A Layered Reference Model of the Brain (LRMB)

Yingxu Wang, *Senior Member, IEEE*, Ying Wang, Shushma Patel, and Dilip Patel

***Abstract*—A variety of life functions and cognitive processes (CPs) have been identified in cognitive informatics, psychology, cognitive science, and neurophilosophy. This paper attempts to develop a layered reference model of the brain (LRMB) that formally and rigorously explains the functional mechanisms and CPs of natural intelligence. A comprehensive and coherent set of mental processes and their relationships is identified in LRMB that encompasses 37 CPs at six layers known as the sensation, memory, perception, action, metacognitive, and higher cognitive layers from the bottom-up. The LRMB reference model provides an integrated framework for modeling the brain and the mind. LRMB also enables future extension and refinement of the CPs within the same hierarchical framework. LRMB can be applied to explain a wide range of physiological, psychological, and cognitive phenomena in cognitive informatics, particularly the relationships and interactions between the inherited and the acquired life functions, as well as those of the subconscious and conscious CPs.**

***Index Terms*—Autonomic computing, cognitive informatics, cognitive processes (CPs), natural intelligence (NI), neuropsychology, reference model, the brain.**

I. Introduction

COGNITIVE informatics [15], [16], [18] is an emerging discipline that studies the internal information processing mechanisms and cognitive processes (CPs) of the natural intelligence (NI)—human brains and minds. The field uses informatics and computing theories to investigate the problem of cognitive psychology and neurosciences, in particular, mechanisms of the NI and CPs of the brain. It is recognized that, although a wide variety of life functions have been identified in related fields [5], [6], [8], [10], [12], [20], they can be treated and described as instances of a finite set of fundamental CPs of the brain [15], [16], [18]. In order to formally and rigorously describe a comprehensive set of mental processes and their relationships, a hierarchical and integrated reference model of the brain is required.

In [21], a cognitive model of the brain was developed to reveal the mechanisms and processes of the brain and their relationships between the inherited and the acquired life functions. For formally describing the life functions of the brain and the CPs of the mind, this paper develops a layered reference model of the brain (LRMB) which consists of six layers of CPs known as the sensation, memory, perception, action, metacognitive, and higher cognitive layers from the bottom-up. In this paper, Section II presents the six layers and their relationships in the reference model of the brain. Section III describes the 37 CPs performing at each layer of the reference model. Section IV discusses interactions between the layers of the CPs of the reference model in the context that treats the brain as an autonomic real-time intelligent system.

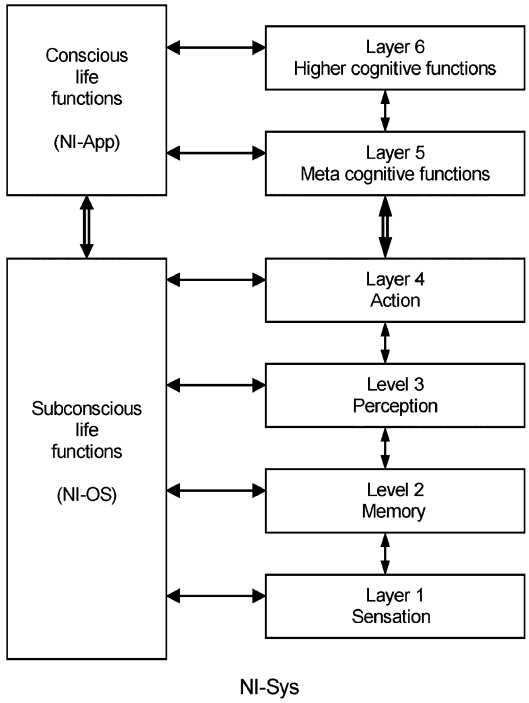

Fig. 1. Layered reference model of the brain (LRMB).

II. Layered Reference Model of the Brain

This section develops the cognitive model of NI by studying relationships between the inherited and acquired life functions and between the memory components of the brain, such as the long-term, short-term, sensory buffer, and action buffer [30] memories.

