graduate School of Information Science and Technology, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

yuki@sacral.c.u-tokyo.ac.jp

Abstract

In this paper, we propose an experimental and computational model to challenge the dynamic body boundary problem, as seen in the rubber hands illusion and phantom limbs. Our strategy examines an agent's "attention shift". A computational model (Iizuka & Ikegami, 2005) was used to explore how a body and sensor can be made inseparable. A model agent was required to determine the number of vanes on a windmill by touching the windmill blindly with a stick. By adding an additional windmill to the first one, we investigated the agent's shift of attention, i.e. the agent could either determine the vanes on the first windmill, or the second windmill by using the first one as a tool. In other words, an agent's body image can shift from its arm tip to the boundary between the first and second windmill. We then introduced an experiment with a real windmill model to test the hypothesis shown by the theoretical model. Subjects were tasked with determining the number of vanes on the second windmill. We found that sensory-motor correlations between their actions and perceptions of the movement of the windmills were helpful for the attention shift but still not enough to extend their body boundaries.

Introduction

A Model to Bridge the Gap between the Self and the Environment

In order to overcome philosophical and scientific problems such as the "hard problem", which asks how and why certain neural processes give rise to subjective experiences (Charlmers 1996); or the symbol grounding problem, which asks how symbols get their meaning (Harnad 1990), we need a radical new framework or model to recast the dichotomies of mind and body, subject and object, agent and the environment, and perception and action.

How we model our cognition is directly connected to how we understand it. Studies on embodied robots and simulations are based on sensory-motor ideas that attempt to describe our psychological processes from sensory-motor connections and interactions with the environment (Walter 1950, 1951; Braitenberg 1984; Pfeifer & Scheier 1999; Brooks 1991a, b). For example, Walter (1950, 1951) discusses cognitive, play-like, and social behaviors by synthesizing artificial vehicles, while Braitenberg (1984) made conceptual robots to discuss the higher functioning of cognition. However, even if the above approaches succeed in shedding light on sensory motor experiences through interaction with the environment, the approaches still fails to consider psychological concepts such as body image, ownership, agency and active perception, which play an important role in resolving the dichotomies.

There are many phenomena in empirical neuropsychological studies that can be described with these psychological concepts. Yamamoto and Kitazawa (2001), for example, demonstrated in the arm-crossing experiment that the perceived temporal ordering of haptic stimuli was reversed when the successive stimuli were temporally close enough. Maravita and Iriki (2004) demonstrated that a macaque monkey's body image was extended to the tip of a tool bar when the monkey learns to use it. Ramachandran and Blakeslee (1998) showed that a human body image can be easily created or destroyed by using visual or auditory information. These experiments and others have revealed that body images and ownership have very dynamic natures, something we would like to implement in our system.

Our body image and ownership bridge the gap between the highly abstract sense of "self" and the physical world where our body is situated. Francisco Varela (1979) proposed a principle of autonomy, stressing the idea of a self-generated boundary. He exemplified autonomy as a "self" that emerged from a chemical system through structural coupling with the environment. In his model, it was shown that some reactive particles created a boundary, which regulated internal reactions of the particles, thus maintaining the boundary structure. The circularity of the physical boundary and the internal dynamics produce the coherence of the self-state. In other words, the self has not been strictly defined but can be described as a dynamic process, and the sensory-motor experiences from the perspective of the emergent self, account for the psychological or highly abstract concepts such as life. One such challenge, with respect to a proto-cell system, can be seen in Suzuki and Ikegami (2004).

Mere sensory-motor modeling surrenders the self because it is pre-defined as a completely different entity to the environment and the boundary is given as the firm distinction between them. Therefore, we provide a new framework for modeling in order to achieve a balance between both ideas of emergent self and sensory-motor flow. In the new framework, we assume no explicit distinction between a sensor and a motor that defines the boundary. An interface between an agent and its environment is only dynamically constructed. Exploiting the model, we investigate active perception and body image as dynamic processes in the emergent self. The psychological notions are clarified first in this paper, after which the computational modeling and results are described. We also report some tentative results of a real windmill model, which has recently been made to investigate how human subjects feel their body boundaries.

