Decision-making and action selection in Two Minds: An analysis based on Model Human Processor with Realtime Constraints (MHP/RT)

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Received 28 February 2013; received in revised form 15 May 2013; accepted 17 May 2013

Abstract

Decision-making and action selection are mental activities for shaping and organizing human behavior in the ever-changing environment. There are, however, important differences between decision-making and action selection. According to "Two Minds" (Evans & Frankish, 2009; Kahneman, 2003; Kahneman, 2011) — a version of dual processing theory — human behavior can be viewed as the integration of output of System 1, i.e., unconscious automatic processes, and System 2, i.e., conscious deliberate processes. System 1 activates a sequence of automatic actions. System 2 monitors System 1's performance according to the plan it has created and, at the same time, it activates future possible courses of actions. Decision-making narrowly refers to System 2's slow functions for planning for the future and related deliberate activities, e.g., monitoring, for future planning. On the other hand, action selection refers to integrated activities including not only System 1’s fast activities but also System 2’s slow activities, not separately but integrally. This paper further discusses the difference between decision-making and action selection on the basis of the architecture model the authors have developed for simulating human beings’ in situ action selection, Model Human Processor with Realtime Constraints (MHP/RT) (Kitajima & Toyota, 2012b). MHP/RT’s simulation of human behavior along the time dimension shows when the processes of decision-making and action selection would be initiated and how they are carried out. © 2013 Published by Elsevier B.V.
1. Introduction

This paper discusses the differences and the interrelationships between decision-making and action selection based on the cognitive architecture, MHP/RT, that outputs moment-by-moment human beings’ action selections by dealing with continuous input from the ever-changing environment (Kitajima & Toyota, 2012b). The function of MHP/RT is analogous to an operating system for modern computers. MHP/RT is equipped with several modules that work autonomously and synchronize with each other when necessary. The modules include a module for processing input from the external environment, a module for transmitting the results of the processing to the external environment, and a module of memories for short-term storage of input information, for long-term storage of information for future use, and for momentary maintenance of information for the internal processes. Operating systems for computers are for appropriately dealing with any input to the computers at any time T without having the computers halt unless it is ordered to do so or some modules make fatal errors. MHP/RT is for appropriately dealing with any input from the external ever-changing environment and internally generated input at any time T to make decisions and action selections that should cause some changes in the environment. The decisions and action selections at each moment should have influence on decisions and action selections thereafter as well.

1.1. Requirement of a cognitive architecture

In general, a cognitive architecture is for specifying ''how the mind will do.'' The following quotation is from Allen Newell’s lecture at Carnegie Mellon University, December 4, 1991 (adapted from Anderson (2007, pp. 3–4)):

The question for me is, how can the human mind occur in the physical universe? We now know that the world is governed by physics. We now understand the way biology nestles comfortably within that. The issue is, how will the mind do that as well? The answer must have the details. I have got to know how the gears clank and how the pistons go and all the rest of that detail. My question leads me down to worry about the architecture.

In order to address the ''how the mind will do'' question, a cognitive architecture needs to place a special emphasis on the nature of strong interactions between the internal human mind and the external environment. In other words, it needs to deal with what we observe in the external environment as the results of human beings’ action selections in relation with the time dimension T. Observable human behaviors in the external environment are equivalent to a series of moment-by-moment behaviors along the time dimension with appropriate grain sizes of time. Considering that human beings’ behaviors are strongly coupled with the external environment, and since the external environment, i.e., physical or physiological, develops as a function of time T, human beings’ behaviors need to be treated as a function of T as well. In summary, the top-level requirement of a cognitive architecture is to provide a substratum for simulating moment-by-moment human beings’ behaviors in the ever-changing environment.

Specific grain sizes of time for describing moment-by-moment human behaviors along the time dimension might be arbitrary. However, as (Newell, 1990, p. 122) suggested, there are a number of characteristic times useful for considering human beings’ behaviors: each is associated with one of distinctive ‘‘bands’’ connected non-linearly with each other as shown in Table 1. This has an important implication to the design of scientific researches towards understanding human being’s behavior, i.e., it is not wise to understand phenomena in a higher band by extrapolating findings in the lower bands.

