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Endo-System View as a Method for Constructive Science

Hideyuki Nakashima (h.nakashima@fun.ac.jp)
Future University – Hakodate
116-2 Kameda-Nakanocho, Hakodate, Hokkaido, 041-8655 Japan

Masaki Suwa (suwa@sist.chukyo-u.ac.jp)
School of Information Science and Technology, Chukyo University
101 Tokodachi, Kaizu, Toyota, Aichi, 470-0348, Japan

Haruyuki Fujii (hfujii@arch.titech.ac.jp)
Graduate School of Science and Engineering, Tokyo Institute of Technology
12-1 Ookayama 2-chome, Meguro, Tokyo, 152-8552, Japan

Abstract

Cognitive Science talks about internal processes and representations of intelligent agents. Since we ourselves are the best examples of such intelligent agents, observation from inside (introspection) is useful. However introspection violates objective criteria required for analytical science. On the other hand, observation from outside has only limited access to internal processes and representations.

We propose to use endo-system view, a methodology in which a constituent of a system of interactions observes the whole system from inside. Meta-cognition, cognition of its own cognitive processes, is an example of such endo-system view. This makes contrast to exo-system view implicitly employed for analytical science. Endo-system view, intrinsically due to its definition, interacts with and therefore affects the very interactions being observed. We, rather, take advantage of this interaction as means to analyze the system of interactions scientifically.

More generally, we are proposing a new way of science, "constructive science", in contrast to "analytical science". The basic methodology of analytical science is to divide a system into its simpler subsystems and recursively analyze them till we understand every subsystems and the structure of their connection. A precondition of doing this is that the analysis process does not affect the system being analyzed. Constructive science, on the other hand, starts from simple units and tries to construct a complex system. In this paradigm, therefore, the system is to be observed as it changes dynamically. This paper is to discuss a possibility to employ endo-system view as objectively testable methodology in constructive science.

Introduction

In this paper, we explore the concept of internal observation and its importance to cognitive science. Internal observation is defined as observation of the behavior of the system by its constituents. A typical example is observation of economical system by its participating agents. Wiener (1948 and 1961) described the situation as follows (pp.163-164):

> On the other hand, the social scientist has not the advantage of looking down on his subjects from the cold heights of eternity and ubiquity. It may be that there is a mass sociology of the human animalcule, observed like the population of Drosophila in a bottle, but this is not a sociology in which we, who are human animalcules ourselves, are particularly interested. We are not much concerned about human rises and falls, pleasures and agonies, sub specie aeternitatis. Your anthropologist reports the customs associated with the life, educated career, and death of people whose life scale in much the same as his own. Your economist is most interested in predicting such business cycles as run their course in less than a generation or, at least, has repercussions which affect a man differentially at different stages of his career. Few philosophers of politics nowadays care to confine their investigations to the world of Ideas of Plato.
>
> In other words, in the social science we have to deal with short statistical runs, nor can we be sure that a considerable part of what we observe is not an artifact of our own creation. An investigation of the stock market is likely to upset the stock market. We are too much in tune with the objects of our investigation to be goof probes. In short, whether our investigation in the social sciences be statistical or dynamic – and they should participate in the nature of both – they can never be good to more than a very few decimal places, and, information which begin to compare with that which we have learned to expect in the natural science. We cannot afford to neglect them; neither should we build exaggerated expectations of their possibilities. There is which we must leave, whether we like it or not, to the un-"scientific", narrative method of the professional historian.

Wiener regarded narrative method as un-"scientific". We claim that internal observation combined with a narrative method can be used scientifically to allow objective experiments. To do so, we have to extend the concept of scientific methods a little.

Here is the outline of our strategy, which will be explained in detail in the following sections.

Experimental psychology adopted methodology of analytical science and excluded use of any retrospection that is known to be incomplete and sometimes wrong. However, when we talk about cognition, mention of some internal process or representation is inevitable. Cognitive science therefore mentions internal structure of cognitive agents. However, applicability of external observation of analytical science to investigate those internal cognitive structures has limitations.

By introducing meta-cognition, we can bring theories on internal cognitive processes into scientific observation. We further have to combine the methodology of constructive science to perform analytical science on internal processes. In this way, we propose a new methodology for cognitive sciences.

In the second section, we explore more details of endo-system views together with definitions of related terminologies used in cognitive science.

In the third section, we focus on meta-cognition and its application to improvement of sports skills. This part contains our main claim that constructive method can be scientific, i.e., internal observation can be used for objective science.

In the fourth section, we turn the subject to more general methodology of constructive science.

Endo-system Views for Cognitive Science

Definitions of Terminologies

Before we describe the details we have to define some terminologies.

"Thought" is an internal process of an agent. For the purpose of this paper, it is not necessary to further distinguish thought and other processes of the agent, such as emotion. We refer to all mental processes as thought.