The hierarchical life functions of the brain as a natural intelligent system (NI-Sys) can be divided into two categories: the subconscious and conscious life functions. The former known as the NI operating system (NI-OS) encompasses the layers of sensation, memory, perception, and action (Layers 1 to 4). The latter known as the NI applications (NI-App) includes the layers of meta- and higher cognitive functions (Layers 5 and 6). According to this classification, an LRMB can be described as shown in Fig. 1. In the LRMB model, cross layer

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Y. Wang is with the Theoretical and Empirical Software Engineering Research Center, University of Calgary, Calgary, AB T2N 1N4, Canada (e-mail: Yingxu@ucalgary.ca).

Y. Wang is with the Fourth City Hospital, Xian, Shaanxi 710004, China (e-mail: wang-ying1@hotmail.com).

S. Patel and D. Patel are with the School of Computing, Information Systems and Mathematics, South Bank University, London SE1 0AA, U.K. (e-mail: Shushma@sbu.ac.uk; dilip@sbu.ac.uk).

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TABLE I
CLASSIFICATION OF CPS IN THE LRMB REFERENCE MODEL

Subconscious Processes		Conscious Processes	
Layer 1	**Layers 2-4**	**Layer 5**	**Layer 6**
Sensational cognitive processes	**Subconscious cognitive processes**	**Meta cognitive processes**	**Higher cognitive processes**
1.1 Vision	2. Memory	5.1 Attention	6.1 Recognition
1.2 Audition	3. Perception	5.2 Concept establishment	6.2 Imagery
1.3 Smell	3.1 Self-consciousness	5.3 Abstraction	6.3 Comprehension
1.4 Tactility	3.2 Motivation	5.4 Search	6.4 Learning
- Heat	3.3 Willingness	5.5 Categorization	6.5 Reasoning
- Pressure	3.4 Goal setting	5.6 Memorization	6.6 Deduction
- Weight	3.5 Emotions	5.7 Knowledge representation	6.7 Induction
- Pain	3.6 Sense of spatiality		6.8 Decision making
- Texture	3.7 Sense of motion		6.9 Problem solving
1.5 Taste			6.10 Explanation
- Salt	4. Actions		6.11 Analysis
- Sweet			6.12 Synthesis
- Bitter			6.13 Creation
- Sour			6.14 Analogy
- Pungency			6.15 Planning
			6.16 Quantification

communications are allowed, which are denoted by the horizontal arrows.

In LRMB, the subconscious layers of the brain (NI-OS) are inherited, fixed, and relatively mature when a person is born. Therefore, the subconscious function layers are usually neither directly controllable nor intentionally accessible by the conscious life function layers. This is why it is called nonconscious life functions in psychology [8], [10], [23].

Contrary to the subconscious NI-OS, the conscious layers of the brain (NI-App) are acquired, highly plastic, programmable, and can be controlled intentionally based on willingnesses, goals, and motivations. Note that there are gray areas in the classification of a given CPs as conscious or subconscious life functions. For instance, as shown in Table I, the conscious part of the memory process is classified as at Layer 5, while the subconscious part of it is at Layer 2. More generally, a daily life function of the brain is conducted as a concurrent and parallel combination of multiple routine CPs at almost all layers.

A formal description of the high-level architecture of the LRMB model, using real-time process algebra (RTPA) [17], [21] is presented in Fig. 2. RTPA is developed for rigorously describing architectures and behaviors of the natural and machine intelligences [20]. Because the syntaxes and semantics of RTPA are well defined and supported by simulation tools, the brain model and detailed CPs specified in RTPA are enabled to be simulated and executed on computers.

Definitions of each layer in LRMB are given below. Detailed description of individual layers of LRMB in RTPA is provided in Section III.