1.2. Outline of the paper

MHP/RT is a cognitive architecture with T as its critical dimension that builds on the important findings in behavioral economics, one major trends of economics, which suggests that ‘‘the mind’’ should consist of two totally different systems, called Two Minds (Kahneman, 2003). System 1 deals with intuitive decisions (action selection, in this paper), and System 2 takes care of deliberate, effort consuming processing such as reasoning (decision-making, in this paper). However, most phenomena the economics treats are not severely sensitive to the time dimension.

This paper starts by describing a cognitive architecture built on Two Minds with the consideration of how to synchronize “very fast” System 1 and “super slow” System 2 in the ever-changing environment for the purpose of creating coherent moment-by-moment behavior. This paper suggests that decision-making is relevant with System 2 and action planning is relevant with System 1. The function of decision making and that of action selection are the same at the point that they both deal with the future of the behaving system but they are different in terms of their characteristic processing times, and therefore each should function at different timings, and interacts with each other appropriately as the time goes by. This paper shows that memory system locates at the central of the entire processes.  2

1.3. Current status of MHP/RT

At present, MHP/RT is not a running computational model but a conceptual simulation model that helps designing ethnographic field studies for understanding people’s in situ decision making and action selection processes. We have developed a methodology, called Cognitive Chrono-Ethnography which includes a process to simulate people’s behavior in question by MHP/RT. Kitajima and Toyota (2012b)

1 MHP/RT is the acronym for Model Human Processor with Realtime Constraints.

2 In this sense, MHP/RT can be regarded as ‘‘TwoMinds(T)’’, a real brain model that shows Two Minds’ features along the time dimension T with the boundary conditions being defined by the performances of the memory systems.
identifies cognitive functions, i.e., attention, planning, and working memory, that should affect the performance of elderly passengers’ signage following behavior at railway stations by performing qualitative simulation of MHP/RT. The simulation predicted that those elderly passengers with the inferior attention function would behave differently from those with normal cognitive functions. A field study was designed after the predictions of MHP/RT simulations and the results of field observations confirmed that the elderly passengers’ behaviors were well characterized by the workings of the identified cognitive functions, and provided deeper understandings for the relationships between the observed behaviors of the elderly passengers and the workings of the cognitive functions. We have conducted a set of CCE studies; Kitajima, Tahira, Takahashi, and Midorikawa (2012) studied how visitors to a hot spring resort enjoy their visits, Kitajima (2012a) studied how spectators visiting a baseball stadium had become loyal fans of a professional baseball team in Japan, and so on.

We have finished the construction of the comprehensive brain activity model that is capable of qualitatively simulating human beings’ daily decision making and action selections, and we have just started to verify it by a series of CCE studies; they used MHP/RT for designing the studies and the observations were consistent with the MHP/RT’s predictions. There are a variety of directions to proceed, e.g., constructing running computational simulation models, but, for the time being, we will continue on the same line we have been taking, i.e., conducting CCE studies to accumulate cases that are explained by Two Minds and understood mechanistically and deeper by MHP/RT.

The main focus of this paper is the cognitive architecture of MHP/RT but equally important is the role of memory that is used in decision making and action selections. In fact, what determines the content of decision-making and action selections is strongly related with the active part of memory at a specific moment. As to the former, i.e., the role of memory in MHP/RT (Kitajima & Toyota, 2012c) will be described in this paper. As to the latter, i.e., the content of memory and how it develops from scratch, its theorization is underway and we are planning to publish it in the near future.

### Table 1

Newell’s time scale of human action. adapted from Newell (1990, p. 122), Fig. 3-3.