We use "cognitive system" to denote a system of interactions between an agent who has thoughts in mind and the surrounding environment, in the sense of "situated cognition" A cognitive agent lives, being embedded in the surrounding environment. He or she perceives something from the environment, has thoughts in mind, and does something onto the environment. These processes are not necessarily sequential. Rather, the situated cognition theory (e.g. Clancey, 97) postulates that perception, thought and action occur in coordination, affecting each other. For example, having a piece of thought in mind or doing something enables perception of something that would be imperceptible without that thought or action. Doing something makes some thoughts happen. Coordination in this way is the very interactions between a cognitive agent and the environment. In other words, the agent and the environment form a system of interactions.

"Cognitive process" therefore consists of all the interactions within the system in interest, including not just "thoughts" in mind of the agent but also interactions between the agent and the surrounding environment.

"Introspection" is self-observation of the thought process. Introspection interferes with the ongoing thought process, which would be fatal for the purpose of objective observation. For the very reason, in the earlier phase of psychology, retrospection was used to maintain objectivity of observation.

"Retrospection" is self-observation of the thought process, too, but applied *after* the process is completed. Retrospection does not interfere with the past thought process because it is separated time-wise. However, there are many cases reported in which retrospection is incomplete or even wrong (e.g. Ericsson and Simon, 1986). Retrospection also failed to be an objective method.

"Reflection" is a thought process on the process itself. Reflection is active, while introspection is passive. Interference with or even controlling the thought process is an essential part of reflection. The purpose of reflection is not observation alone, but rather to actively use the result of observation to change its own behavior.

The notion of "meta-cognition" was advocated around the beginning of 1970's. Since then it has been understood and used as something similar to reflection, because its main thrust is thought to be monitoring one' own thought and thereby self-control. We would argue that the difference between reflection and the conventional meta-cognition is rather ambiguous. Here, we define "meta-cognition" as a good example of "internal observation" described later and therefore as something quite different from reflection. Generally speaking, meta-*X* is *X* of *X*. Reflection is meta-thought, since it is an act of thinking of thoughts in mind. On the other hand, meta-cognition is cognition of cognitive process. It is an act of reflecting on and verbalizing what kind of interactions are, or were, occurring between the self and the surrounding environment, either while achieving some task or after its completion. We discussed earlier that thought is part of cognitive processes. This means that the target of verbalization in meta-cognition includes not only thought in mind but also the interactions, e.g. perception and action, between the self and the surrounding environment. Since the self reflects on and verbalizes the ways of interactions with the surrounding environment, it will surely interfere with the interactions and change the way in which the interactions occur. In this respect, meta-cognition is similar to retrospection and introspection. However, like reflection, meta-cognition does not try to exclude the interference. Rather, changing the way the self interacts with the environment is within the very purpose of meta-cognition.

We discussed in the introduction that "internal observation" is an act of a constituent of a system observing the behavior of the system, i.e. endo-view. Meta-cognition in our sense is a kind of internal observation, because it is an act of the self's reflecting on and verbalizing a system of interactions occurring between the self and the surrounding environment, where the self is a constituent of the system of interactions. This argument, again, makes the distinction between reflection and meta-cognition clear. Reflection is an act of observing the inner processes of oneself. The self does not necessarily stand in endo-view, and therefore is not internal observation.

The social scientist observing our society, as described in the above quote of Wiener, is such an internal observer. Internal observation affects the course of events of the system. This self interference makes internal observation un-scientific in its narrow sense. However, if we have many relatively independent systems and transfer the result of internal observation to another, there revives a possibility of scientific experimentation. We will elaborate on this possibility in the following sections. We use meta-cognition of an agent as an example of internal observation.

From Experimental Psychology to Cognitive Science

Experimental psychology adopted methodology of analytical science and refused use of retrospection or introspection that is known to be incomplete and sometimes wrong. Consequently, experimental psychology neglected cognitive processes altogether. However, as we talk about cognition, we inevitably need mention of cognitive processes or inner representation. That is the very intention that the movement of cognitive science occurred during 60's. However, applicability of external observation of analytical science to investigate those cognitive processes has limitations. In particular, it is hard to know how and when a cognitive process takes place. We need some scientific methodology to observe cognitive processes.

By introducing meta-cognition, we can bring theories on cognitive processes into scientific observation. We further have to combine the methodology of constructive science to perform analytical science on internal processes. In this way, we propose a new methodology for cognitive sciences.

Suppose that an agent *A* is trying to improve its own skill on a task *T*. *A* puts himself in a custom of meta-cognition, and this may promote improvement of *A*'s performance on a task *T*. Suppose that *A* is able to tease out *P*, something like knacks or ways of attention in conducting *T*, as a product of meta-cognition. Then, by doing an experiment in which another agent *B* has an opportunity to listens to or read *P*, we can see if *B*'s skill on *T* will also improve. Our hypothesis is that *P* will bring about inspiration to *B*'s meta-cognition and change *B*'s performance on *T*. We can analytically examine improvement on *T*, since the performance of *T* is objectively measurable. By conducting the same experiment on many *B*'s, then, we are able to test the hypothesis on the relation between *P* and *T*. This way, we are able to employ internal observation as part of scientific methodology.

