Artif Life Robotics (2001) 5:88–92


ORIGINAL ARTICLE

**Andrzej Buller · Katsunori Shimohara**

# On the dynamics of judgment: does the butterfly effect take place in human working memory?

Received: October 30, 2000 / Accepted: May 24, 2002

**Key words** Working memory · Memes · Social judgment · Artificial neural networks

**Abstract** Why do people hesitate – to do something, or not to do something – even when the data available to them remain constant? The neural model of human working memory (WM) we present in this paper explains hesitation as an emergent property of a complex dynamic structure of stored/processed information. WM is considered as a geometric space inhabited by a "society" of memes, i.e., complex informational structures. A large population of identical memes can cause a feeling, judgment, or intention in an individual. The memes navigate all over WM and interact with one another in a way resembling genetic crossover; hence, new memes are born at several places in WM. Since the birth of contradictory memes is possible, populations of memes contributing to contradictory feelings, judgments, and plans grow in WM and fight for domination. A computer simulation of the process showed that WM's state sometimes goes to a two-focal "strange" attractor. Hence, sudden mental shifts, as, say, from love to hate and back from hate to love, may be caused by minute fluctuations in the densities of meme streams entering WM. The complex system theory calls this phenomenon the "butterfly effect." We argue that this effect takes place in the human mind and also can take place in an advanced robot.

A. Buller (✉) · K. Shimohara
ATR International Human Information Science Laboratories, 2-2-2 Hikaridai, Seika-cho, Soraku-gun, Kyoto 619-0288, Japan
Tel. +81-774-95-1009; Fax +81-774-95-2647
e-mail: buller@atr.co.jp

This work was presented in part at the Fifth International Symposium on Artificial Life and Robotics, Oita, Japan, January 26–28, 2000

## Introduction

Every person, except for the mentally ill, judges autonomously; hence, we cannot perfectly predict individuals' behaviors.[1] Moreover, there is empirical evidence that social judgment shows temporal variations even in the absence of new information or social stimuli.[2,3] When building a psychologically plausible model of the mind, it should also be remembered that information processed in the brain is often incomplete, and full of fuzzy notions as well as contradictory statements. We present a neural model which (1) explains hesitation as an emergent property of a complex dynamic structure of information stored/processed in working memory (WM), (2) copes with fuzzy, incomplete, and contradictory data, and (3) is formulated in terms of a "society of mind"[4] and "memes." Since the usefulness of a cognitive model depends on the possibilities of its implementation, we consider its implementation as a large-scale neural network to be evolved in a cellular automata in the framework of ATR's CAM-brain project.[5]

Our *working memory* (WM) allows us to keep five to nine chunks of information active for a few seconds. It may play a key role in higher cognitive processes regulating the flow of information during categorization, planning, reasoning, problem solving, etc.[6] In the ACT-R (seemingly the best elaborated cognitive model) WM is a "blackboard" from which productions read information and to which they write conclusions.[7] In Tulving's taxonomy of memory systems,[8] WM works in parallel and seems to integrate information stored in four other types of memories. Buller[9] proposed the "4 + 1 memory model," which is considered as the target structure of an artificial brain being built in the framework of ATR's CAM-brain project.[10]

A *fuzziness* of notions seems to be a natural consequence of the way we categorize perceived objects. As Eleanor Rosch[11] experimentally confirmed, people judge objects to be members of a particular category to different degrees. This observation fits well with the earlier concept of fuzzy sets.[12] In order to employ the notion of fuzzy sets in large-scale brain-like neural networks, a nonsymbolic representation of fuzziness has been proposed.[13,14] One of the recent solutions employs a frequency-based representation of fuzzy notions, and assumes the possibility that in the working memory contradictory statements may coexist.[15,16]