<table>
<thead>
<tr>
<th>Scale (s)</th>
<th>Time units</th>
<th>System</th>
<th>World (theory)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^7$</td>
<td>months</td>
<td></td>
<td>Social band</td>
</tr>
<tr>
<td>$10^6$</td>
<td>weeks</td>
<td></td>
<td>Social band</td>
</tr>
<tr>
<td>$10^5$</td>
<td>days</td>
<td></td>
<td>Social band</td>
</tr>
<tr>
<td>$10^4$</td>
<td>h</td>
<td>Task</td>
<td>Rational band</td>
</tr>
<tr>
<td>$10^3$</td>
<td>10 min</td>
<td>Task</td>
<td>Rational band</td>
</tr>
<tr>
<td>$10^2$</td>
<td>min</td>
<td>Task</td>
<td>Rational band</td>
</tr>
<tr>
<td>$10^1$</td>
<td>10 s</td>
<td>Unit task</td>
<td>Cognitive band</td>
</tr>
<tr>
<td>$10^0$</td>
<td>1 s</td>
<td>Operations</td>
<td>Cognitive band</td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td>100 ms</td>
<td>Deliberate act</td>
<td>Biological band</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>10 ms</td>
<td>Neural circuit</td>
<td>Biological band</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>1 ms</td>
<td>Neuron</td>
<td>Biological band</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>100 μms</td>
<td>Organelle</td>
<td>Biological band</td>
</tr>
</tbody>
</table>

### 2. Understanding people’s behavior along the time dimension $T$

#### 2.1. Two Minds

“`Understanding people’s behavior” is an important study issue in economics. How does a person decide to purchase a new commodity for daily use? He or she selects one from a number of candidates in order to realize the states where he/she wants to be. Human decision-making underlies these activities, and therefore it has been a central topic in economics to be studied extensively. 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; Simon, 1996). Simon claimed that agents, or human beings, face uncertainty about the future and cost 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” (Evans & Frankish, 2009; Kahneman, 2003; Kahneman, 2011), a version of dual processing theory, consisting of System 1 and System 2. Fig. 1 (adapted from Kahneman (2003)) illustrates the workings of the two systems. System 1, the first type of process, is a fast feedforward control process driven by the cerebellum and oriented toward immediate action. Experiential processing is experienced passively, outside of conscious awareness (one is seized by one’s emotions). In contrast, System 2, the second type of process, is a slow feedback control process driven by the cerebrum and oriented toward future action. It is experienced actively and consciously (one intentionally follows the rules of inductive and deductive reasoning).

#### 2.2. Decision-making and action selection

Two Minds is naturally mapped onto two mental activities of the main topic of this paper, i.e., decision-making and action selection, that lead to moment-by-moment observable behaviors. Decision-making is the act or process of choosing a preferred option or course of actions from a set of alternatives. It precedes and underpins almost all deliberate or voluntary behavior. Action selection is the process for selecting “what to do next” in dynamic and unpredictable environments in real time. The outcome of decision-making is regarded as part of resources that are available when selecting actions (Suchman, 1987). As dual-processing theories suggest, e.g., Kahneman (2003), two qualitatively different mechanisms of information processing operate in forming decisions. The first is a quick and easy processing mode based on effort-conserving heuristics. The second is a slow and more difficult rule-based processing mode based
on effort-consuming systematic reasoning. The first type of process, action selection, is often unconscious and tends to automatic processing carried out by System 1 of Two Minds, whereas the second, decision-making is invariably conscious and usually involves controlled processing carried out by System 2 of Two Minds.

2.3. 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 appropriate to consider that activities that occur on a certain time scale evolve continuously to the next higher 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 (1–10 ms), the cognitive band (100 ms to 10 s), the rational band (a few minutes to a few hours), and the social band (a few hours to months). It is important to consider appropriately which band is dominant when examining people’s behavior. Phenomena governed mainly by consciousness, or System 2, would be considered in rational, social, or cognitive band, whereas those controlled mainly by unconsciousness, or System 1, would be considered in cognitive or biological band. Note that the cognitive band would reside both processes.