Artificial Intelligence

We will explore the idea more in detail in the domain of Artificial Intelligence (AI) research where programs play the central role. AI is the research area that seeks for the definition of intelligence. The target is the concept of intelligence in the abstract level which does not rely on any particular hardware. The basic methodology of AI is to construct a program that exhibits intelligent behaviors. The behavior of the program is then compared with that of natural intelligence such as human.

In the above sense, AI is not a natural science. If it were, then the target of AI research would have been limited to naturally existing intelligent systems. Since it seeks for the abstract definition, its research methodology is closer to those of mathematics or philosophy.

Cognitive system, in case of AI, includes researchers, a program and the environment of the execution of the program. It is important to note that the researcher is in the system. Why? Firstly, a programmed system largely differs from living intelligence. Therefore, a program shows intelligent behavior only under certain view frame that is set by the researcher. Secondly, and more importantly, a program seldom shows perfect behavior even under some restricted designed domains. It is thus important to fix the program to overcome some behavioral shortcomings in certain conditions. The programmer or the researcher is the integrated part of programs development. Once the program is complete, if ever, it is not important to keep it running any more. In other words, the development process of the program itself is the research on AI.

Reflective capability of programs or mechanism for reflection is one of the major research topics of computer science. In this context, reflection means that a program has access to its own execution status and can change it if necessary. It is a theoretical interest that drives the area. However, it is very rare that this capability is actually used to monitor its own behavior and change it. To investigate on the nature of intelligence, we come to believe that studying on reflection is not a good strategy. We should use internal observation.

Internal observation in AI should have a new meaning. It may not be a program itself that observes the program's behavior. It rather should be the researcher who does internal observation. Since the researcher is within the system, AI cannot be regarded as a natural science. It is closer to philosophy as we stated before. The output of the research may not be an objective hypothesis that can be tested by conducting some experiment. What AI research produces is a story of intelligent systems. Many papers published in AI describe a viewpoint from which the programmed system can be regarded as being intelligent.

For an AI program to be a model of intelligence, we need to set a proper viewpoint. The restriction is similar to physical model. In physics, when we talk about motion of objects (Newton's laws), we exclude environmental interference such as movement of air, microscopic irregularity of surface and so on. Physical law talks about ideal cases. The same simplification and abstraction applies to traditional AI models. However, many researchers come to believe that intelligence is not a single and simple mechanism such as Newton's law. It is rather a complex combination of many specialized modules as described in Fodor (1983). Traditional AI programs that work only in limited domains (called "toy programs") get less attention. As the result, AI programs cannot be tested in simplified ideal environment. It must be run and observed in more realistic complex environment, requesting that the programmer is in the loop to fix any shortcomings in the design of the program.

Recent AI needs analysis by synthesis: construct a program, observe its behavior, and then fix any shortcomings, run it, observe its behavior – This loop is repeated infinitely. The whole story is the model of intelligence and must be described as a story rather than a theory which depicts a single cut frame of dynamically changing model.

Meta-Cognition

Meta-Cognition Applied to Promote Acquisition of Embodied Expertise

As we defined in the second section, meta-cognition is an act of recognizing and verbalizing interactions occurring between an agent and the environment. It is a typical example of internal observation, i.e. the constituent of a system of interactions observing and describing the whole interactions.

The target of verbalization includes not only inner thought process, but also perception from the environment, actions onto the environment, the own body movements, and even somatic sensation that arises through a system of muscles and joints. This makes meta-cognition difficult. There even are claims that some part of perception and body movements cannot be reflected upon nor verbalized. That seems to be why past literature in cognitive science and psychology limited the target of reflection to inner thought process only. Meta-cognition changes the whole system of interactions between the cognitive agent and the environment. We understand that when someone learns something, the whole system of interactions between the person and the environment changes more or less. It is especially true when what is learned is a skill or expertise involving body, e.g. in the domain of sports, art, design and so on. In this section, we argue, by showing evidence in sports, that meta-cognitive verbalization can actually promote acquisition of embodied expertise.

What kinds of cognitive interactions are involved when someone acquires embodied expertise and how does meta-cognition promote the process? Ecological psychologist (e.g. in Gibson and Gibson, 1955) argued that differentiation of so-far unattended variables is a necessary step for general learning. Variables lie in one's own body as well as in the environment, that is, throughout the whole system. They claim that some of those processes are tacit and inaccessible to the cognitive agent.

We argue that meta-cognition can be used to make the process explicit and accessible to the agent. The structure of our argument is as follows:

(1) Meta-cognitive verbalization maintains awareness to variables ever attended explicitly, and at the same time, draws focused attention to previously implicit variables.

