The Role of Memory in MHP/RT: Organization, Function and Operation

Muneo Kitajima (mkitajima@kjs.nagaokaut.ac.jp)
Nagaoka University of Technology
1603-1 Kamitomioka Nagaoka, Niigata 940-2188 Japan

Makoto Toyota (pubmtoyota@me.com)
T-Method
Chiba 264-0032 Japan

Abstract

To develop a unified theory of human decision-making in daily behavior selections, the authors propose an architecture model called Model Human Processor with Real Time constraints (MHP/RT) (Kitajima & Toyota, 2012). This model integrates the established theory of decision-making by Kahneman (2003), Two Minds, and the idea that human behavior is organized in the ever-changing environment (Newell, 1990) into a construct that is capable of simulating such daily behavior as driving a car or watching a baseball game at a stadium. Kitajima and Toyota (2012) proposed that MHP/RT operates in one of four modes that are defined by the active components of MHP/RT at a specific time. Kitajima and Toyota (2011a) demonstrated that at a specific moment MHP/RT is processing one of four aspects of a certain event. This paper demonstrates how memory is used in the four operation modes and the four processing modes of MHP/RT.

Keywords: decision making; behavior selection; Two Minds; time scale of action; MHP/RT; autonomous memory;

Introduction

Traditionally, human behavior is considered as the outcome of conscious and unconscious processes, which involve conscious and unconscious operations using necessary pieces of information from long-term memory in which experiences are stored in representations accessible to these processes. From this perspective, the role of memory is similar to a database system. It stores a huge amount of data to be used on request by other systems that work to accomplish some goals.

However, an increasing voice suggests that the memory system is better viewed as an autonomous system, rather than a passive database system. For example, Marcus (2008) wrote:

> Nobody knows for sure how this [memory] works, but my best guess is that each of our brain's memories acts *autonomously*, on its own, in response to whatever requests it might match, thereby eliminating the need for a central agent to keep a map of memory storage locations. Of course, when you rely on matches rather than specific locations that are known in advance, there's no guarantee that the *right memory* will respond; the fewer the cues you provide, the more "hits" your memory will serve up, and as a consequence the memory that you actually want may get buried among those that you don't want. – *adapted from pp.22–23 of Marcus (2008)*

The authors (Kitajima & Toyota, 2012) developed an architecture model capable of simulating human behavior selections in real-world situations. The basic idea is that observed human behavior is the result of synchronized integration of the output of conscious and unconscious processes, with the support of the memory system which works autonomously and information in long-term memory becomes available by means of resonance processes, not by retrieval processes initiated by either the conscious or unconscious process.

The architecture model is an integration of two established principles of human behavior: 1) Two Minds, which refers to conscious and unconscious processes that work in decision-making, proposed by Kahneman (2003); J. S. B. Evans (2003) and 2) the time scale of human action suggested by Newell (1990), which regards conscious processes as very slow feedback processes and unconscious processes as very fast feedforward processes (see the next section for brief descriptions of these principles). Kitajima and Toyota (2012) describes the architecture model, Model Human Processor with Real-Time constraints (MHP/RT), as integrating Two Minds and Newell's time scale of action with special consideration of how to synchronize these two totally different systems in terms of their characteristic times. We also demonstrated that this model can plausibly simulate passengers' behaviors at train stations (*e.g.*, transferring to another line, using the toilet, and purchasing train tickets). Kitajima and Toyota (2011a) demonstrated that for a certain behavioral event $Event(T)$ that happens at a certain time T, MHP/RT addresses this event in four different ways, or modes, that occur serially. In other words, human behavior is considered to be a series of these four different modes: conscious or unconscious processes concerning $Event(T)$ before it happens $(t < T)$ or after it happens $(t > T)$.