In summary, decision-making is associated with the activities of System 2 working in rational, social, or cognitive band, and action selection is associated with the activities of System 1 working in cognitive or biological band, and both are non-linearly connected to exhibit moment-by-moment observable behaviors in the ever-changing external environment. The question is how System 1 activities, including action selection, and System 2 activities, including decision-making, interrelate with each other. This paper addresses this issue by using the cognitive architecture, MHP/RT.

2.4. Decision-making and action selection in Two Minds: An illustration

Here is an example to illustrate the point.

When you hear the car-navigation system start speaking in synthesized voice, you switch your attention to listening to what it says and try to comprehend it for planning your driving for the near future. The navigation system is designed to speak, for example, "Slight right turn in point five miles on South Lynn Street" with the screen shown in Fig. 2 at some specific moment.

A driver, who is not familiar with the route, is supposed to listen to the instruction and read the screen consciously and carefully, and integrate the provided information from the car-navigation system with the current driving situation for imagining and planning the immediate future driving and creating automatically executable action sequences for the maneuver; when to start reducing speed, when to start braking, and so forth. These activities are carried out by System 2.

When the navigation system starts speaking at time $T$ "Slight right turn ... ", it should intervene the driver’s on-going processes carried out under System 1 and/or System 2 and initiates a new interactive process stream on the part of the driver. This process should interact with whatever Two Minds processes the driver engages in. The newly initiated process might negatively interfere with or positively enhance the other on-going processes; some processes must be suspended and resumed at a proper timing with little cost, and the other processes should continue with no interference from the car-navigation system, e.g., keep conversing with a person in the passenger seat.

After completing the instruction, the driver would be able to comprehend the meaning of rather ambiguous concept "slight right turn" by integrating it with what the driver has just seen, i.e., the real road scene, deliberately by using System 2. This knowledge might be useful for the driver to predict what would happen when he/she is given another version of the instruction "Slight right turn in ... on

![Fig. 1 Two Minds (adapted from Kahneman (2003)).](image-url)
This reflection on the just-completed behavior by System 2 would be carried out while driving on the street by using System 1. In addition, the driver would learn the specific procedures associated with this turn, e.g., where to look at for safety driving, how to enter the street, etc. by using System 1. In summary, at each moment, the driver would use System 2 for future planning or reflect on the experience, or use System 1 for on-going driving or integrating the just-completed behavior with the learnt procedure.

3. MHP/RT: cognitive architecture for simulating people’s behavior

Kitajima and Toyota (2012b) proposed MHP/RT as a simulation model of human behavior selection as shown in Fig. 3. It stems from the successful simulation model of human information processing, Model Human Processor (MHP) proposed by Card, Moran, and 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). MHP/RT includes a mechanism for synchronizing autonomous systems (rectangles with rounded corners in Fig. 3), working in the “Synchronous Band.” MHP/RT was created by combining MHP (Card et al., 1983) and Two Minds (Kahneman, 2011; Kahneman, 2003) by applying the conceptual framework of Organic Self-Consistent Field Theory (Toyota & Kitajima, 2010). See Kitajima (2012b) for more information.

3.1. MHP/RT works as a function of time $T$

MHP/RT is a real brain model comprising of System 1’s unconscious processes and System 2’s conscious processes at the same level as shown in Fig. 3, in which both System 1 and System 2 receive input from the Perceptual Information Processing System in one way, and from the Memory Processing System in another way. System 1 and System 2 work autonomously without any superordinate-subordinate hierarchical relationships but interact with each other when necessary.

This feature of MHP/RT should be contrasted with the goal-oriented cognitive architectures such as ACT-R (Anderson & Lebiere, 1998; Anderson, 2007) in which the conscious processes are considered as the processes to control people’s behavior and the unconscious processes are considered subordinate to the conscious or intentional processes. What ACT-R tries to do is to show how System 2 can be implemented on top of System 1. The procedural memory system is very similar to System 1 (fast, learning based on rewards/experience, intuitive), and then ACT-R models tend to consist of a set of production rules that (when run on this System 1 module and in combination with symbolic working memory buffers and a long-term memory system) give rise to the slower, deliberative planning behaviors seen in System 2. This is a very different approach to that given in this paper. However, ACT-R models are totally adequate for simulating stable human activities with weak time constraint in which deliberate decision making would work effectively, but might be hard for the situations with strong time constraint where the environmental condition changes chaotically and deliberate decision making implemented on System 2 might not work as effective.