(2) However, merely differentiating various variables does not lead to acquisition of embodied expertise in a straightforward manner. Those attended variables are not necessarily interrelated with each other. Maintaining awareness to those variables by meta-cognition will promote thinking of relations among those. It is just as externalized media like design sketches encourage detection of implicit relations between elements that were sketched at different times during a design process (Suwa, Gero and Purcell, 2000).

(3) Thinking of relations among variables will trigger sudden understanding of ideal coordination of the whole body movement and its interaction with the environment.

(4) Understanding of how the body ideally works entails a mental effort of attending to a discrepancy of the current body movement from the ideal way. It thereby encourages setting up goals about how to perceive, think and move the body. This is a kind of problem-finding act. The significance of problem-finding acts is ubiquitously recognized, not just in acquisition of embodied expertise, but also in the domain of design and art. Lawson (1990), a design theorist, discussed that design activity is not a mere problem-solving act. Not only solving a given design problem but also finding what are important problems to be solved is essential in design. In art as well, Getzels and Csikszentmihalyi (1976) found from a longitudinal analysis of artist that a zeal and trait of finding problems in one's own life is well associated with the success as an artist.

(5) If understanding and proper execution of the ideal body work is accomplished, performance improves suddenly. Even after reaching this stage, however, keeping a problem-finding custom is still significant. Body easily deviates from the ideal state without awareness. The environment often changes. Consequently, the ideal state of the body working in match with the environment holds no more. At this very moment self-awareness and meta-cognitive verbalization of how the body deviates will enable explicit intention on revising the way of body movement and perception for the better match. In order to become an expert, merely exploring a fixed and best way of body movement and perception does not suffice. Rather, one should be able to revise the self for a better match with the environment through an act of problem-finding. Meta-cognition encourages this act.

To summarize, understanding of body movement entails increase of conscious thoughts; detecting problems in the current body movement and perception, setting up goals, being self-aware of deviation from the match with the environment, and revising the way of body movement and perception. As we discussed earlier, the situated cognition view suggests that the generation of conscious thoughts, in turn, will change the ways of perceiving one's own body and the environment. This will, again, become the driving-force for differentiation of so far unheeded variables, the first step. Consequently, through those steps mentioned above, a custom of meta-cognitively verbalizing the interactions occurring between the self and the environment promotes changes of the interactions in a productive cycle, and thereby contributes to acquisition of embodied expertise.

Empirical Evidence in Sports

In recent years case studies on applying a method of meta-cognitive verbalization to learning skills in sports have been reported (e.g. Suwa, 2004; 2005). Here we will present evidence suggesting that meta-cognition as internal observer's view, not a mere reflection, promotes acquisition of embodied expertise in sports, i.e. bowling in this experiment. A participant was a male university student. His said that the average of his score before participation was approximately between 90 and 100. During 9 months, from March 2005 through December 2005, he went to bowling alleys on 204 dates and played 999 games. During this period, he was in a custom of meta-cognitive verbalizing, in the form of writing down on a note, what he thought and perceived and how he moved body parts. He took a note as he played a game, afterwards on all (204) dates he played games, and also on 6 dates he did not.

In playing sports, generally, perception of the surrounding environment plays a crucial role. The surrounding environment in case of bowling is the ball, the lane and the pins. Perception of the environment includes how the ball rolls and rotates on the lane in what trajectory, how the condition of the lane affects the rotation and rolling of the ball, he the ball hits the pins in what angle, how the pins fall down and scatter away, and so on. What constitutes a system of interactions occurring between a bowler and the surrounding environment is

- perception of the environment,
- intention on the usage of body parts,
- perception of the actual movement of body parts,
- somatic sensation as a result of moving body parts,
- explicit thoughts about relations between the movement and usage of body parts and the speed and rotation of the ball, and
- strategic planning in a game.

Our participant to the experiment who meta-cognitively verbalized on these interactions is an internal observer of the system.

How did his performance improve during 9 months? Figure 1 shows how the daily average score changed during the period, with the horizontal axis being the date he played games and the vertical axis being the average score of the day. The daily average score rose first from approximately 120 to 165, and then gradually declined until recording the local minimum, 91.6, on the 40th day. We call the first 39days "1st period". Then, until the 76th day when the score recorded the local minimum, 112.3, the daily average score hovered at a relatively low level. We call these 37 days "2nd period". Then, the daily average score suddenly rose and hover at a higher level, i.e. approximately 150, until it dropped to 116 on the 113th day. We call these 37 days "3rd period". Then, until the 158th day when the score dropped to 95, the daily average score moved up and down with a relatively large variance, reaching below 120 several times. We call these 45 days "4th period". After 158th day, the daily average score never went below 120. We call the last 46 days "5th period". The four horizontal dotted lines in Figure 1 represent the boundaries between the periods. Table 1 shows, for each period, the number of days, the number of games he played, and the average and variance of the daily average scores over the period.