A *meme* (a term coined by Richard Dawkins), according to Plotkin[17] (p. 251), is a unit of cultural heredity analogous to a gene. Brodie[18] sees a meme as a unit of information in a mind whose existence influences events in such a way that more copies of itself get created in other minds. In order to avoid confusing memes with their expressions, Buller[19] defines memes as "units of cerebral code representing signals, or words, or sentences, or rules, or plans, or feelings, or verbal or non-verbal ideas, which interact with each other in a course analogous to genetic interactions." Such a view of memes provides a united framework for a synthesis of a model of the mind seen as a society of interacting agents (cf Minsky[4]), which is compatible with Calvin's proposal of a hexagon-based neural workspace in which populations of memes grow and fight for domination in the workspace.[20]

## Modular working memory

In the model of a mind discussed in this paper, WM is a space inhabited by a society of memes representing feelings, judgments, and plans. The memes navigate all over the space. When two memes meet, they may interact. Meme interaction consists of an exchange of parts of their informational contents in a way resembling genetic crossover. As we show, such interactions can explain an individual's hesitation in the face of the need to make a decision in a specific social situation.

### An example of social behavior

Let us consider a subject who is determined to follow the rule: "I can have a date only with a person who is nice and rich." The rule can take the form "I can have a date with X, if X is nice and X is rich." Now let us assume that the subject meets somebody who proposes a date, but there are no visible clues about the richness or poverty of that person, while, according to the subject's criteria, only 60% of the features taken into account let the date proponent be labeled "nice." The subject hesitates. "To agree or not to agree?" The roots of the phenomenon still remain an open question. The cognitive model enables us to explain this in terms of meme interaction.

Let us assume that in response to cues causing contradictory conclusions, the sensorium of the subject, in cooperation with the subject's semantic memory, produces streams of memes representing contradictory data and directs them to WM. Since the level of the date proponent's "nicety" is 60%, the number of memes representing the assertion "[the date proponent is] nice" and arriving at WM in a certain period of time will be 1.5 times greater than the number of memes representing the assertion "[the date proponent is] not nice" arriving within the same period of time. The lack of clues about the date proponent's richness or poverty causes equal streams of memes representing the assertions "[the date proponent is] rich" and "[the date proponent is] not rich." Gradually, WM becomes full of contradictory memes.

### Meme interaction

Let us imagine WM as a workspace resembling a honeycomb, i.e., a structure consisting of hexagonal tiles. Let us assume that each meme can, by jumping from one tile to another, navigate all over the workspace. Let us consider a simple model in which only three memes can occupy a single tile, and assume the rule of meme traffic is such that all meme movement vectors must have nonzero positive horizontal projection. Memes that meet in a cell interact. The interaction is equal to an elastic collision with a possible exchange of informational content.

Every meme is a pair of patterns, denoted here as characters. If the second character is **O** (empty), the meme contributes to the awareness of a fact. A nonempty second character is a condition making the meme a contribution to a rule in which the first character is a conclusion. Let us assume that **R|O** = "rich," **r|O** = "not rich," **N|O** = "nice," **n|O** = "not nice," **A|N** = "agree [to the date] if [the date proponent] is nice," and **A|R** = "agree [to the date] if [the date proponent] is rich." The most important kind of interaction is local production: a navigating meme, contributing to the awareness of a fact, meets a meme contributing to a related rule, matches it, and then, as a result of the union, a meme contributing to the awareness of a new fact is born. For example, **R|O** meets **A|R**, matches it, and the meme **A|O** appears (Fig. 1). The interaction is equal to an exchange of single characters, which resembles genetic crossing-over. A meeting of **A|R** (a meme contributing to a rule) with **r|O** (a meme contributing to the awareness of the