3.1.1. MHP/RT’s basic flow

As depicted in Fig. 3, MHP/RT operates 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.

MHP/RT works as follows (Fig. 4):

1. Inputting information from the environment and the individual.
2. Building a cognitive frame in working memory, which resides between the conscious process, System 2, and the unconscious process, System 1, to interface them—depicted between System 1 and System 2.
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, corresponding to either decision-making or action selection depending on the time difference between the time when the prediction is made and the time when an event associated with the prediction happens, namely, whether the prediction is made mainly by System 2, decision-making, or by System 1, action selection.
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, i.e., under control of 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, i.e., under control of System 2, the updating rate of the cognitive frame and
the degree of fineness of the information are flexibly determined by the context.

3.2. Basic MHP/RT behaviors

At a given time, T, MHP/RT’s state is viewed by two ways;

1. which part of MHP/RT is working, and
2. which content MHP/RT is processing

In the following subsections, the "which part" question will be decied in 3.2.1, the "Four Operation Modes" subsection (Kitajima & Toyota, 2012b), and the "for what" question in 3.2.2, the "Four Processing Modes" subsection (Kitajima & Toyota, 2011a).

3.2.1. Four operation modes of MHP/RT

At a given time, T, MHP/RT’s state is considered from the viewpoint "which part of MHP/RT is working." In MHP/RT as illustrated by Fig. 4, 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 or System 2. Both systems work synchronously by sharing working memory. The former is called Mode 1, and the latter, Mode 2. However, in some situations, both work asynchronously, Mode 3, or independently, Mode 4; working memory may be shared weakly or used solely for one of these layers (see Table 2).

- **Mode 1 (System 1 controls behavior):** 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, which is System 2’s mission in this mode. As long as the output of behavior is consistent with the representation of the contents of activated memory, or prediction, no feedback control is applied. No serious decision-making is required but a series of unconscious action selections would result in smooth behavior. An example of this behavior mode is riding a bicycle on a familiar road.

- **Mode 2 (System 2 controls behavior):** When System 2 governs behavior, the bicycle ride would cause a certain amount of delay in action. This mode is characterized by isolation of System 1 from System 2, which means that each uses different portion of working-memory for the respective processes. System 2 could be either totally detached from System 1, e.g., daydreaming, or in the deliberate thinking mode like Mode 2, in which System 2 mainly controls behavior and System 1 works under the control of System 2 by using the area of working memory for this process. Mode 3 and Mode 4 are similar because the process System 1 takes control and the one initiated by System 2 are car-

<table>
<thead>
<tr>
<th><strong>Table 2</strong> Four operation modes of MHP/RT and their relationships to decision-making and action selection.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous mode</td>
</tr>
<tr>
<td>Mode 1: System 1 controls behavior</td>
</tr>
<tr>
<td>Skilled performance, i.e., no serious decision-making is necessary for most part of behavior but still necessary to decide whether continue, change, or terminate actions, but most part of behavior can be regarded as a series of effortless action selections</td>
</tr>
<tr>
<td>Mode 2: System 2 controls behavior</td>
</tr>
<tr>
<td>Unskilled activities, e.g., learning, thinking, etc.; a series of serious decision-makings will be required</td>
</tr>
</tbody>
</table>
ried out quasi-independently, but they are different in terms of the usage of working memory, i.e., Mode 3 has the area in working memory that holds information available to the two processes but Mode 4 does not.

- **Mode 2 (System 2 controls behavior):** 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).