The Layered Reference Model of the Brain (LRMB)

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§LRMB ≙ §NI_Sys            // The Natural Intelligent system
      = NI_OS  // The subconscious NI operating system
        || NI_App          // The conscious NI applications
      = ( Layer1_Sensation
          || Layer2_Memory
          || Layer3_Perception
          || Layer4_Action
        )
        || ( Layer5_Meta_Cognitive_Functions
             || Layer6_Higher_Cogntive_Functions
           )
```

Fig. 2. Formal description of the overall structure of LRMB.

A. Layer 1: The Sensation Layer of LRMB

Definition 1: The *sensation layer* of LRMB is a subconscious layer of life functions of the brain for detecting and acquiring cognitive information from the external world via physical and/or chemical means.

The sensation layer encompasses all input-oriented senses such as vision, audition, smell, tactility, and taste. Corresponding to the sensation layer of life functions, the sensory buffer memory (SBM) is a set of input-oriented temporary memory, which is located at the memory layer of the reference model. The logical model of SBM is a set of parallel queues corresponding to each of the sensors of the brain [21].

B. Layer 2: The Memory Layer of LRMB

Definition 2: The *memory layer* of LRMB is the fundamental layer of life functions of the brain: 1) to retain and store information about both the external and internal worlds; 2) to maintain a stable state of an animate system; 3) to provide a working space of abstract inference; and 4) to buffer programmed actions and motions to be executed by the body.

It is recognized that the NI is memory-based [15], [18], [21]. The memory layer is a part of the subconscious life functions. The memory layer encompasses the following types of memories [1], [4], [13], [21]:

1) the sensory buffer memory (SBM);
2) the short-term memory (STM);
3) the long-term memory (LTM);
4) the action buffer memory (ABM),where the ABM is originally identified and modeled by Wang [15], [21].

The major organ that accommodates memories in the brain is the cerebrum or the cerebral cortex [7], [12], [21]. In [21], the relations between memories and their corresponding parts in the cerebral cortex and lobes are established. The LTM, as the key memory of the brain, is mainly located at the association cortex in the frontal lobe of cerebrum. The logical and cognitive models of the memories are explained in Section IV.

C. Layer 3: The Perception Layer of LRMB

Definition 3: The *perception layer* of LRMB is a subconscious layer of life functions of the brain for maintaining conscious life functions and for browsing internal abstract memories in the cognitive models of the brain.

The cognitive functions of the perception layer can be considered as the thinking engine of the brain and the kernel of the NI. Perception may also be considered as the sixth sense, supplementary to the five external sensations at Layer 1, known as vision, audition, smell, tactility, and taste, which implements self consciousness inside the abstract memories of the brain.

The perception layer is a core part of the subconscious life functions. The perception layer is the internal sensory layer that encompasses the CPs of self-consciousness, motivation, willingness, goal setting, emotions, sense of spatiality, and sense of motion.

D. Layer 4: The Action Layer of LRMB

Definition 4: The *action layer* of LRMB is a subconscious layer of life functions of the brain for output-oriented actions and motions that implement human behaviors, such as a sequence of movement and a preprepared verbal sentence.

The action layer is a part of the subconscious life functions. The action layer encompasses all motor control and execution functions such as looking, reading, and writing.

Supplementary to the input-oriented SBM, the ABM is an output-oriented temporary memory [15], [21]. The functional model of ABM is a set of parallel queues, each of them represents a sequence of actions or a process. Both the action and the sensation layers form a closed-loop for implementing various life functions, particularly the cognitive life functions at the conscious layers.

E. Layer 5: The Meta-CPs Layer of LRMB

Definition 5: The *meta-CP layer* of LRMB is a conscious layer of life functions of the brain that carries out the fundamental and elementary CPs commonly used in higher CPs.