Body Image

Our body images are not restricted to the physical boundary that separates our bodies from the external world. When an expert driver drives a car, he/she can traverse narrow streets easily, as though the car were part of his/her own body. Indeed, he/she is aware of the whole car, and when the car runs over a rock, he/she feels as though he/she has stepped on it with his/her foot. Another example is an artificial tooth. We feel uncomfortable and cannot taste food when using an artificial tooth for the first time. However, over time, we adapt to the artificial tooth and learn to taste again. Yet another instance of this can be seen in a blind person's stick. As he/she adapts to its use, the stick changes from mere matter to a real body part, and the person is eventually able to perceive his/her environment with the stick. These examples show that one's body image can be extended beyond his/her physical body boundaries. Body images are formed through interactions between brain, body, tool, and environment. Nevertheless, the dynamic mechanisms underlying the changes of body images are still not fully understood, despite their importance in areas such as medical care, robotics, cognitive development, enactive cognitive science (Varela et al. 1991; Thompson 2007), the "extended mind" (Clark et al. 1998), and "radical embodied cognitive science" (Chemero 2009). We propose a model for body images by extending the windmill model proposed by Iizuka and Ikegami (Iizuka & Ikegami 2005). The windmill model proposed by Iizuka and Ikegami is a computer simulation model to study "active perception" (Gibson 1962).

Active Perception

A difference between human perception and an artificial system based on current technology is the fact that two modes of perception exist in humans, active and passive modes of perception. When we touch an object with our hands, we perceive the shape, texture, and temperature of the object. Gibson (1962) reported on experiments in which blind subjects touched different shapes of cookie cutters. When the cutter was pushed randomly on the subject's palm, the subject recognized the correct shape with 72% accuracy. By touching the cutter in a self-guided manner, the subjects recognized the object more than 95% of the cases. The former case is an example of passive perception and the latter case is active perception. This study illustrates that perception does not merely entail receiving information from the outside. It is instead a form of exploration. Moving our hands is not just a method we use to arrive at perception, but rather, the moving of one's hands is an ongoing exploratory process, which we think of as a generic property of perception. Edward Reed (1996) has further developed Gibson's idea, and this idea of perception has become a core principle of new psychology (often called ecological psychology).

Even though the idea of active and passive perception is subjectively apparent and has been studied empirically, it is still difficult to implement the two modes within the context of an artificial model. Iizuka and Ikegami (2005) studied the simulation model of object discrimination, which implement the two modes of perception. The present study further develops this research by studying the changing of body images.

Computational Model

Windmill Model for Active/Passive Perception

In this section, we briefly introduce the model for active/passive perception, and in the next section, we propose a model for body images and report results. In the proposed model, the agent consists of a body with a straight arm that can move and touch an object (Figure 1). The object is a windmill with a certain number of vanes, and the agent can rotate the windmill by pushing the vanes. This is what we call an active condition. When the agent perceives the windmill by its arm being pushed by the vane, this is a passive condition. In other words, the windmill has an infinite mass in the passive condition, and the agent cannot change the initial velocity of the windmill by pushing its vane. One of the aims of this windmill model was to examine the difference between the two methods of perception in terms of dynamic systems.

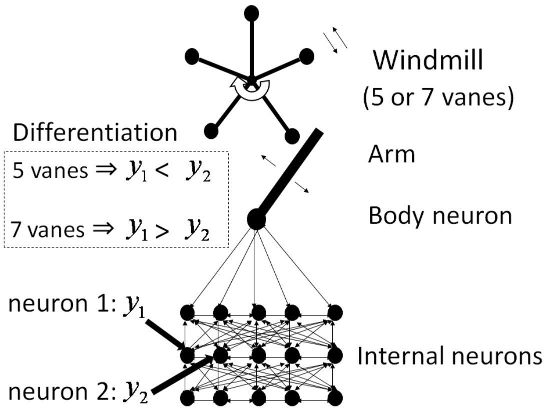


Figure 1: Windmill model for active/passive perception. The agent consists of an arm, a "body neuron", and internal neurons. The windmill has 5 or 7 vanes. Differentiation of the windmills is made by comparing the activities of neurons 1 and 2.

Firstly, the dynamics of the arm and the windmill are controlled by the deterministic equation:

$$M_a \ddot{\theta}_a + D_a \ddot{\theta}_a + F_a + F_{col}(\theta_a, \theta_w) = 0, \quad (1)$$

$$M_w \ddot{\theta}_w + D_w \ddot{\theta}_w + F_{col}(\theta_a, \theta_w) = 0, \quad (2)$$

where θ_a and θ_w denote the angles of the arm and the windmill, respectively; M_a and M_w denote the mass of the arm and the windmill, respectively; D_a and D_w denote the friction coefficient of the arm and the windmill, respectively; F_{col} is a function giving the potential of collision; and F_a is the force of the agent used to rotate the arm.