Mode 1, or System 1 control mode, would require least cognitive resources for stringing pieces of behavior in the ever-changing environment. On the other hand, Mode 2, or System 2 control mode, would consist of resource consuming activities including reasoning, recalling weak memory, etc. System 1 control may break down due to unexpected change in the environment, which would be detected by System 2’s monitoring activity, leading to System 2 control mode for searching for procedures for escaping from the undesirable situation. Note that, in daily life, human beings are normally in System 1 control mode because human beings normally prefer effortless behavior, but occasionally forced to operate in System 2 control mode for the purpose of resuming ”normal” System 1 control mode as soon and easily as possible.

### 3.2.2. Four processing modes of MHP/RT

At a given time, \( T \), MHP/RT’s state is considered from the viewpoint ”which content of memory MHP/RT is processing.” As far as observable behaviors are concerned, human behavior is considered as a series of moment-by-moment behavioral selections, either decision-making or action selection, in the ever-changing environment. Each process is carried out by System 1 and System 2 of Two Minds under real time constraints, which basically requires synchronization between 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 human action (Fig. 1). The result of behavioral selection is an event, that includes the direct output of behavior and the resultant state of the external world.

There are four processing modes:

- **System 2 Before Mode:** Conscious use of long-term memory before the event, i.e., System 2’s operation for anticipating the future event, or decision-making.
- **System 1 Before Mode:** Unconscious use of long-term memory before the event, i.e., System 1’s operation for automatic preparation for the future event, or action selection.
- **System 2 After Mode:** Conscious use of long-term memory after the event, i.e., System 2’s operation for reflecting on the past event.
- **System 1 After Mode:** Unconscious use of long-term memory after the event, i.e., System 1’s operation for automatic tuning of long-term memory related to the past event.

Fig. 5 illustrates the Four Processing Modes along the time dimension expanding before and after the event, which is shown as ”boundary event” in the figure. Table 3 shows the resultant Four Processing Modes of in situ human behavior; at each moment along the time dimension human behaves in one of the four processing modes and he/she
In the diagram of Two Minds depicted by Kahneman (2003), the memory module is placed rather independently with System 1 and System 2 as shown by Fig. 1. MHP/RT extends Two Minds by specifying the role of memory when System 1 and System 2 work (Kitajima & Toyota, 2012c). This is critical because the contents stored in memory determine what System 1 and System 2 would do in the ever-changing environment, and we are interested in interactions between the two systems with different characteristic times.

### 3.3.1 Memory organization

As Fig. 3 illustrates, the memory system operates asynchronously with the systems which are working synchronously with the environment. Memory processes include storage of information and usage of stored information. In order to carry out real time simulation of human decision-making in daily life, memory processes play very important role.

#### 3.3.2 Memory storage

MHP/RT assumes that memory is organized by “Multi-Dimensional Frame” for storing information (Fig. 7). MD-frame is a conceptual extension of Minsky’s frame (Minsky, 1988). It is a primitive cognitive unit that conveys information that can be manipulated by brain under various constraints, similar to the concept in the ICM (Idealized Cognitive Model) theory by Lakoff (1987), the schema theory by Rumelhart (1980), and so on. There are three kinds of MD-frame in MHP/RT. PMD-frame (Perceptual Multidimensional Frame) is created and used by the Perceptual Information Processing. BMD-frame (Behavior Multidimensional frame) is created and used by the Autonomous Automatic Behavior Control Processing. RMD-frame (Relational Multidimensional frame) is created and used by the Conscious Processing. BMD-frame and RMD-frame are mutually connected by sharing OBJECT, originated from the Perceptual Processing.

#### 3.3.3 Memory usage

Object cognition occurs as follows: 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 necessary objects to live in the environment are obtained. These objects are then used independently in Systems 1 and System 2 of Two Minds, and memorized after integrating related entities associated with each system. Due to the limitation of the brain’s processing capability, the range of integration is limited; therefore, System 1 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 the common elements to combine System 1 memory and System 2 memory to form an inter-system memory. We call this memory the Multi-Dimensional (MD) Frame.