MHP/RT defines memory as an autonomous system. However, previous publications (Kitajima & Toyota, 2011a, 2012) have not described in detail how memory is used. The purpose of this paper is to fill this gap by demonstrating the operation of the four processing modes of MHP/RT from the viewpoint of the role of memory. This paper starts by briefly describing MHP/RT (see Kitajima and Toyota (2012) for more detail), then discussing the four operation modes of MHP/RT (see Kitajima and Toyota (2011a) for more detail), and finally describing the role of memory in the four processing modes of MHP/RT.

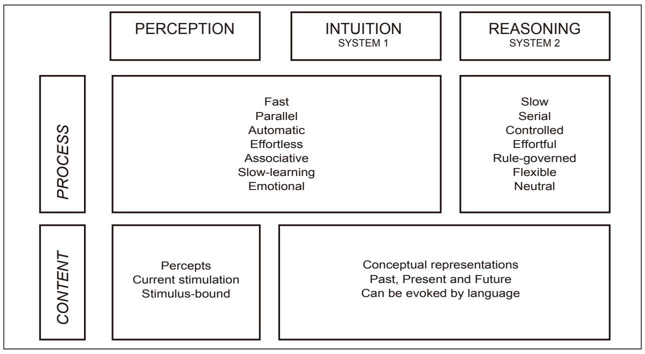

Figure 1: Two Minds (Kahneman, 2003).

The Principles for Understanding Human Behavioral Selections

In this section, we will review briefly Kahneman's Two Minds (Kahneman, 2003) and Newell's time scale of human action (Newell, 1990).

Two Minds: The Theory of Decision-Making

Human decision-making has been a central topic in economics. Herbert A. Simon, winner of the Nobel Prize in economics in 1978, proposed principles of human beings' decision-making processes. He described the decision-making process as a "bounded rationality principle" as well as a "satisficing principle" (Simon, 1956, 1996). Simon claimed that agents, or human beings, face uncertainty about the future and costs when acquiring information in the present. These factors limit the extent to which human beings can make a fully rational decision. Thus, they possess only "bounded rationality" and must make decisions by "satisficing," or choosing the path that might not be optimal, but which will make them happy enough.

Recently, Kahneman, winner of the Nobel Prize in economics in 2002, introduced behavioral economics, which stems from the claim that decision-making is governed by the so-called "Two Minds" (Kahneman, 2003; J. S. B. T. Evans & Frankish, 2009). In other words, a human being's behavior is the outcome of two different systems including an "experiential processing system (System 1)" and a "rational processing system (System 2)." Figure 1, adapted from (Kahneman, 2003), illustrates the workings of the two systems. In short, System 1 is a fast feed-forward control process driven by the cerebellum and oriented toward immediate action. In contrast, System 2 is a slow feedback control process driven by the cerebrum and oriented toward future action.

Newell's Time Scale of Human Action

The two systems, System 1 and System 2, work jointly and in synchronous with the ever-changing external world to exhibit moment by moment coherent human behavior. However, there is a large difference in processing speed between the two systems. Rational processing typically takes minutes to hours whereas experiential processing typically extends from hundreds of milliseconds to tens of seconds. Figure 2 illustrates the time scale of human action consisting of the following four bands, 1) Biological Band, 2) Cognitive Band, 3) Rational Band, and 4) Social Band, each has its characteristic processing time (Newell, 1990). A large part of human beings' daily activities are immediate actions and are therefore under control of the experiential processing system (System 1). The rational processing system (System 2) intervenes with the experiential processing system to better organize the overall outcome of the processing through consciously envisioning possible futures.

Time Sale of Human Action

Scale (sec)	Time Units	System	World (Theory)
10^7	months		Social Band
10^6	weeks		
10^5	days		
10^4	hours	Task	Rational Band
10^3	10 min	Task	
10^2	minutes	Task	
10^1	10 sec	Unit Task	Cognitive Band
10^0	1 sec	Operations	
10^{-1}	100 ms	Deliberate Act	
10^{-2}	10 ms	Neural Circuit	Biological Band
10^{-3}	1 ms	Neuron	
10^{-4}	100 µs	Organelle	

Figure 2: Newell's time scale of human action (Newell, 1990).