Secondly, this agent also has a "brain" that consists of internal neurons (Figure 1). The dynamics of these neurons are controlled by a continuous-time recurrent neural network (CTRNN) (Beer 1995). The dynamics of the neural system are expressed by the following equations:

$$\tau_i \dot{y}_i = -y_i + \sum_{j=1}^{M} w_{ji} g_j(y_j), \quad (3)$$

$$g_i(x) = \frac{1}{1 + e^{-x-b_i}}, \quad (4)$$

where y is the state of each neuron, τ is its time constant, b is a bias term, and w_{ji} is the strength of the connection from the neuron, j to i. It should be noted that we adopted a sparse structure rather than a fully-connected network. The neurons are arranged in 3 layers.

Thirdly, the agent has a body neuron at the interface between the arm and the internal neurons. The body neuron simultaneously plays the role of sensor and motor. That is, this neuron determines the value of F_a and the angle of the arm is assigned to the body neuron (Figure 2). The agent has no explicit functional division of sensors and motors. The distinction between moving and being moved becomes implicit. Whether an arm motion is caused spontaneously or externally, it is internally evaluated by investigating the body neurons and internal neurons. In an empty space, an agent can freely move his/her arm. When an arm hits an object, the collision produces de-coherence of the arm movement, which is interpreted as sensory information.

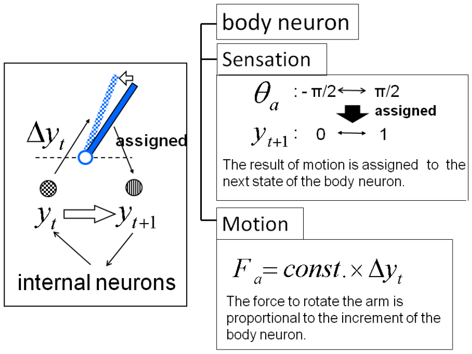


Figure 2: Updating the state of the body neuron, which plays the role of sensor and motor at the same time. Δy_t denotes the increment of the body neuron, which is given by equation (3). Δy_t is used to determine the force to rotate the arm.

Active/Passive Agents. An agent interacts with the windmill and distinguishes the number of vanes present (5 or 7) given the two conditions (cf. the beginning of the previous section). Specifically, an active agent distinguishes a windmill by actively touching the vanes. A passive agent does the same task by being pushed by the windmill. In both cases, this differentiation is made by comparing the neural activities of two neurons, neuron 1 and neuron 2 (Figure 1). If y_1 is greater than that of y_2, the agent distinguishes the windmill as having 7 vanes, and if y_1 is less than y_2, the agent distinguishes the windmill as having 5 vanes.

To train both active and passive agents, we adopted a standard genetic algorithm (GA) (Holland 1975) by encoding w_{ji} (the neural weight), τ_i (time constant), and b_i (bias neural states) (cf. equation (3), (4)) into the real-valued strings. These strings are taken as artificial genomes and will be selected according to the fitness value of the corresponding agent (Figure 3). The value is calculated by multiplying the percentage of correct answers. The best-performing agent is preserved in the population without a genetic operation (elitism). The other agents are reproduced from the best agents by adding small random values (without sexual reproduction).

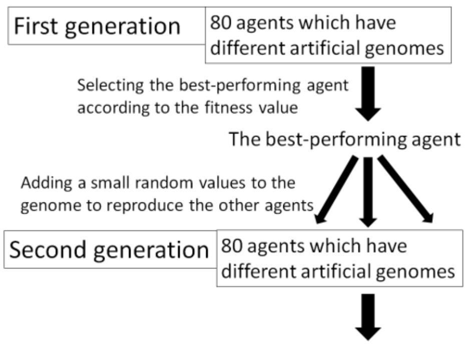


Figure 3: A schematic view of the genetic algorithm (GA) used in this study. We prepared 80 agents with different artificial genomes. The best-performing agent is selected according to the fitness value of the corresponding agent. The best-performing agent is preserved in the population. The other agents are reproduced from the best agents by adding small random values.

General Observations. A computational model shows that an agent becomes sensitive to the number of vanes. One difference exists in active and passive classifications: active classification is less stable against time delay compared to passive classification (Iizuka & Ikegami 2005). This is the dynamic system's interpretation of active and passive perception. In the following sections we further extend this model by adding the second windmill next to the first and gear the two windmills to move associatively. Our concern is to study how an agent's discrimination capability can be extended to the second windmill. We shall also discuss the synthesis of body images with the windmill.