#### 3.3.4 Memory function: Resonance

At a given moment, MHP/RT is working in one of the four operation modes as described above. However, the memory

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### Table 3 Four processing modes Kitajima and Toyota (2011a).

<table>
<thead>
<tr>
<th>System 2 conscious processes</th>
<th>System 1 unconscious processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>Before</td>
</tr>
<tr>
<td>Time constraints</td>
<td>Time constraints</td>
</tr>
<tr>
<td>None or weak</td>
<td>None or weak</td>
</tr>
<tr>
<td>Network structure</td>
<td>Network structure</td>
</tr>
<tr>
<td>Feedback</td>
<td>Feedback</td>
</tr>
<tr>
<td>Processing</td>
<td>Processing</td>
</tr>
<tr>
<td>Main serial conscious process + subsidiary parallel process</td>
<td>Main serial conscious process + subsidiary parallel process</td>
</tr>
<tr>
<td>Newell’s time scale</td>
<td>Newell’s time scale</td>
</tr>
<tr>
<td>Rational/social</td>
<td>Rational/social</td>
</tr>
<tr>
<td>Before</td>
<td>Before</td>
</tr>
<tr>
<td>Processing</td>
<td>Processing</td>
</tr>
<tr>
<td>Simple parallel process</td>
<td>Simple parallel process</td>
</tr>
<tr>
<td>Before</td>
<td>Before</td>
</tr>
<tr>
<td>Newell’s time scale</td>
<td>Newell’s time scale</td>
</tr>
<tr>
<td>Rational/social</td>
<td>Biological/cognitive</td>
</tr>
</tbody>
</table>

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**Figure 3**

[diagram of Two Minds]

**Figure 7**

[diagram of Multi-Dimensional Frame]
system works autonomously to make some part of long-term memory active so that it can be used by System 1’s processing and/or System 2’s processing through resonance processes. However, as depicted in Fig. 6, how the memory system should react to the environment may depend on the degree of time constraints that the human-environment system should pose on itself. When real time constraints are strong, slow memory processes that use long-term memory should not participate in the whole processing. In other words, only the unconscious side of the Two Minds system, System 1, should work and have a chance to use memory through resonance. On the contrary, when there are little real time constraints, both systems, consciousness and unconsciousness systems, work collaboratively in some cases, i.e., Mode 1 and Mode 2, and independently, Mode 3 and Mode 4, in other cases. Both systems would have chance to use as many resonated contents as possible.

### 3.3.5. Memory operation: pipelining

As described in 3.2.2, at a given moment, MHP/RT is processing contents in one of four types; a future event consciously or unconsciously, or a past event consciously or unconsciously. For “future/conscious” processing, MHP/RT uses memory that conveys sequence of actions with symbolic representations for accomplishing a goal that is held at the moment, 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 elaborate on a certain symbolic event by using activated pieces of knowledge through resonance processes, and for “past/unconscious” processing, existing memory would be modified by using activated pieces of knowledge, non-symbolic, that is currently activated in working memory.

It is important to note that memory activation process is a totally parallel process, and this means that there is no way of knowing which part of activated memory is used. It solely depends 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 conceived as a pipeline process of four primitive processes. Depending on the nature of a task MHP/RT is facing, the nature of pipelining may change; when learning a new task, it is impossible to foresee the future, and therefore, “past/conscious” processing may dominate, or deliberate planning and decision making by inference using information stored in long-term memory; on the other hand, when an experienced piano player is playing a well-trained tune, “future/unconscious” processing may dominate.

### 3.4. Interactions between the future and the past

#### 3.4.1. Event memory creation and utilization

The four processing modes are defined by referring to a single event, boundary event. Therefore, it is useful to consider how each of the four processing modes works when one encounters an event for the first time, and it encounters the same event in the future.

When one encounters an event for the first time, “System 1 After” processing and/or “System 2 After” processing will work to create encodings of the event as an experiential memory frame. “System 2 After” processing will elaborate on the outcome of “System 1 After” processing. Usually, several times of repetition of encountering the same event will be necessary to establish a cohesive memory frame.