MHP/RT: Integration of MHP and Two Minds

Brief Description of MHP/RT

Toyota and Kitajima (2010a) and Kitajima and Toyota (2012) proposed MHP/RT as a simulation model of human behavior selection[1]. It stems from the successful simulation model of human information processing, Model Human Processor (MHP) (Card, Moran, & Newell, 1983), and extends it by incorporating three theories we have published in the cognitive sciences community. The Maximum Satisfaction Architecture (MSA) deals with coordination of behavioral goals (Kitajima, Shimada, & Toyota, 2007), the Structured Meme Theory (SMT) involves utilization of long-term memory, which works as an autonomous system (Toyota, Kitajima, & Shimada, 2008), and Brain Information Hydrodynamics (BIH) involves a mechanism for synchronizing the individual with the environment (Kitajima, Toyota, & Shimada, 2008).

[1] Unfortunately, the detailed description of the model is available only in Japanese in Kitajima and Naito (2010) and Kitajima and Toyota (2011b).

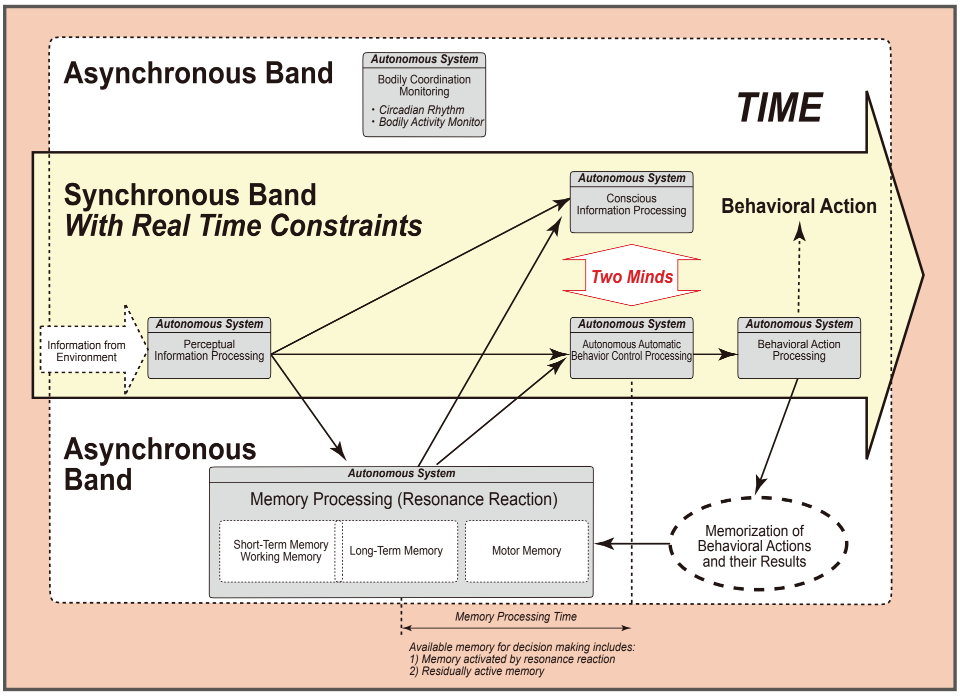

Figure 3: Schematic diagram of MHP/RT (Kitajima & Toyota, 2012).

MHP/RT includes a mechanism for synchronizing autonomous systems (rectangles with rounded corners in Figure 3), working in the "Synchronous Band." MHP/RT was created by combining MHP and Two Minds by applying our conceptual framework of Organic Self-Consistent Field Theory (Toyota & Kitajima, 2010b). See Kitajima (2011) for more information.)

MHP/RT works as follows:

1. Inputting information from the environment and the individual,
2. Building a cognitive frame in working memory, which is not depicted in the figure but it resides between the conscious process and the unconscious process to interface them,
3. Resonating the cognitive frame with autonomous long-term memory to make available the relevant information stored in long-term memory; cognitive frames are updated at a certain rate and the contents in the cognitive frames are continuously input to long-term memory to make pieces of information in long-term memory accessible to System 1 and System 2,
4. Mapping the results of resonance on consciousness to form a reduced representation of the input information, and
5. Predicting future cognitive frames to coordinate input and working memory.