The meta-CP layer is a part of the conscious life functions that can be controlled directly by the conscious mind (or the thinking engine) as mental applications. The meta-CP layer encompasses the basic processes of attention, concept establishment, abstraction, search, categorization, memorization, and knowledge representation.

F. Layer 6: The Higher Cognitive Functions Layer of LRMB

Definition 6: The *higher cognitive functions layer* of LRMB is a conscious layer of life functions of the brain that carries out a set of specific CPs under the support of the meta CPs.

The higher CP layer is a part of the conscious life functions. This layer encompasses 16 CPs, such as recognition, imagery, learning, reasoning, and problem solving, as shown in Table I.

More complicated and diversified life functions can be implemented by the serial, parallel, interleaved, and/or concurrent combinations of these fundamental CPs in LRMB. That is, complex and instant intelligent behaviors of the brain and mind can be reduced to the combinations of the six-layer CPs, as modeled in LRMB. Therefore, LRMB may be used as a unified framework to explain a wide range of cognitive and psychological phenomena of the NI.

III. Description of the CPs in the LRMB Reference Model

According to the LRMB reference model as described in Section II, detailed cognitive life functions interacting between the subconscious and conscious layers can be categorized as shown in Table I.

In cognitive informatics, it is a great curiosity to explore the insides of the brain and to explain its basic mechanisms by a set of CPs as identified and categorized in Table I. This section defines and describes the CPs of the LRMB and the scope of each process. More rigorous and detailed descriptions of these CPs of the reference model may be referred to specific reports [19], [20], [22].

A. Sensational CPs

Definition 7: A *sensational CP* of the brain is a subconscious life function that forms the interfaces between the internal and external worlds for information detection, acquisition, and input into the brain.

Sensations are mental states caused by the stimulation of sensory organs affected by matter or energy and their changes of states. The sensational CPs at Layer 1 of LRMB encompass the basic cognitive life functions of vision, audition, smell, tactility, and taste. A formal description of the Layer 1 CPs is shown in Fig. 3, where $\|$ denotes a parallel relation between two or more processes. In Fig. 3, tactility can be further divided into senses of heat, pressure, weight, pain, and texture; and taste can be categorized as that of salty, sweet, bitter, sour, and pungency. Note that in the following sections, a label "Definition $x \cdot y$" indicates the layer number x and process number y corresponding to the sequence numbers as shown in Table I.

Definition 1.1: Vision is a sensational CP of the brain at the sensation layer that detects and receives visual information from entities of the external world in the forms of images, shapes, sizes, colors, and other attributes or characteristics.

Definition 1.2: Audition is a sensational CP of the brain at the sensation layer that detects and receives aural information from sources of the external world in the forms of intensity, frequency, location, and other attributes and characteristics.

Definition 1.3: Smell is a sensational CP of the brain at the sensation layer that detects and receives scent by the olfactory nerves from sources of the external world.

Definition 1.4: Tactility is a set of sensational CPs of the brain at the sensation layer that detects and receives touching information by the contact between an external object and a part of the body surface in the forms of heat, pressure, weight, pain, and texture.

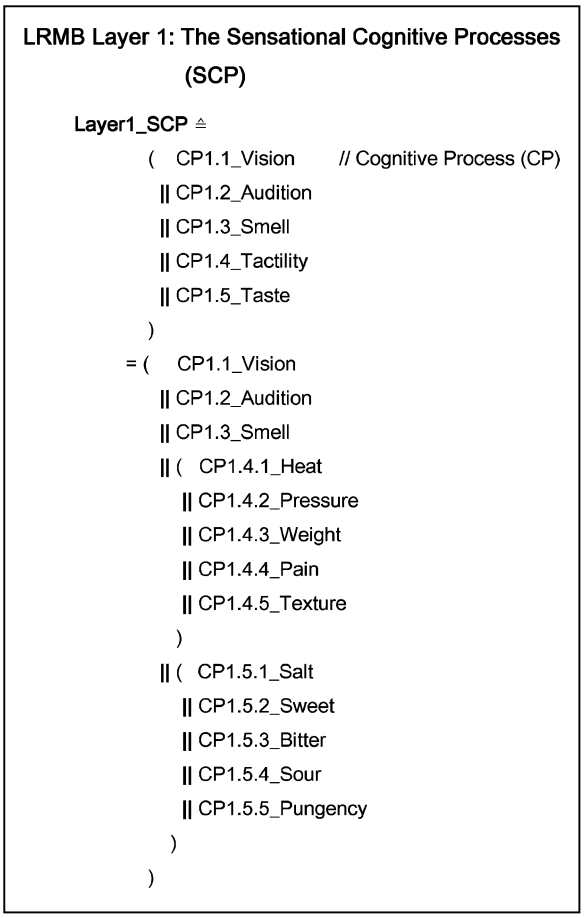

Fig. 3. Cognitive processes at the sensational layer of LRMB.

Definition 1.5: Taste is a set of sensational CP of the brain at the sensation layer that detects and receives flavor information, such as salty, sweet, bitter, sour, and pungent, via the taste buds from sources of the external world.

The above five categories of senses of the brain are external and oriented to the physical world. In addition to them, there is an internal and the abstract world-oriented sense in the brain known as the sense of perception, which is described in Section III-B2.

B. Subconscious CPs

Definition 8: A *subconscious CP* of the brain is a subconscious life function that fully or partially operates without intervention or awareness of the intended and conscious cognitive functions.