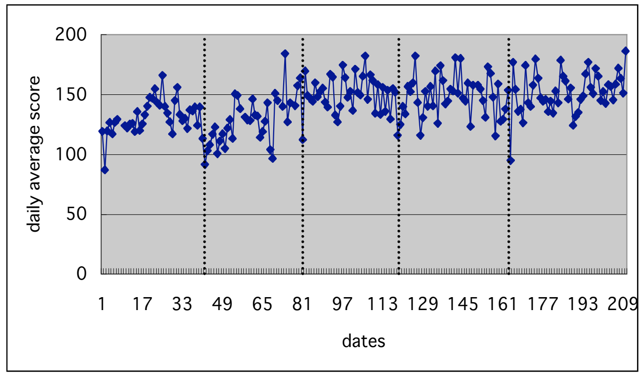

Figure 1: The change of the daily average score for 9 months

Table 1: The statistics of the five periods

	1st	2nd	3rd	4th	5th	total
Num.of days	39	37	37	45	46	204
Num.of games	295	187	164	175	178	999
Average	131.3	128.4	151.9	147.0	153.4	
Variance	194.1	413.0	179.0	364.5	225.0	

Table 2: The F values obtained by one-way ANOVA for pair-wise examinations among the periods

periods	2nd	3rd	4th	5th
1st	0.541	*43.3	*18.0	*48.7
2nd	---	*34.7	*18.2	*41.5
3rd	---	---	1.76	0.203
4th	---	---	---	3.13

Note: the symbol '*' denotes statistically significant difference at the level below 0.001.

Table 3: Ratio of variances for the pair-wise examinations among the periods

periods	2nd	3rd	4th	5th
1st	*2.13	1.08	*1.88	1.16
2nd	---	**2.31	1.13	*1.83
3rd	---	---	*2.04	1.26
4th	---	---	---	1.61

Note: the symbols '*' and '**' denote statistically significant difference at the 0.05, 0.01 levels, respectively.

One-way ANOVA indicates, as shown in Table 2, that the averages of the daily average scores for the last three periods are higher in a statistically significant manner than for the first two periods, suggesting that our participant's skill in bowling remarkably improved around the beginning of the 3rd period. The F test indicates, as shown in Table 3, that the variances for the 2nd and 4th periods are larger in a statistically significant manner than for any of the 1st, 3rd and 5th periods, suggesting that our participant's performance for the 2nd and 4th periods was more instable than for the other three periods.

These results suggest the following about the improvement of our participant's skill in bowling. The performance seemed to rise at the beginning of the 1st period, but did not last long. The performance quickly turned worse and became more instable for the 2nd period, i.e. the first-time slump. Then, a sudden improvement occurred around 80th day, and the high score lasted for the rest of the 3rd period in a relatively stable manner. But, there came a period of instability for 45 days or so, i.e. 4th period, although the daily average scores hovered around 147, not significantly different from the scores for the 3rd period. Then, again, there came a period of stability with the daily average score being similar to the 3rd period. Toward the end of the 5th period, the score seems to rise even to a higher level than the 3rd and the beginning of the 5th periods, although the tendency is ambiguous since the duration is too short.

Now, let's look into the contents of meta-cognitive verbalization. We first examined, for the verbalized note on each day, the number of words describing body parts, including precise parts such as fingers, wrist, elbow, thigh and etc. as well as overall descriptions such as body trunk, upper body and lower body and etc. Figure 2 shows, by five days' moving average, how the number of words describing body parts changed during the 9 months. The four horizontal dotted lines represent the boundaries between the periods. Except for the 2nd period, there are peaks for the number of words for body parts. Compared to the 1st period during which our participant's attention to body parts was frequent, attention to body parts sharply declined as soon as the 2nd period began.

Then, we examined, for the verbalized note on each day, the number of sentences describing the surrounding environment or relations between body parts and the environment. We discussed earlier that the environment in case of bowling is the ball, the lane and the pins. Descriptions about these are evidence showing that our participant perceptually differentiated some variables from the environment or attended to relations between his body and those variables. Figure 3 shows, by five days' moving average, how the number of sentences describing the environment changed during the 9 months. The four horizontal dotted lines represent the boundaries between the periods. Except for the 4th period, there are peaks for the number of sentences. Toward the end of 4th period, our participants became unable to attend to the surrounding environment.

Let us compare both figures with Figure 1, the change of the daily average score. We analyzed earlier that the 2nd period was immediately before the sudden improvement of our participant's skill for the 3rd period, and that the scores then were more instable than for the 1st period. Further, the scores for the 4th period, too, were more instable than for 3rd or 5th periods. The 2nd and 4th periods are regarded as a period of "slump". Our participant paid little attention to body parts during the 2nd period, as shown in Figure 2, and to the environment during the 4th period, as shown in Figure 3. The commonalities for 1st, 3rd and 5th periods, all of which are stable and therefore "good" periods, are that our participants paid frequent attention to both body parts and the environment.