As depicted in Fig. 3, human beings operate in two bands, the asynchronous band and the synchronous band. The Bodily Coordination Monitoring System and the Memory Processing System operate in the asynchronous band. The Perceptual Information Processing System, Conscious Information Processing System, Autonomous Automatic Behavior Control Processing System, and Behavioral Action Processing System operate in the synchronous band. These systems work autonomously. System 1 of the Two Minds corresponds to the Autonomous Automatic Behavior Control Processing System, and System 2 corresponds to the Conscious Information Processing System.

The density of information in working memory is the product of the updating rate of the cognitive frame and the degree of fineness of the information represented in the cognitive frame. When the system is under the control of automatic behavior (System 1), the updating rate of the cognitive frame tends to be high; however, the degree of fineness of the information represented in the cognitive frame is coarse. When the system is under the control of consciousness (System 2), the updating rate of the cognitive frame and the degree of fineness of the information are flexibly determined by the context.

Hierarchical structure of behavior. Observed behavior should be regarded as a compound of activities that occur on different time scales. The time scales may be milliseconds, hundreds of milliseconds, a few minutes, or even a few weeks. It is not true that activities that occur on a certain time scale evolve continuously to the next time scale. Rather, it is more appropriate to assume that a set of activities that occur on a certain time scale are discontinuously connected with higher-level activities, and therefore the relationship between a pair of related activities at two different levels is non-linear. Newell (1990) explained the time scale of human action, and identified four bands and their characteristic times: the biological band (1msec $\sim$ 10msec), the cognitive band (100msec $\sim$ 10sec), the rational band (a few minutes $\sim$ a few hours), and the social band (a few hours $\sim$ a few hours).

Interaction between System1 and System 2. MHP/RT transforms the input information from the environment to the output behavior to the environment. The actual operation is determined by the relative balance between the following two factors, which is determined by the degree of participation of consciousness in the manifestation of behavior at each moment:

1. The effect of feedback from the conscious layer (System 2) on shaping behavior, and
2. The effect of feedforward control from the autonomous automatic behavior control layer (System 1) on shaping behavior.

How System 1 and System 2 interact appears in the relationship between the updating rate of the cognitive frame and the density of information represented in the cognitive frame. In the following, this will be explained in more detail.

- **System 1 control mode:** When System 1 governs behavior, the updating rate of the cognitive frame is the fastest, and the system behaves unconsciously. The system refers to the memory that is activated via the resonance reaction, and the outcome of behavior is consciously monitored. As long as the output of behavior is consistent with the representation of the contents of activated memory, no feedback control is applied. An example of this behavior mode is riding a bicycle on a familiar road. It is not necessary to monitor the behavior with high frequency. As a result, System 2 may initiate tasks that are not directly relevant to unconscious behavior. In such a situation, consciousness is free from behavior that is tightly embedded in the environment. Therefore, for example, the system may use a mobile phone to talk with a friend while riding a bicycle.
- **System 2 control mode:** When System 2 governs behavior, the systems try to behave according to the image System 2 created or meditate with no bodily movement. The least resources are allocated for initiating behavior according to input from the environment. This corresponds to a situation in which the amount of flow of information in System 1 is small. Working memory is occupied by activities related to System 2. However, the sensory-information filter functions so that the system can react to a sudden interruption from the environment (*e.g.*, a phone call).

How MHP/RT Works

At a given time, T, MHP/RT's state is viewed in two ways; 1) which part of MHP/RT is working and 2) what content MHP/RT is processing. In the following subsections, we describe the "which part" question in the "Four Operation Modes" subsection (Kitajima & Toyota, 2012), and the "for what" question in the "Four Processing Modes" subsection (Kitajima & Toyota, 2011a).