Coupled Windmill Model

In studying the coupled windmill model, we fix the number of vanes of the first windmill to 5 and require the agent to determine the number of vanes of the second windmill (which has 5 or 7 vanes). See Figure 4 for an illustration. An agent now uses the first windmill as a "tool" to determine the number of vanes on the second windmill. If an agent can successfully use the first windmill as a tool, we can say that, for the agent, the first windmill has shifted from an object to a tool. At this time, the agent's body image is thought to be extended to the first windmill. In the following sections, we only focus on the "active" agents, which actively use their arms to rotate the windmill in order to classify the number of vanes present.

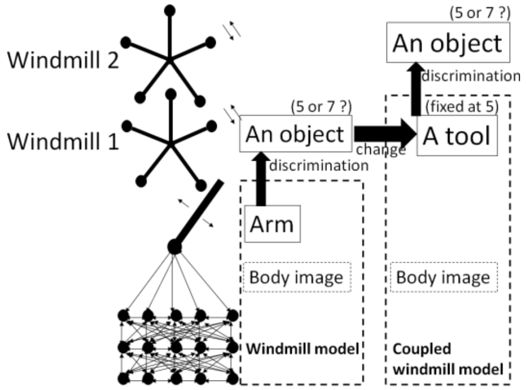


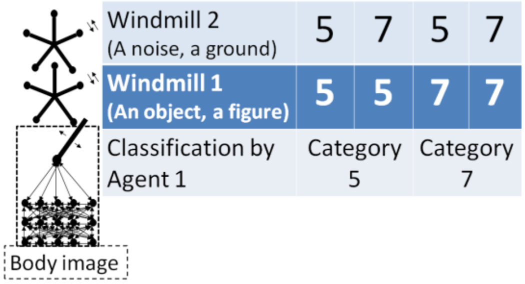
Figure 4: A coupled windmill model for studying body images. This agent determines the number of vanes on Windmill 2. In the previous windmill model, Windmill 1 was an object to be distinguished. On the other hand, in the coupled windmill model, Windmill 1 changed from an object to be distinguished to a tool to determine the number of vanes on Windmill 2. At this time, the agent's body image is thought to be extended to Windmill 1.

Is the First Windmill a Tool or a Mere Object? The first windmill is proposed to become an extension of the agent's body, thereby shifting his/her body image. If an agent can judge the number of vanes of the second windmill, can we identify this as an emergence of the body image? In this case, even if the agent can distinguish between the windmills, we cannot simply say that the agent has shifted his/her body image. The agent might just distinguish two windmills as (5, 5)[1] and (5, 7). In other words, the first windmill might not be a tool but a mere object. We cannot decide which is right if the agent differentiates between two combinations of windmills. These are, (5, 5), (5, 7).

To overcome this problem, we required the agent to distinguish not two combinations ((5, 5), (5, 7)), but four combinations, which are, (5, 5), (5, 7), (7, 5), and (7, 7). We want to compare two different agents to discuss the boundaries of body images. If an agent classifies the four combinations as two groups, which are, {(7, 5), (7, 7)} and {(5, 5), (5, 7)}, then the agent is sensitive to the vanes of the first windmill (this is called Agent 1) (Figure 5). This is because Agent 1 classifies the combinations within the same/different category if the first windmill has the same/different number of vanes and the agent does not care about the second windmill. In contrast, if an agent classifies the combinations as {(5, 5), (7, 5)} and {(5, 7), (7, 7)}, the agent is sensitive to the vanes of the second windmill (this is called Agent 2) (Figure 6). Here, Agent 2 classifies the combinations with respect to the second windmill and does not care about the first windmill. In other words, for Agent 1, the first windmill functions as an object to be distinguished, and the second windmill works as a noise (Figure 5). Or, we might say that the first windmill is perceived as a "figure" by Agent 1 and the second windmill is seen as a "ground". In contrast, for Agent 2, the second windmill becomes an observed object (or a "figure"), and the first windmill is a tool (or a "ground") to distinguish the second windmill (Figure 6).

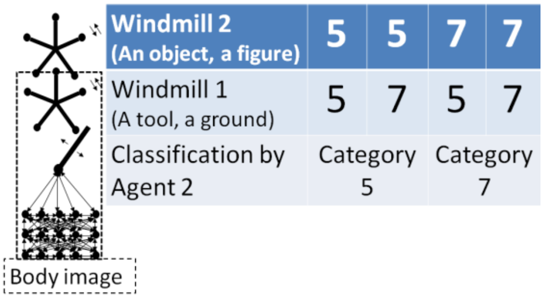
---

[1] The first and second components (,) are the number of vanes of the first and second windmills, respectively.