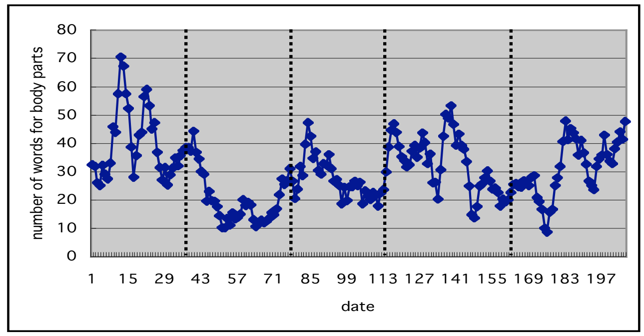

Figure 2: The change of the number of words describing body parts for 9 months

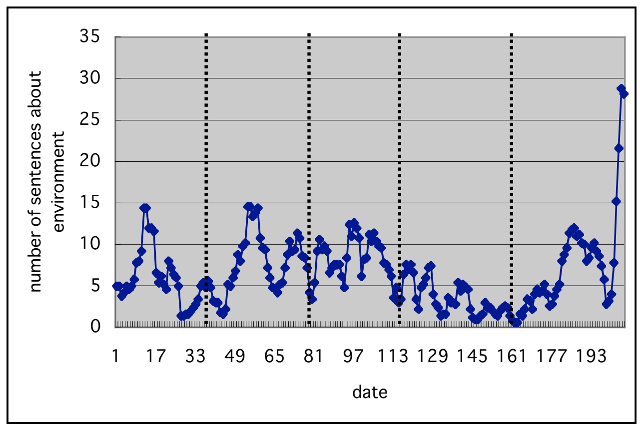

Figure 3: The change of the number of sentences describing the environment and its relations to body parts for 9 months

These results provide, we conjecture, empirical evidence suggesting that it is not reflective verbalization of the inner thought processes but meta-cognitive verbalization of interactions between oneself and the environment that facilitates acquisition of embodied expertise.

Architectural Design as Constructive Science

In the previous sections, we illustrated the use of endo-system view and how it serves as a methodology of constructive science. This section tries to further discuss the significance of constrictive science in the domain of architectural design because it is a better and a more straightforward example of constructive science and studied longer in history.

Architectural Design and Modern Science

Architectural design is performed when a certain situation[1] different from the current one is desired and the new building is believed to have a potential for the fruition of the desired situation. Where, the concrete form of the new building has not been clear and distinct. The product of architectural design is the description of the building or the building itself that is expected to provide the aimed situation. The goal of architectural design is to provide us with new lifestyles and culture, where a lifestyle is an aggregate of situations.

It is said that architectural design had begun no sooner than a person who made a building became conscious of her process of making the building (Alexander, 1964). The beginning of architectural design is earlier than the beginning of modern science, which is the current representative of analytical science.

The prime objective of research in architecture is to contribute to providing a class of buildings that fit the target lifestyles and environment. The research interests include the methodologies of architectural design and the methods of architectural programming, planning, designing, and drawing. The former is a product in the abstract level, while the latter in the concrete level. The products of researches of these sorts are the principles and conception of architectural design, the conception of a building, and the technologies for translating the conceptions to reality. The conception of architectural design refers to how architectural design is being, and should be, performed. The conception of a building refers to how architecture is being and ought to be. The technologies show what and how to instantiate a good design and designing.

Research in architectural design has shared the benefit of natural science, mathematics, information science, AI, cognitive science, philosophy and so on. Modern natural science, especially, has had a great influence on architectural design research and practice of today. It enables us to objectively describe, explain, understand, and predict the physical properties and behaviors of a building.

Modern science encourages us to explain things and phenomena from an exo-system view. Objectivity is guaranteed if its methodology is correctly employed. However, things and phenomena inexplicable by use of this methodology are set aside as subjective things and abandoned (Norberg-Schulz, 1986). However, in architectural design, understanding how an architect interacts with her design environment plays an important role. An endo-system view helps us to understand such interactions.

Constructive Nature of Architectural Design

The science of architectural design is a science of the artificial (Simon, 1996). The subjects of research in architectural design are different from those of natural science. The research on architectural design mainly deals with a process of producing a building as well as a building itself. A process of producing a building is a human activity involving a diverse form of thoughts and bodily movements. A building is an artifact. It is of course true that research in architecture often deals with natural objects and phenomena. We will show how this analysis is incorporated as a part of constructive science.