The subconscious CPs as described at Layers 2 to 4 of LRMB encompass the basic cognitive life functions of memory, perception, and action as formally described in Fig. 4.

Definition 9: Memory is a set of subconscious CPs of the brain at the subconscious cognitive function layers that retains the external or internal cognitive information in various memories of the brain, particularly in LTM.

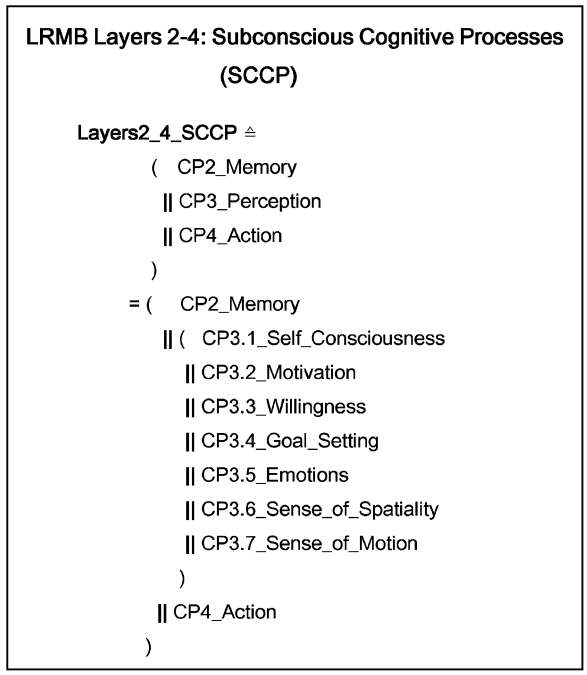

Fig. 4. Cognitive processes at the subconscious layers of LRMB.

The memory layer is the fundamental layer of life functions of the brain for maintaining a stable state of an animate system. The major means of interaction between the conscious and the subconscious layers of LRMB are all forms of memories and the information retained in them.

Definition 10: Perception is a set of internal sensational CPs of the brain at the subconscious cognitive function layers that detects, relates, interprets, and searches internal cognitive information in the mind.

The cognitive functions of perception encompass self-consciousness, motivation, willingness, goals, emotions, and senses of spatiality and motion. Perception may be considered as the sixth sense of human beings, which almost all cognitive life functions rely on. Perception is also an important cognitive function at the subconscious layers that determines personality. In other words, personality is a faculty of all subconscious life functions and experience cumulated via conscious life functions.

Definition 3.1: Self-consciousness is a CP of the brain at the perception layer that maintains a stable mental state of human beings for sensation, perception, occurrent thought, and actions to function properly.

A fundamental question in cognitive psychology is how consciousness can be the product of physiological processes in our brains. The classification of self-consciousness as a subconscious process, or an operating system (NI-OS) level life function, helps to answer the question [21]. It is based on the observations that self-consciousness is inherited when a person is born and it has already been relatively mature before a person's conscious life experience begins.

Definition 3.2: Motivation is a CP of the brain at the perception layer that explains the initiation, persistence, and intensity of CPs.

Motivation is a modulating and coordinating influence on the direction, vigor, and composition of behavior. This influence arises from a wide variety of internal, environmental, and social sources and is manifested at many levels of behavioral and neural organizations.

Definition 3.3: Willingness is a CP of the brain at the perception layer that is the faculty of conscious, deliberate, and voluntary choices of actions.

Definition 3.4: Goal setting is a CP of the brain at the perception layer that establishes a desired and valued outcome for a motivation or an action.

Definition 3.5: Emotions are a set of states or results of perception that interpret the feelings of human beings on external stimuli or events in the categories of pleasant or unpleasant, such as joy/worry, happiness/sadness, safety/fear, and pleasure/angry.

An organ known as the *hypothalamus* in the brain is supposed to subconsciously interpret the properties or types of an external event or stimulus in terms of pleasant or unpleasant [7]. Sometimes the same event or stimulus may be explained in different types due to the real-time context of the perceptual status of the brain. For instance, the emotional phenomenon, angry, may be explained in some extent as a default or generic reaction for an emotional event when there was no better solution available.

Definition 3.6: Sense of spatiality is a CP of the brain at the perception layer that generates an abstract and internal sense of perception on spatiality and allows the brain to aware and assess the location of entities in space as one moves through the world in real time.

How the brain builds spatial representations and what the neural and cognitive mechanisms underlying them are have become a topic of great interest in cognitive informatics. Sensory and motor information may be used together to construct an internal representation of the space we perceive.

Definition 3.7: Sense of motion is a CP of the brain at the perception layer that generates an abstract and internal sense of perception on motion, detects and interprets status changes related to space and time of external objects or the observer himself in real time.