Windmill 2 (A noise, a ground)	5	7	5	7
Windmill 1 (An object, a figure)	**5**	**5**	**7**	**7**
Classification by Agent 1	Category 5		Category 7	

Figure 5: Agent 1. This agent is sensitive to the first windmill in the classification and does not care about the second windmill. The first windmill functions as an object to be determined, and the second windmill works as a noise, which means that the first windmill is not a part of the body image of Agent 1.



Windmill 2 (An object, a figure)	**5**	**5**	**7**	**7**
Windmill 1 (A tool, a ground)	5	7	5	7
Classification by Agent 2	Category 5		Category 7	

Figure 6: Agent 2. This agent is sensitive to the second windmill in the classification and does not care about the first windmill. The second windmill becomes an observed object, and the first windmill is a tool to distinguish the second windmill, which means that the first windmill is a part of the body image of Agent 2.

Shift of Attention. We think that this "shift of attention" is essential in defining the boundary of body image. For example, when we use a word processor for the first time, we pay attention not to the characters on the screen, but to the keyboard. At this stage, the keyboard is still an observed object and our body image is not extended to the keyboard. However, the attention is shifted from the keyboard to the screen as we become accustomed to typing. At this time, the keyboard's status changes from being a mere object to a real tool, and our body image is extended to the keyboard. In our model, Agent 1 pays attention to the first windmill and does not care about the second windmill, which means that the first windmill is not part of the body image of Agent 1. In contrast, Agent 2 pays attention to the second windmill and does not care about the first windmill, which means that the first windmill is a part of the body image of Agent 2.

Key Observations By using a genetic algorithm, we successfully trained agents to become sensitive to the vanes of the first (Agent 1) or of the second windmill (Agent 2).

Changing the number of vanes successively from (5, 5) to (5, 7) to (7, 7) to (7, 5), we see that in the case of Agent 1, neuron 1 and neuron 2 are sensitive to the first windmill and do not care about the second windmill (Figure 7); in the case of Agent 2, neuron 1 and neuron 2 are sensitive to the second windmill and do not care about the first windmill (Figure 8).

For example, from (5, 5) to (5, 7), as in the case of Agent 1, no transition occurs in the neural states. However, in the case of Agent 2, a sharp transition occurs, and the magnitude relation is changed. In contrast, from (5, 7) to (7, 7) in the case of Agent 1, a sharp transition occurs, but in the case of Agent 2, the neural states maintain the magnitude relation.

As far as we know if we change the number of vanes, it won't give the same result. However, as we already reported, a system properly count the number of the vane, when there is only one wheel (Sato et al. 2009). But counting two wheels case was also tough for the computational model.

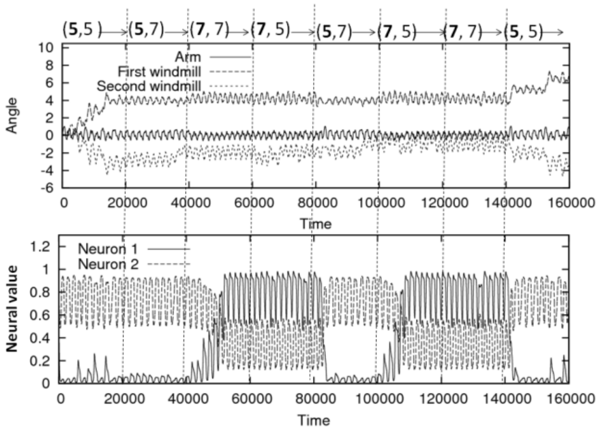


Figure 7: Agent 1: the time series of the arm, the first windmill, the second windmill (top) and of neurons 1 and 2 (bottom).

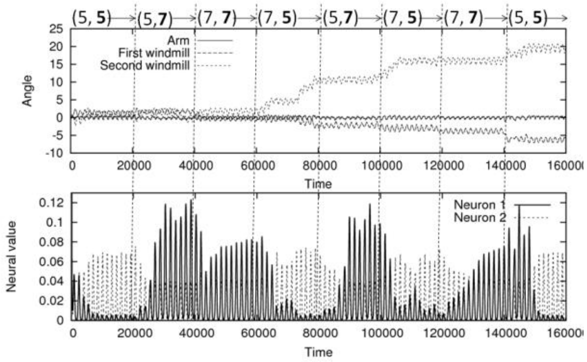


Figure 8: Agent 2: the time series of the arm, the first windmill, the second windmill (top) and of neurons 1 and 2 (bottom).

Experimental Setup

Real Windmill Model

In order to test the hypothesis shown by the theoretical model, we have conducted a real experiment and constructed two windmills with crossed metal bars. In this setup we fix the number of vanes on the first windmill to 5 and ask subjects to determine the number of vanes on the second windmill (which has 5 or 6 vanes).