One of the significant characteristics of research in architectural design, due to which architectural design is different from natural science, is that all of the facts stipulated in research in architectural design are not just descriptions from an exo-system view of a world where one lives. Some facts may remain true but other facts may have to be improved, or at least changed. Sometimes, even the laws relating the facts with each other, are found to be improved. In addition, performance of a researcher, a designer, or a practitioner is part of the subjects to be studied or modeled. The fact that the research subject involves those who observe and alter the subject requires an endo-system view. Therefore, the science of architectural design might be one of good examples of constrictive science.

A Framework of Architectural Design

To produce a building is a subclass of action. Action is the totality of the bodily movements that animal life performs and is accompanied by intention. Designing a building is a purposive action since the purpose in producing the building exists. An architect intends to provide a certain situation by producing a building.

Action changes a state of affairs to another state of affairs. A transition of states consists of two phases. One is a direct transition done by a bodily movement which is the extensional aspect of an action. The state reached through this transition is the result of the action. The other is an indirect transition caused by a subsequent event, which is the intensional aspect of an action and is different from the bodily movement itself. The state brought about by this transition is the consequence of the action. Figure 4 depicts the relationship among an action, the result of the action and the consequence of the action. The diagonal arc indicates an action to reach the consequence at the upper-right. The horizontal arc indicates the direct transition by a bodily movement. The vertical arc is the indirect transition by a subsequent event. The horizontal and vertical arcs compose the action. By performing an action, we intend to achieve a certain consequence. When we perform an action, we picture how the bodily movement of the action synthesizes the result, i.e. the lower-right node, from the current state, i.e. the lower-left node, and analyze what event follows the bodily movement and changes the result to the target consequence, i.e. the upper-right node. Here, we assume that there is a causal relationship between the result and the consequence. For example, a person opens a window with the intention to facilitate airing. The person pictures the bodily movement to open the window and analyzes what

[1] We use "situation" here to denote a subject's relation to a setting in which a new functionality is called for.

happens when the window opens. In this case, the result is the state that the window is open and the consequence is the state that airing is facilitated if the action is performed successfully and the wind blows as the person analyzes. The distinction and articulation between the result of action and the consequence of action as well as the notions of synthesis and analysis are helpful to model the basic framework of a process of architectural design.

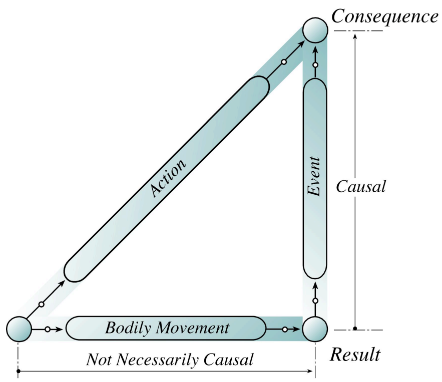

Figure 4: Action, result, and consequence

Figure 5 depicts a conceptual framework of designing. The left triangle models a macroscopic process of designing and the right triangle models a macroscopic process of providing a certain situation. Each triangle is a counterpart of the action-result-consequence triangle shown in Figure 4 in the world of designing and that of building, respectively. The red arrows show the referential relation between the constituents of the framework. The constituent at the head of the arrow is the referent of the constituent at the tail.

As mentioned earlier, it is the main purpose in producing an artifact to bring about a situation that cannot be brought about without the artifact. The result of producing an artifact is the artifact incarnated in the real world and its consequence is the situation brought about by the artifact. During producing an artifact, it may be pictured what kind of situation will be encountered if the artifact exists, or what operations should be applied on the building materials.

When a person is conscious of her or his process of producing a building, the form of a building, which is expected to bring about the target situation, is pictured. The picture is internally and externally expressed and becomes more concrete as the operations and the thoughts on the picture proceeds. A sketch, a drawing, a pictorial diagram, a sentence in natural language, and a proposition in formal language are the media of the external expression. Such a process of operating and thinking on the picture constitutes the prototype of a macroscopic framework of architectural design.

The macroscopic framework of architectural design is composed of two sub-processes, namely, synthesis and analysis. Synthesis is a process of giving concrete form to the structure of an artifact being designed. Analysis is process of confirming whether the artifact has a potential for providing an expected situation. The result of synthesis is design description. Design description refers to the form and specification of an artifact. The result of analysis, which is equivalent to the consequence of designing, is situation description. Situation description refers to the situation predicted to be brought about when the artifact is produced. The situation is derived from the context composed of the artifact and its environment on the basis of the causal relations between the form and specification of an artifact and its environment.