The experiential memory frame thus created may be activated before the event happens through “System 1 Before” processing and/or “System 2 Before” processing. Action selection corresponds to “System 1 Before” processing and decision-making corresponds to “System 2 Before” processing. Since the characteristic times of System 1 and those of System 2 are significantly different, they have different meanings for the behavior to be taken for the event. As shown in Fig. 8, “System 2 Before” processing, or decision-making, for the future event will work long before the event happens when there is time available for collecting possible actions through deliberate thinking, whereas “System 1 Before” processing, or action selection, for the immediate future anticipatory event will happen; one will be able to select action to behave appropriately, not only experiencing the event but also avoiding the event (not experiencing the event but an alternative event).

#### 3.4.2. Transition from experiential memory to prospective memory

An experiential memory frame that “System 1 After” processing has created will be converted into an prospective memory frame, that can be used by “System 1 Before” processing for anticipating and preparing for future events. This conversion process can be automatic when “System 1 After” processing is able to identify the perceptual objects that are associated with the encoding of the event stored in the experiential memory frame. For example, when one has encountered a harmful insect and been stung, he or she would immediately and automatically establish a link between the visual and auditory perceptual signals of the insect and the action to drive away the insect by his/her
hand. Otherwise, “System 2 After” processing will be required for identifying the objects that might be useful for anticipating the event and associating them with perceptual features of the objects that can be detected by the perceptual system before the event happens in the future.

### 4. Summary: decision-making and action selection in MHP/RT

In this paper, we showed that MHP/RT would work in one of four operation modes for dealing with boundary events in one of four processing modes. In addition, two important activities for organizing human behavior, i.e., decision-making and action selection, are discussed in the entire space of human behavior defined by the real brain model MHP/RT. Table 4 summarizes MHP/RT’s behavior. There are 16 possible combinations generated by the four operation modes and four processing modes. However, some of them may not happen. While MHP/RT is working either in Mode 3 or Mode 4, working memory will not be effectively used for reflection of the past events for, for example, connecting BMD-frame and RMD-frame by sharing OBJECT, originated from the Perceptual Processing — neither of System 1 After nor System 2 After processing would be initiated concerning the event.

On the other hand, while MHP/RT is working in Mode 1, which is the normal behavior mode most of the time we are in, the four processing modes would work coherently with the state of the ever-changing environment for generating smooth behavior by appropriately switching among the four processing modes. However, while MHP/RT is working in Mode 2, System 2 Before processing would take the highest priority among the four processing modes, resulting in weak reflection in System 2 After processing and weak tuning in System 1 After processing. However, any events, initially carried out in Mode 2, will be carried out in Mode 1 after a number of practices.

We want to understand a variety of observable human behaviors in terms of those produced by a cognitive architecture. This paper focused on decision-making and action selection that should reside in observable human behaviors, and showed how they should come in along the human

### Table 4 MHP/RT’s behavior.

<table>
<thead>
<tr>
<th>Operation modes</th>
<th>Processing modes</th>
<th>System 2 before</th>
<th>System 1 before</th>
<th>System 2 after</th>
<th>System 1 after</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous Mode 1—System 1 controls behavior</td>
<td>Rough planning</td>
<td>Action selection</td>
<td>Monitoring System 1’s performance</td>
<td>Tuning</td>
<td></td>
</tr>
<tr>
<td>Synchronous Mode 2—System 2 controls behavior</td>
<td>Deliberate planning and decision-making</td>
<td>Action selection</td>
<td>Weak reflection</td>
<td>Weak tuning</td>
<td></td>
</tr>
<tr>
<td>Asynchronous Mode 3—System 1 and System 2 are weakly coupled</td>
<td>Thinking things relevant to the boundary event</td>
<td>Action selection</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Asynchronous Mode 4—System 1 and System 2 are isolated</td>
<td>Thinking things irrelevant to the boundary event</td>
<td>Action selection</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>
beings’ behavior that should evolve along the time dimension T in the ever-changing environment.

References