Subjects wear a blindfold and touch the first windmill with only a stick, which is also fixed in space. The stick is introduced to constrain the movement of the subjects. Subjects are requested to determine the number of vanes on the second windmill in 30 seconds. The experiment is repeated over 30 trials.

Result. Subjects (N=5) come to discriminate windmills about 80 percent accuracy at the end (Fig.9a). Observationally, in the early stages, the stick and the windmills move randomly but they switch to regulatory behavior in the end in cases of a single (Fig. 9b) and coupled windmill experiment.

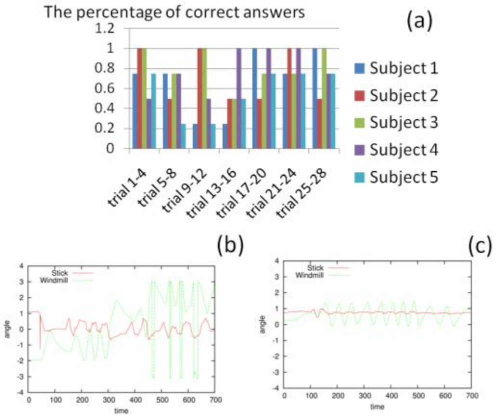


Figure 9; (a) The percentage of correct answers in a coupled windmill experiment. (b), (c) The time series of the stick and the windmill in a single windmill experiment. Movement of the stick changes from random motion (b) to periodic motion (c) as the subjects adapt to its use.

The body boundary of subjects is still not extended. Although subjects could count the number of vanes usually, they reported that they just paid attention to the touch feeling of collisions between the stick and the first windmill (Fig. 10a).

Because the number of vanes on the first windmill is fixed to 5, the collision events between the stick and the first windmill increase in frequency when the second windmill has 6 vanes, and decreases if it has fewer vanes (=5). With this trick, subjects could count the vanes on the second windmill. In this case, the first windmill is still an object to the subjects so that the body boundary is not extended to the boundary between the first and second windmill.

Figure 10b shows the time series of the positions of the stick and the vane of the first windmill which collide with the second windmill (the red vane in Fig. 10a). The supporting point of the stick and the windmills are fixed on the horizontal line in Fig 10a. But the center of the oscillation of the stick and the vane of the first windmill is not on the line (Fig.10b).

Something is needed to extend a subject’s body boundary. Our hypothesis is that subjects need more visual information about the windmills to learn the sensory-motor correlations between their action and the movement of the windmills. But if subjects can see the windmills they also recognize the number of vanes of the second windmill.

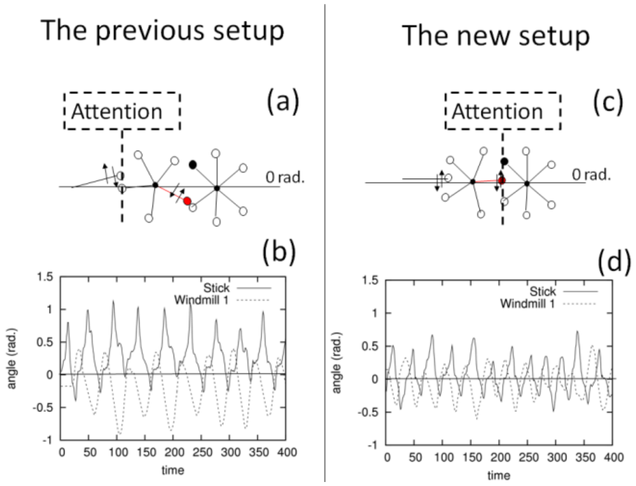


Figure 10: (a) The subjects reported that they paid attention to the collisions between the stick and the first windmill. The supporting point of the stick and the windmills are fixed on the horizontal line. (b) The direction of the first windmill from the supporting point of the stick is 0 radian (the horizontal line in Fig. 10a), but the center of the oscillation of the stick is more than 0 radian and that of the vane of the first windmill which collide with the second windmill (the red vane) is less than 0 radian. (c) In the new setup some subjects paid attention to the collisions between the first windmill and the second one and did not care about the collisions between the stick and the first windmill. The supporting point of the stick and the windmills are fixed on the horizontal line. (d) The direction of the first windmill from the supporting point of the stick is 0 radian (the horizontal line in Fig. 10c), and the center of the oscillation of the stick and the vane of the first windmill which collide with the second windmill (the red vane) is 0 radian.

New Setup

In order to extend the body boundary of subjects, we introduced visual inputs (Fig. 11). A video camera captures the windmills and displays them on the monitor, while subjects do the task, watching the monitor.