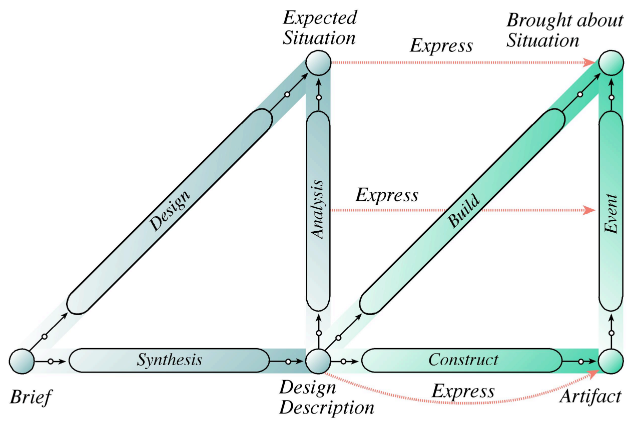

Figure 5: A conceptual framework of designing

Research in architectural has been revealing such causal relations with the help of analytical science. The result of the prediction helps us evaluate whether a designed artifact has potential to bring about the expected situation. Analysis of design description becomes more precise as the theories employed in the prediction are sophisticated. However, even if the theories become sophisticated enough to cover everything required for precise analysis, they are not sufficient enough for architectural design. They don't determine how the form of an artifact should be to provide an expected situation. Any causal relation doesn't derive a certain form from an expected situation. Mere accumulation of the theories discovered in analytical science doesn't produce promising principles in synthesis of the form. Therefore, in architectural design, a cycle of synthesis and analysis is repeated until it is confirmed that a designed artifact may provide an expected situation.

A repetition of the cycle of synthesis and analysis is often likened to a process of problem solving. Synthesis and analysis correspond to a process of solution generation and that of solution verification, respectively. On the contrary, the authors liken the repetition of the cycle to that of a thought experiment. An imaginary apparatus is synthesized on the basis of the assumptions to get an expected consequence, and then the behavior of the apparatus is analyzed. If the behavior cannot be identified to the expectation, the apparatus will be revised on the basis of the modified assumptions acquired through the previous cycle.

Architectural design is constructive. A building is an assemblage of building materials and elements. They are integrated into a building and acquire a comprehensive meaning as architecture (Gero and Fujii, 2000). The important thing in the repetition of synthesis and analysis is the nature that each cycle is consciously observed by the architect and therefore that the contents of observation of the cycle from endo-system view become a constituent to synthesize the next apparatus. Once an architect synthesizes a form by organizing its constituents, a comprehensive meaning of the form arises. The comprehensive meaning prompts the architect to find a new issue to be considered as well as a succeeding move to improve the form. Neither the issue nor the move could have been defined before the architect gives the comprehensive meaning to the mere assemblage of the constituents. This characteristic does not just derive from ill-definedness of a design problem. Even if a design problem is well-defined and all of the issues to be considered are listed, new issues will arise during a process of designing. Therefore, it is not sufficient for architectural design to fully furnish the analytical theories found in an exo-system view. On the other hands, an endo-system view provides the researchers and practitioners in architectural design with an opportunity to think how to deal with the phenomena where they find a new issue during the process of designing.

Therefore, the constructive nature of architectural design appears in two different contexts. One is macroscopic constructiveness of research in architectural design, and the other is microscopic constructiveness of practice of architectural design. In research in architectural design, part of unconscious process of making a building has been changed into self-conscious process of designing. The principles of synthesis and the theories for analysis are externally expressed. The expression encourages us to give new aspects to look at architecture and opportunities to become aware of other issues through the aspect. In practice of architectural design, it is essential for an architect to use internal as well as external expressions of the things and thoughts. The expressions and the designer produce the reflective relations. An architect interacts with sketches, models, and drawings. Each of them is a form of language expression in the broader sense. They externalize the internal picture and thoughts concerning the thing being designed. The expression is fluid in the sense that the interpretation of it is situated and doesn't remain the same. The architecture gives a comprehensive meaning to the referents of the expressions. The invented meaning is internalized and utilized in the succeeding thought to sophisticate the internal picture of the building. This utilization of repetitive externalization and internalization as a cycle plays such an important role in practice of architectural design. Therefore, it is plausible to say that the macroscopic as well as microscopic cycles of synthesis and analysis is equivalent, or at least analogical, to the repetition of externalization and internalization that is a core of the methodology of constructive science.

Conclusion

We proposed to take endo-system view in some part of cognitive science. Endo-system view enables observation of processes in a system that would be unobservable from outside. However, internal observation violates the objectivity requirement of the scientific methodology. Thus, we further proposed meta-cognition to turn a theory built by observation from endo-system view into an objectively testable hypothesis.

When a narrative (*P*) is produced as a result of meta-cognition of system *A* to improve its own performance, *P* could invoke interactions with another system *B*. Then, we can objectively test if the interactions will promote similar improvements on *B*'s performance. We believe that this is a new methodology for constructive science, in which endo-system view is taken and at the same time objective ways of hypothesizing and testing could be realized.

We showed, in a case study on bowling game, that meta-cognition promotes improvement of one's performance. However we have not yet tested if applying the narratives obtained by the experiment to others is possible and it helps improve their performance. This is left as our future issue.

We then contrasted constructive science against analytical science and showed their relationship using an example in the domain of architectural design. We claimed that analytical method is a part of constructive science.

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