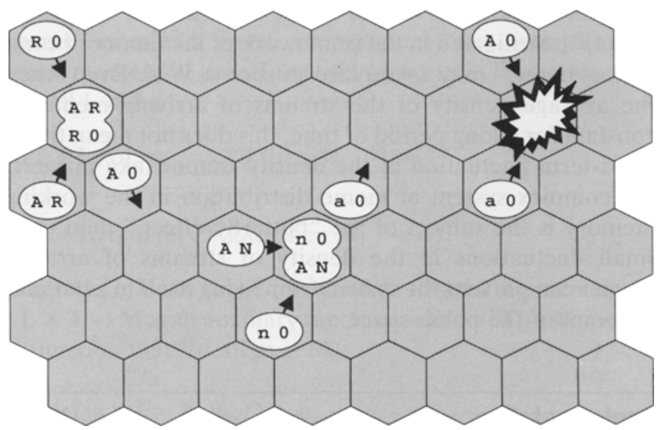


**Fig. 1.** Meme interaction in a tile-based working memory. The meme **R|O** ("rich") meets the meme **A|R** ("agree [to the date] if [the date proponent] is rich"), matches it, and the meme **A|O** ("agree!") appears. A meeting of **A|N** ("agree if nice") with **nO** ("not nice") results in the appearance of the meme **a|O** ("don't agree"). When contradictory memes **A|O** ("agree") and **a|O** ("don't agree") meet, they cancel each other out

fact "not rich") results in an immediate appearance of the resulting meme **a**|**O** ("don't agree"). When memes contributing to contradictory facts, such as, for example, **A**|**O** ("agree") and **a**|**O** ("don't agree"), meet, they cancel each other out. Since the same thing happens at the same moment at several places in WM, and memes contributing to particular facts and rules exist in multiple copies, WM becomes a "war theater" in which the populations of memes contributing to contradictory feelings, judgments, and plans fight for domination.

### Plan generation and decision making

The idea of WM presented seems to be suitable as an explanation of how people work out their plans. In a simplified model, a three-character meme may represent a three-step plan. From a small set of randomly generated sequences, through meme interactions, a population of best plans may dominate WM. To implement this, an external evaluating device (based on a model, an environment, and a simulation of its changes when a given plan is executed) has been suggested.[21]

The final decision of the individual is based on changes of the state of WM for a certain period of time. The state is assumed to be a point ($y$, d$y$) located in a 2D phase-space, where $y$ is the percentage of memes contributing to a given resulting statement ⟨Q⟩ amongst memes contributing to the statement either ⟨Q⟩ or ⟨not Q⟩, while d$y$ is assumed to be $y(t) - y(t\text{-}1)$. A simulation of the process shows that the state, depending on the perceived data, goes to an appropriate attractor. In typical situations, the attractor is either the point (0, 0) or the point (100, 0). However, it has been observed that in some cases the state goes to a two-focal "strange attractor," which means that the agent "hesitates" about what to do.[15] Figure B1 in Appendix B shows three typical plots of $y(t)$.

Why, even in the case of a constant average density of meme streams arriving at the modeled WM, does the modeled mind hesitate? Buller[19] suggests that the "butterfly effect," investigated in the framework of the theory of complex systems,[22] may take place in such a WM. Even when the average density of the streams of arriving memes is constant for a long period of time, this does not mean that a short-term fluctuation in the density cannot take place. If the complex system of meme distribution in the working memory is the subject of the "butterfly effect," then even small fluctuations in the density of streams of arriving memes can prevent the system from fixing itself in a particular point of the phase space.

## Implementation

Vast computational power is necessary to build a full working space for the society of memes. Such power can be attained by the CoDi ("collect and distribute") technique combining neural engineering with genetic programming and a cellular automata paradigm.[23] Every tile of WM can be implemented as a circuit consisting of one or more CoDi modules.

A CoDi module is a cube consisting of 24 × 24 × 24 3D cellular automata cells. A chromosome containing growth instructions is used to grow a neural network inside the module, which means that some of the cells form neuron bodies, dendrites, and axons. 1-bit signals are collected by dendritic cells and directed to a relevant neuron-body cell. When certain conditions are satisfied, a 1-bit signal is generated and, using axons, delivered to other neurons. Up to 1152 neurons may be grown inside a single CoDi module.