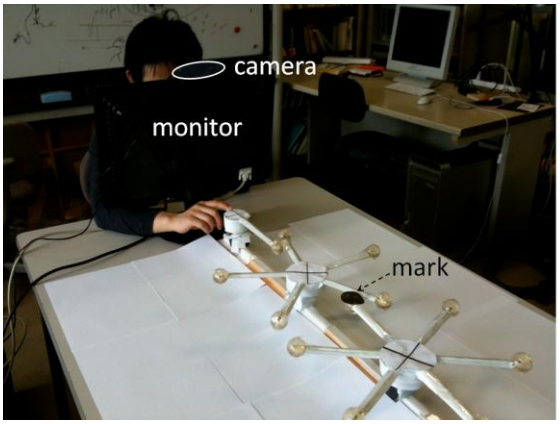


Figure 11: New setup. Here, there is a stick, the first windmill, and the second windmill, which is white. There is also a monitor, camera and one black mark attached to a vane on the second windmill. The camera captures the windmills and displays them on the monitor.

Now subjects can observe the global configuration of two windmills and how they move around (the left image of Figure 12). By using a black-white screen and painting the two windmills in different colors, a subject can only see the movement of one windmill at a time.

In the right image of Figure 11, subjects can only see the second windmill. Since we only put a mark on one vane, subjects can't recognize the number of vanes, but they can see the movement of the second windmill.

Figure 12: Two kinds of images on the monitor. The left image has full color. In this case subjects can see all and recognize the number of vanes. On the other hand, the right image is in black and white. In this case, subjects can only see the black mark attached to a vane of the second windmill.

Observations of the new setup

In the 14th trial, a subject reported that he discovered how to use the first windmill to distinguish the number of vanes on the second windmill. He tried to use one vane on the first windmill (the red vane in Fig. 10c) to oscillate the second windmill. He reported that he felt as if the first windmill was the stick to distinguish the second one. He also reported that he paid attention to the collisions between the first windmill and the second one and did not care about the collisions between the stick and the first windmill (Fig. 10c).

Figure 10d shows the time series of the stick and the vane on the first windmill which collides with the second windmill (the red vane) in the 14th trial. The center of the oscillation of the stick and the vane of the first windmill is on the horizontal line in Fig.10c.

A remarkable difference between Fig.10b and Fig.10d is the following. When the visual information is available (Fig.10d), subjects try to use a vane of the first windmill (the red vane) as a "controlling handle" to move the second windmill. As a result, that vane and the stick before the first windmill align in a straight line.

Summary and Discussion

In this paper, we firstly demonstrated that even simple computational agents can have two different sensitivities to the windmills. It should be worth noting that the agents can ignore the number of vanes of the unattended windmill. An agent becomes either sensitive to the first windmill or the second one, neglecting the other. We claim that this shift of attention from the first windmill to the second is a dynamic shift of the body boundary.

In the real windmill model, we found that there are two ways to distinguish the second windmill. In the previous setup, subjects do the task with a blindfold. In this case subjects could not learn the sensory-motor correlations between their action and the movement of the windmills' vanes, and felt that the first windmill was an object to be distinguished. On the other hand, in the new setup subjects could see the movement of a vane on the second windmill, so some subjects could learn the sensory-motor correlations between their action and visual information of the second windmill. In this case, some found how to use the first windmill as a tool to distinguish the second windmill, and they could pay attention not to the collisions between the stick and the first windmill but to the collisions between the first windmill and the second one.

But this shift of attention is still weak and not enough to extend their body boundaries for most of the subjects. We are now planning to change the material of the ball attached to the tip of the vanes to a heavier material, so that subjects can feel the collisions between the first windmill and the second one clearly. It will help subjects with a blindfold to determine the movement of the second windmill and to learn the sensory-motor correlations between their action and perception. Some reported that due to the noisy setting up of the experiment, it was difficult to predict the movement which prevented the body boundary from extension. Also we are afraid that since the present setting up uses a single stick + a first windmill + second windmill, the discrimination task became inevitably complex. We are improving the point to simplify the structure.

The value of this paper lies in the ambiguity of the first windmill, which is a tool (a part of a subject) and an object (an environment) at the same time. Our insights are beneficial for the biology of cognition, enactive cognitive science, the "extended mind" (Clark et al. 1998), and "radical embodied cognitive science" (Chemero 2009; Dotov et al. 2010). In our study, the dichotomy of object and subject is rejected and the active role of an observer in perception is considered.