Perception of motion is crucial not only for predicting the future state of the dynamic environment, but also for providing a wealth of information about space-and time-related changes of objects.

Definition 11: Action is a set of subconscious CPs of the brain at the subconscious cognitive function layers that executes both bodily (external) and mental (internal) actions via the motor systems of the body or the perceptional engine of the brain.

It is noteworthy that there are mental perceptual actions inside the brain via the thinking engine of the mind. This observation is significant in explaining how perceptive and thinking processes are carried out in the abstract or information world of the brain.

LRMB Layer 5: Meta Cognitive Processes (MCP)

Layer5_MCP ≜
(CP5.1_Attention
|| CP5.2_Concept_Establishment
|| CP5.3_Abstarction
|| CP5.4_Search
|| CP5.5_Categorization
|| CP5.6_Memorization
|| CP5.7_Knowledge_Representation
)

Fig. 5. Cognitive processes at the metacognitive function layer of LRMB.

C. Metacognitive Functions

Definition 12: A *metacognitive function* of the brain is a fundamental and elemental life function of the brain that is commonly used (or called) to support the higher layer cognitive life functions.

The metacognitive functions at the Layer 5 of LRMB encompass the basic cognitive life functions of attention, concept establishment, abstraction, search, categorization, memorization, and knowledge representation as formally described in Fig. 5.

Definition 5.1: Attention is a meta-CP of the brain at the metacognitive layer that focuses the mind, or the perceptive thinking engine, on one of the objects or threads of thought by selective concentration of consciousness.

Contrary to the above voluntary or goal-oriented attention, there is stimuli-oriented attention that may be classified into a cognitive function at the perception layer.

Definition 5.2: Concept establishment is a meta-CP of the brain at the meta cognitive layer that constructs a "to be" relation between an object or its attributes and existing objects/attributes.

Concepts are used to construct propositional thought to interpret our current experience by classifying it as being of a particular kind relating to prior knowledge and to be a means of understanding the world. Concept establishment is a fundamental CP in developing knowledge representation systems.

Definition 5.3: Abstraction is a meta-CP of the brain at the meta cognitive layer that establishes an abstract model (or concept) for an entity of external world by eliciting the information of its common and qualitative/quantitative attributes or properties in order to mentally process it.

Abstraction is a powerful and fundamental mental function of human beings and most of the higher CPs of the brain are relied on it.

Definition 5.4: Search is a meta-CP of the brain at the metacognitive layer that is based on trial-and-error explorations to find a set of correlated objects, attributes, or relations for a given object or concept; or to find useful solutions for a given problem.

A search process may be systematic or nonsystematic. The former takes a global search strategy that guarantees to find an optimal solution if one exists. The latter is based on stochastic approaches that do not guarantee to find a solution.

Definition 5.5: Categorization is a meta-CP of the brain at the metacognitive layer that identifies common and equivalent attributes or properties shared among a group of entities or objects and then uses the common attributes or properties to identify this group of entities.

Categorization, or classification, is one of the most fundamental and pervasive CPs, because it enables reasoning to be carried out at a higher abstract level and permits predictions to be derived on the basis of common properties of a category of entities or phenomena. Categorization may be carried out subjectively and in an unlimited number of ways. Basic strategies of categorization are similar and coherent attributes identification.

Definition 5.6: Memorization is a meta-CP of the brain at the meta cognitive layer that encodes, stores, and retrieves information in LTM, partially controlled by the subconscious processes of sensation, memory, and perception.

The types of memory can be classified as STM, LTM, SBM, and ABM as defined in Section II-B. They can also be distinguished as semantic and episodic memory. The former refers to the stored knowledge of the world that underlies not only our capacity to understand language but also our ability to take advantage of prior knowledge in perceiving and organizing both the physical and information world around us. The latter is principally concerned with the laying down of new memory traces.