Desired CoDi modules can be obtained by using a genetic algorithm. A special purpose-built supercomputer "CBM" (cellular [automata-based] brain machine) is being built in the framework of ATR's CAM-brain project.[5,24] The CBM should update a 64640-module structure about 150 times a second, which will provide sufficient computational power to control a life-sized animal in real time, as well as several types of memory model.[25] In order to implement a tile-based WM on the CBM, a hierarchy of CoDi modules has been designed to facilitate meme movement, as well as meme interactions.[16]

## Concluding remarks

We have proposed a model of human working memory (WM) as a geometric space populated by a "society" of memes. The results of a computer simulation of processes in WM show that a "debate" in the society of memes can be equal to a massively parallel fuzzy inferencing from contradictory statements. We argue that the phenomenon of hesitation observed during the simulation of this process is the "butterfly effect" observed in other complex systems. If the idea is close to a correct model of the human mind, it must be taken into account that artificial brain-like systems, built using such equipment as the CBM described herein, may also demonstrate limited predictability. Their social judgments and decisions may appear in their working memories as emergent phenomena with their intrinsic dynamics.

## Appendix A

### Formal description of the model of working memory

Let **S** = {∅, **N**, **n**, **R**, **r**, **A**, **a**} be the set of selected basic notions, where ∅ is an *empty set*, **N** represents *niceness*, **n** represents *nonniceness*, **R** represents *richness*, **r** represents *nonrichness*, **A** represents *agreement*, and **a** represents *nonagreement*. Let us also introduce the operator of negation "¬" that works such that ¬**N** = **n**, ¬**R** = **r**, and ¬**A** = **a**.

Let $\mathbf{M}_0$ = {∅|∅, **N**|∅, **n**|∅, **R**|∅, **r**|∅, **A**|**N**, **A**|**R**}, where ∅|∅ is an *empty meme*, and $\mathbf{M}_0$ is the set of types of *meme* arriving at working memory. Let us assume that **N**|∅ means

**Table A1.** The values of the meme interaction function Ψ(g,h)

| g | h | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | ∅\|∅ | **N**\|∅ | **n**\|∅ | **R**\|∅ | **r**\|∅ | **A\|N** | **A\|R** | **A**\|∅ | **a**\|∅ |
| ∅\|∅ | ∅\|∅ | ∅\|∅ | ∅\|∅ | ∅\|∅ | ∅\|∅ | ∅\|∅ | ∅\|∅ | ∅\|∅ | ∅\|∅ |
| **N**\|∅ | **N**\|∅ | **N**\|∅ | ∅\|∅ | **N**\|∅ | **N**\|∅ | ∅\|∅ | **N**\|∅ | **N**\|∅ | **N**\|∅ |
| **n**\|∅ | **n**\|∅ | ∅\|∅ | **n**\|∅ | **n**\|∅ | **n**\|∅ | ∅\|∅ | **n**\|∅ | **n**\|∅ | **n**\|∅ |
| **R**\|∅ | **R**\|∅ | **R**\|∅ | **R**\|∅ | **R**\|∅ | ∅\|∅ | **R**\|∅ | ∅\|∅ | **R**\|∅ | **R**\|∅ |
| **r**\|∅ | **r**\|∅ | **r**\|∅ | **r**\|∅ | ∅\|∅ | **r**\|∅ | **r**\|∅ | ∅\|∅ | **r**\|∅ | **r**\|∅ |
| **A\|N** | **A\|N** | **A**\|∅ | **a**\|∅ | **A\|N** | **A\|N** | **A\|N** | **A\|N** | **A\|N** | **A\|N** |
| **A\|R** | **A\|R** | **A\|R** | **A\|R** | **A**\|∅ | **a**\|∅ | **A\|R** | **A\|R** | **A\|R** | **A\|R** |
| **A**\|∅ | **A**\|∅ | **A**\|∅ | **A**\|∅ | **A**\|∅ | **A**\|∅ | **A**\|∅ | **A**\|∅ | **A**\|∅ | ∅\|∅ |
| **a**\|∅ | **a**\|∅ | **a**\|∅ | **a**\|∅ | **a**\|∅ | **a**\|∅ | **a**\|∅ | **a**\|∅ | ∅\|∅ | **a**\|∅ |