Four *Operation* Modes of MHP/RT

In MHP/RT, behavior is the outcome of activities in System 1 and System 2, both of which use working memory to prepare for the next action. Depending on the situation, behavior is driven mainly by either System 1 (MHP/RT Mode 1) or System 2 (MHP/RT Mode 2). Both systems work synchronously by sharing working memory. However, in some situations, both work asynchronously (MHP/RT Mode 3) or independently (MHP/RT Mode 4); working memory may be shared weakly or used solely for one of these layers.

Four *Processing* Modes of MHP/RT

Human behavior is considered a series of moment-by-moment decision-making processes in the ever-changing environment. Each decision-making process is carried out by System 1 and System 2 of Two Minds under real-time constraints, which basically requires synchronizing the workings of System 1 and System 2 in the real world by taking into account each system's characteristic times defined by Newell's time scale of action (Fig. 2). The result of decision-making is an event that includes the direct output of decision-making or behavior, and the resultant state of the external world.

The four processing modes in human decision-making are: (1) conscious (System 2) behavior before the event, (2) conscious (System 2) behavior after the event, (3) unconscious (System 1) behavior before the event, and (4) unconscious (System 1) behavior after the event.

Figure 4 illustrates these four processing modes along the time dimension expanding before and after the event, which is denoted as the "boundary event" in the figure.

The Role of Memory in MHP/RT

Organization

As Figure 3 illustrates, the memory system operates *asynchronously* with the systems working synchronously with the environment. Memory processes include the storage of information and the use of stored information, which play a very important role in the real-time simulation of human decision-making in daily life.

Memory storage. We assume that memory is organized by a "Multi-Dimensional Frame" (MD frame) for storing information. The MD frame is a conceptual extension of Minsky's frame (Minsky, 1988). It is a primitive cognitive unit that conveys information that the brain can manipulate under various constraints, similar to the concept of the Idealized Cognitive Model (ICM) theory by Lakoff (1987) and the schema theory by Rumelhart (1980). Our theory involves two kinds of MD frame. The Behavior Multidimensional frame (BMD frame) is created and used by Autonomous Automatic Behavior Control Processing. The Relational Multidimensional frame (RMD frame) is created and used by Conscious Processing. The BMD frame and RMD frame are connected by a sharing Object originating from Perceptual Processing.

Due to the limitation of the brain's processing capability, the range of integration is limited; therefore, System 1

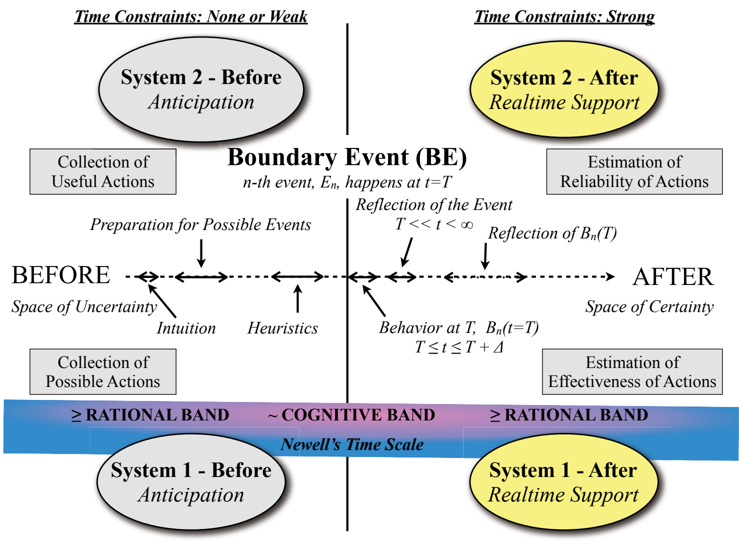

Figure 4: How the Four Processing Modes work (Kitajima & Toyota, 2011a).

memory and System 2 memory may differ. However, they may share objects originating from perceptual sensors. Thus, when objects that are the result of the just-finished integration and segmentation process are processed in the next cycle, representation of the objects may serve as common elements to combine System 1 memory and System 2 memory to form an intersystem memory. We call this memory the Multidimensional (MD) Frame.