Definition 5.7: Knowledge representation is a meta-CP of the brain at the metacognitive layer that describes how information can be appropriately encoded and utilized in the cognitive models of the brain.

Knowledge representation focuses on both the representational formalism and the information to be encoded in it. The field of study on knowledge representation, known as knowledge engineering, attempts to identify an appropriate conceptual vocabulary and a set of coherent formal concepts called an ontology. The formalism encompasses a precisely defined syntax, useful semantics, and a tractable inference procedure that are based on first-order logic, semantic networks, Bayesian networks, or fuzzy reasoning.

D. Higher Cognitive Functions

Definition 13: A *higher cognitive function* is an advanced life function of the brain that is developed and acquired to carry out common cognitive life functions under the support of the meta cognitive life functions at Layer 5.

LRMB Layer 6: Higher Cognitive Processes (HCP)

Layer6_HCP ≜
(CP6.1_Recognition
|| CP6.2_Imagery
|| CP6.3_Comprehension
|| CP6.4_Learning
|| CP6.5_Reasoning
|| CP6.6_Deduction
|| CP6.7_Induction
|| CP6.8_Desision_Making
|| CP6.9_Problem_Solving
|| CP6.10_Explanation
|| CP6.11_Analysis
|| CP6.12_Synthesis
|| CP6.13_Creation
|| CP6.14_Analogy
|| CP6.15_Planning
|| CP6.16_Quantification
)

Fig. 6. Cognitive processes at the higher cognitive functions layer of LRMB.

The higher cognitive functions at Layer 6 of LRMB encompass recognition, imagery, comprehension, learning, reasoning, deduction, induction, decision making, problem solving, explanation, analysis, synthesis, creation, analogy, planning, and quantification as formally described in Fig. 6.

Definition 6.1: Recognition is a higher CP of the brain at the higher cognitive layer that identifies an object by relating it to a concept or category, or comprehends a concept by known meanings.

Object and word recognition are typical recognition processes related to knowledge representation, learning, perception, and memory. One of the major problems that must be solved in visual object recognition is the building of a representation of visual information that allows recognition to occur relatively independent of size, contrast, spatial frequency, position on the retina, and angle of view, etc.

Definition 6.2: Imagery is a higher CP of the brain at the higher cognitive layer that abstractly sees acquired visual images stored in the brain without any sensory input, or establishes a relation between a mental image and the corresponding external entities or events.

Imagery has played a central role in theories of the mind for centuries. The introspective dilemma on imagery is that there is no way to objectively verify what we see with our inner eye by imagination for the third party, and hence the phenomenon smacks of unscientific fanciful confabulation. Watson emphasized the precept that scientific phenomena must be publicly

observable, and imagery clearly is not. However, the mental phenomena and CPs are truly experienced by everybody everyday. Therefore, the sixth sense—perception and related CPs—should be recognized as a special exception occurring in the abstract and information world that does not obey the specific rules developed in the physical world [9], [16].

Definition 6.3: Comprehension is a higher CP of the brain at the higher cognitive layer that searches relations between a given object (O) or attribute (A) and other objects, attributes, and relations (R) in LTM, and establishes a representative OAR model [21] for the object or attribute by connecting it to appropriate clusters of the LTM.

Comprehension is the action or capability of understanding. In cognitive psychology, comprehension involves constructing an internal representation based on the existing knowledge previously gained in the brain [14], [29].

Definition 6.4: Learning is a higher CP of the brain at the higher cognitive layer that gains knowledge of something or acquires skills in some action or practice by updating the cognitive models of the brain in LTM.

The most significant result of learning is the change of the cognitive model in LTM. Learning also results in behavioral or capacity changes, while some of them may not be observed immediately or explicitly. There are various forms of learning such as associative, latent, procedural, and declarative learning.