**Table A2.** The values of the function $m$, where: p = $M_{\varphi p,\lambda p,2,t-1}$, q = $M_{\varphi q,\lambda q,1,t-1}$, r = $M_{\varphi r,\lambda r,0,t-1}$; $\varphi p = (\varphi + \varphi_{max}) \bmod \varphi_{max} + 1$, $\varphi q = \varphi$, $\varphi r = (\varphi + 1) \bmod \varphi_{max} + 1$; $\lambda q = (\lambda + \lambda_{max}) \bmod \lambda_{max} + 1$; if $\varphi \bmod 2 \neq 0$ then $\lambda p = \lambda r = \lambda$; if $\varphi \bmod 2 = 0$ then $\lambda p = \lambda r = (\lambda + \lambda_{max}) \bmod \lambda_{max} + 1$

| p ≠ ∅\|∅ | q ≠ ∅\|∅ | r ≠ ∅\|∅ | $m_{\varphi,\lambda,0,t}$ | $m_{\varphi,\lambda,1,t}$ | $m_{\varphi,\lambda,2,t}$ |
|---|---|---|---|---|---|
| 0 | 0 | 0 | ∅\|∅ | ∅\|∅ | ∅\|∅ |
| 0 | 1 | 0 | ∅\|∅ | q | ∅\|∅ |
| 0 | 0 | 1 | r | ∅\|∅ | ∅\|∅ |
| 0 | 1 | 1 | ∅\|∅ | Ψ(q, r) | Ψ(r, q) |
| 1 | 0 | 0 | ∅\|∅ | ∅\|∅ | p |
| 1 | 1 | 0 | Ψ(p, q) | Ψ(q, p) | ∅\|∅ |
| 1 | 0 | 1 | Ψ(p, r) | ∅\|∅ | Ψ(r, p) |
| 1 | 1 | 1 | Ψ(p, r) | q | Ψ(r, p) |

"[the date proponent is] **nice!**," **n**|∅ means "[the date proponent is] **not nice!**," **R**|∅ means "[the date proponent is] **rich!**," **r**|∅ means "[the date proponent is] **not rich!**," **A|N** means "**agree** [to the date **if** the date proponent is] **nice!**," **A|R** means "**agree** [to the date **if** the date proponent is] **rich!**." As a result of meme interactions, the memes **A**|∅ and **a**|∅ will appear in working memory. **A**|∅ means "**agree!**," while **a**|∅ means "**don't agree!**."

Let $\mathbf{M} = \mathbf{M}_0 \cup \{A|\varnothing, a|\varnothing\}$, where A|∅ and a|∅ are memes that appear as a result of meme interactions in working memory. Meme interactions are determined by the meme interaction function $\Psi \mid \mathbf{M}^2 \to \mathbf{M}$ that returns the values given in Table A1.

The functions $\mu, \eta \mid \mathbf{M}_0 \to [0; 1]$ regulate the distribution of particular types of meme in the stream of memes flowing into working memory. Hence, the pair $\langle \mu, \eta \rangle$ plays the role of a *control parameter* of working memory understood as a dynamic system. The values of μ, η for particular types of meme are input data to the model discussed. The output data are the function $y \mid \mathbf{T} \to [0; 1]$ that, for a given moment $t \in \mathbf{T}$, returns the *order parameter*, which is a real number equal to $N(\mathbf{A}|\varnothing, t)/(N(\mathbf{A}|\varnothing, t) + N(\mathbf{a}|\varnothing, t))$, where $N(meme, t)$ is the number of copies of *meme* in working memory at the moment $t$, while $\mathbf{T}$ is the space of integers representing moments in time.