Memory usage. Object cognition involves collecting information from the environment via perceptual sensors; integrating and segmenting the collected information, centering on visually collected objects; and continuing these processes until the objects necessary to live in the environment are obtained. These objects are then used independently in System 1 and System 2 of Two Minds, and memorized after integrating related entities associated with each system.

Function: Resonance

At a given moment, MHP/RT is working in one of the four operation modes described above. However, the memory system works autonomously to make part of long-term memory active so that it can be used in System 1 and/or System 2 processing through resonance processes. However, as depicted in Figure 5, how the memory system reacts to the environment may depend on the degree of time constraints that the human-environment system imposes on itself. When real-time constraints are strong, slow memory processes that use long-term memory do not participate in the processing. In other words, only the unconscious side of the Two Minds system, System 1, works and has a chance to use memory through resonance. In contrast, with few real-time constraints, the conscious and unconscious systems work collaboratively in some cases and independently in other cases. Both systems have a chance to use as many resonated contents as possible.

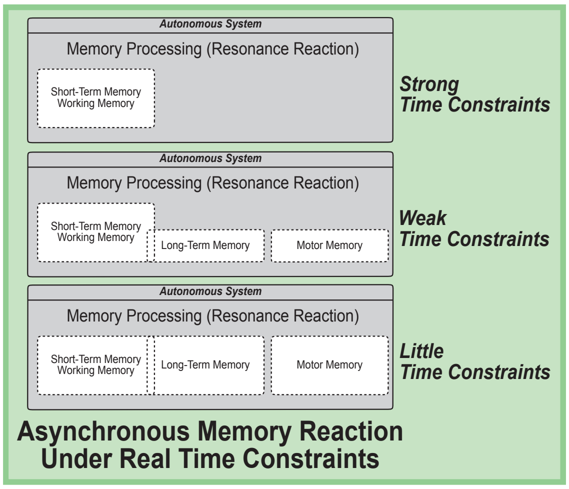

Figure 5: Memory reaction under real time constraints.

Operation: Pipelining

At a given moment, MHP/RT is processing one of four content types: a future event consciously or unconsciously, or a past event consciously or unconsciously. For future/conscious processing, MHP/RT uses memory that conveys a sequence of actions with symbolic representations for accomplishing a currently held goal. For future/unconscious processing, it uses memory that is associated with an automatic sequence of actions that should lead to the goal. For past/conscious processing, it reflects on and elaborates a certain symbolic event by using activated pieces of knowledge through resonance processes. For past/unconscious processing, existing memory is modified by using activated non-symbolic pieces of knowledge that is currently activated in working memory.

It is important to note that memory activation is a totally parallel process; therefore, there is no way of knowing which part of activated memory is used. It depends completely on which object MHP/RT is processing. MHP/RT's resonance process makes available the relevant part of activated knowledge through resonance. Along the time dimension, MHP/RT, working in one of four operation modes, switches among the four processing modes and uses activated knowledge through resonance. MHP/RT's processing is a pipeline process of four primitive processes. The nature of this pipelining may change depending on the nature of the task. When learning a new task, it is impossible to foresee the future; therefore, past/conscious processing may dominate. In contrast, for example, when an experienced piano player is playing a well-practiced tune, future/unconscious processing may dominate.

Conclusion

This paper demonstrated the role of memory in MHP/RT, the architecture model of human behavior selection. The purpose of MHP/RT is to simulate human behavior; therefore, the organization, function, and operation of memory were specified accordingly. According to the specification of MHP/RT in Fig. 3, the organization of memory is defined as the MD frame. The content in long-term memory is made available through resonance processes in MHP/RT. Given that MHP/RT works in one of four different operation modes and that it processes contents associated with an event in one of four different ways, the portion of activated memory that is used may differ. We believe MHP/RT with an autonomous memory system is capable of simulating human behavior in real-world settings.

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