We argue that the ambiguity of the first windmill corresponds to the ambiguity of our body, something that is known in German as *Körper* (a physical living body) and *Leib* (a subjectively lived body) (Thompson 2007: 231). The two aspects of our body are intimately related to changes of our body images. For example, a blind person's stick changes from a mere object (Körper) to a real hand (Leib) when he/she adapts to it. In our model, on the one hand, the first windmill is observed as a material thing in the world (by Agent 1), which means the first windmill is *Körper* at this time. On the other hand, the first windmill is used to perceive the second windmill (by Agent 2), which means the first windmill functions as *Leib* at this time.

From this point of view, we need to recast the "hard problem". Thompson recasts the explanatory gap between mental and physical as the *body-body problem*: the problem of relating one's subjectively lived body to the organism or living body that one is (Thompson 2007: 244).

Moreover, we are extending the current model to study communications between two agents by introducing one more agent instead of the second windmill. The two agents interact with each other through the first windmill and discriminate each other's neural state. The agents convey and receive messages. At this time the windmill functions as their interface or some kind of "language". Also, these agents eventually conform their neural states with each other. We think this is a kind of primitive communication (empathy or imitation).

In this way we could understand the course of humankind's mental development from active perception to extension of body images, and to inter-subjective communication by extending our windmill model further. We will also employ our model for robot learning by using a servo motor.

References

Beer, R. D. (1995) On the dynamics of small continuous-time recurrent neural networks. *Adaptive Behavior*, vo13, no 4: 469-509.

Bovinick, M. & Cohen, J. (1998) Rubber hands 'feel' touch that eye see. *Nature* 391: 756.

Braitenberg, V. (1984). Vehicles: Experiments in synthetic psychology. MIT Press, Cambridge.

Brooks, R. A. (1991a) Intelligence without representation. Artificial Intelligence Journal (47): 139–159.

Brooks, R. A. (1991b) New approaches to robotics. *Science* 253: 1227-1232.

Chalmers, D. (1996) The conscious mind: In search of a fundamental theory. Oxford University Press, USA.

Chemero, A. (2009), Radical embodied cognitive science. MIT Press, Cambridge.

Clark, A. & Chalmers, D. (1998) The extended mind. *Analysis* 58:10-23.

Dotov, D., Nie, L., & Chemero, A. (2010) A demonstration of the transition from readiness-to-hand to unreadiness-to-hand. *PLoS ONE* 5(3): e9433.

Gibson, J. (1962) Observation on active touch. *Psychological Review* 69:477-491.

Harnad, S. (1990) The symbol grounding problem. *Physica D* 42: 335-346.

Holland, J. H. (1975) Adaptation in natural and artificial systems, University of Michigan Press, Ann Arbor.

Iizuka, H. & Ikegami, T. (2005) Emergence of body image and the dichotomy of sensory and motor activity. In proceedings of the symposium on Next Generation Approaches to Machine Consciousness: 104-109, Hatfield, UK.

Iriki, A., Tanaka, M., & Iawamura, Y. (1996) Coding of modified body schema during tool use by macaque postcentral neurons. *Neuroreport* 7:2325-30.

Pfeifer, R., & Scheier, C. (1999) Understanding intelligence. MIT Press, Cambridge.

Reed, E. S. (1996) *Encountering the world*: Toward an ecological psychology. Oxford University Press, New York.

Ramachandran, V. S. & Blakeslee, S. (1998) *Phantoms in the brain*: Probing the mysteries of the human mind. William Morrow, New York.

Sato, Y., Iizuka, H., & Ikegami T., Generation of Body Images in an Active/Passive Perception Model, In, Proceedings of the Fifth Asia-Pacific Computing and Philosophy Conference, Tokyo, pp.100-105, (October 2009)

Suzuki, K. & Ikegami, T. (2004) Self-repairing and mobility of a simple cell. Artificial Life IX: Proceedings of the Ninth International Conference on the Simulation and Synthesis of Living Systems: 421-426. MIT Press.

Thompson, E. (2007) *Mind in life*: biology, phenomenology, and the sciences of mind, Harvard University Press.

Varela, F. (1979) *Principles of Biological Autonomy*, North-Holland

Varela, F., Thompson, E. & Rosch, E. (1991) *The embodied mind*: Cognitive science and human experience, MIT Press, Cambridge.

Walter, W. G. (1950) An imitation of life. *Scientific American* 182(5): 42-45.

Walter, W. G. (1951) A machine that learns. *Scientific American* 185(2):60-63.

Yamamoto, S. & Kitazawa, S. (2001) Reversal of subjective temporal order due to arm crossing. *Nature Neuroscience*, 4(7): 759-765.