The set of cells constituting the model of working memory discussed is represented by the set $\mathbf{L}$ such that

$$\mathbf{L} = \left\{(\varphi,\lambda,\delta) \in \mathbf{I} \,\middle|\, 0 \leq \varphi \leq \varphi_{max}, 0 \leq \lambda \leq \lambda_{max}, 0 \leq \delta \leq 2\right\}$$

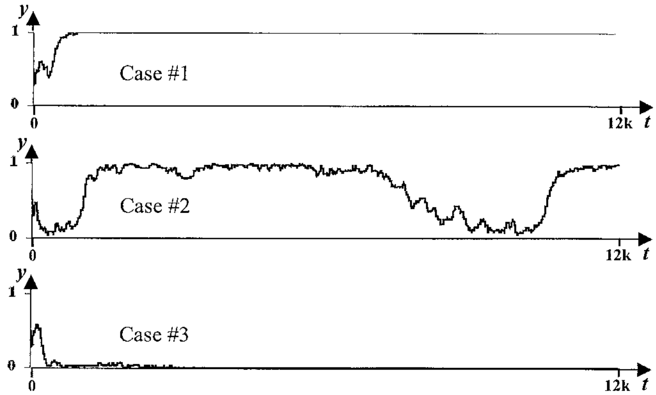


**Fig. B1.** Three plots of the *order parameters* (function ***y*** to be interpreted as the degree of the simulated subject's determination to agree to a date). In case 1, both criteria considered are met by the date proponent. In case 3, no criteria considered are met by the date proponent. In case 2, one criterion is met, while the second one is not. The dynamics of the simulated judgment is in agreement with the data obtained during the experiments with human subjects

where $\mathbf{I}$ is the space of integers, (φ, λ) is the location of a given tile, while δ is the location of a compartment inside a given tile. The function $M \mid \mathbf{L} \times \mathbf{T} \to \mathbf{M}$ determines which meme occupies a given compartment of a given tile in a given moment of time. Function $M$ works in such a way that for all $L \in \mathbf{L}_0$,

$$\text{if } L \notin \mathbf{L}_0 \text{ or } m_{L,t} \neq \varnothing|\varnothing \text{ then } M_{L,t} = m_{L,t}$$

$$\text{if } L \in \mathbf{L}_0 \text{ and } m_{L,t} = \varnothing|\varnothing \text{ then } M_{L,t} = \nu(t)$$

where $\mathbf{L}_0 \subseteq \mathbf{L}$ is a set of input points to working memory, $m \mid \mathbf{L} \times \mathbf{T} \to \mathbf{M}$ is an auxiliary function, while $\nu \mid \mathbf{T} \to \mathbf{M}_0$ is such a function that for all $\mathbf{m} \in \mathbf{M}_0$,

$$P(\nu(t) = \mathbf{m}) = \eta_{\mathbf{m}}\mu_{\mathbf{m}} / \sum_{\mathbf{m} \in \mathbf{M}_0} \eta_{\mathbf{m}}\mu_{\mathbf{m}}$$

where for all Z, $P(Z)$ is the probability of Z.

Function $m$ returns the values given in the Table A2.

**Table B1.** Input data for the simulation experiment with the model of working memory discussed. The meaning of the symbols used is described in Appendix A

| | | m | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | ∅\|∅ | N\|∅ | n\|∅ | R\|∅ | r\|∅ | A\|N | A\|R |
| Case 1 | $\mu_m$ | 0.00 | 0.55 | 0.45 | 0.55 | 0.45 | 1.00 | 1.00 |
| | $\eta_m$ | 0.00 | 0.67 | 0.67 | 0.67 | 0.67 | 0.20 | 0.20 |
| Case 2 | $\mu_m$ | 0.00 | 0.60 | 0.40 | 0.40 | 0.60 | 1.00 | 1.00 |
| | $\eta_m$ | 0.00 | 0.67 | 0.67 | 0.67 | 0.67 | 0.20 | 0.20 |
| Case 3 | $\mu_m$ | 0.00 | 0.45 | 0.55 | 0.45 | 0.55 | 1.00 | 1.00 |
| | $\eta_m$ | 0.00 | 0.67 | 0.67 | 0.67 | 0.67 | 0.20 | 0.20 |

## Appendix B

Simulation experiments on the model of working memory

Three simulations have been run. The input data (elements of the *control parameters*) for the three cases are given in Table B1. The values obtained for output function $y$ (*order parameters*) are shown in Fig. B1.

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