Definition 6.5: Reasoning is a higher CP of the brain at the higher cognitive layer that inferences a possible causal conclusion from given premises based on known causal relations between a pair of cause and effect proven true by empirical arguments, theoretical inferences, or statistical predications.

Reasoning may be classified as causal, deductive, inductive, and probabilistic. Definition 6.5 is focused on causal and probabilistic reasoning. The other reasoning processes are referred to in Definitions 6.6 and 6.7.

Definition 6.6: Deduction is a higher CP of the brain at the higher cognitive layer by which a specific conclusion necessarily follows from a set of general premises.

Deduction is a reasoning process that discovers or generates new knowledge based on generic beliefs one already holds, such as abstract rules or principles. The validity of deduction consists in conformity to valid deductive principles at the same time that deductive principles are evaluated according to deductive practice.

Definition 6.7: Induction is a higher CP of the brain at the higher cognitive layer by which a general conclusion is drawn from a set of specific premises based mainly on experience or experimental evidences.

Induction is a reasoning process that derives a general rule, pattern, or theory from summarizing a series of stimuli or events. Contrary to the deductive inference, induction may introduce uncertainty during the extension of observations into general rules. Inductive inferences encompass rule learning, category formation, generalization, and analogy.

Definition 6.8: Decision making is a higher CP of the brain at the higher cognitive layer by which a preferred option or course of action is chosen from among a set of alternatives on the basis of given criteria.

There are three approaches to decision making: normative, descriptive, and prescriptive. The normative approach assumes a rational decision maker who has well-defined preferences that obey certain axioms of rational behavior. The descriptive approach is based on empirical observation and on experimental studies of choice behavior. The prescriptive approach focuses on methods of improving decision making, bringing it more in line with normative desiderata.

Definition 6.9: Problem solving is a higher CP of the brain at the higher cognitive layer that searches a solution for a given problem or finds a path to reach a given goal.

In problem solving, the representation of the problem is crucial that includes a description of the given situation, predefined operators for changing the situation, and assess criteria to determine whether the goal has been achieved. In most problems of interest, the problem space can be very large to be searched exhaustively. Typical approaches to reduce search complexity in problem solving are using heuristic rules to select a few promising states for consideration and recognition of cues in the situation that access relevant knowledge and suggest heuristics for the next transition.

Definition 6.10: Explanation is a higher CP of the brain at the higher cognitive layer that assists comprehension or understanding of a given concept by providing related categories, detailed relations, and useful analogies.

Deduction from laws is one of the ways that facts can be explained by fitting them into a more general unifying framework. While some explanations are inductive and statistical rather than deductive, showing only that an event to be explained is likely or falls under some probabilistic laws.

Definition 6.11: Analysis is a higher CP of the brain at the higher cognitive layer that divides a physical or abstract object into its constitute parts in order to examine or determine their relationship deductively.

Definition 6.12: Synthesis is a higher CP of the brain at the higher cognitive layer that combines objects or concepts into a complex whole inductively.

Definition 6.13: Creation is a higher CP of the brain at the higher cognitive layer that discovers a new relation between objects, attributes, concepts, phenomena, and events, which is original, proven true, and useful.

Wallas identified five stages of the creative process [14] as follows:s 1) preparation; 2) incubation; 3) insight; 4) evaluation; and 5) elaboration. Csikszentmihalyi pointed out that creativity can best be understood as a confluence of three factors: a

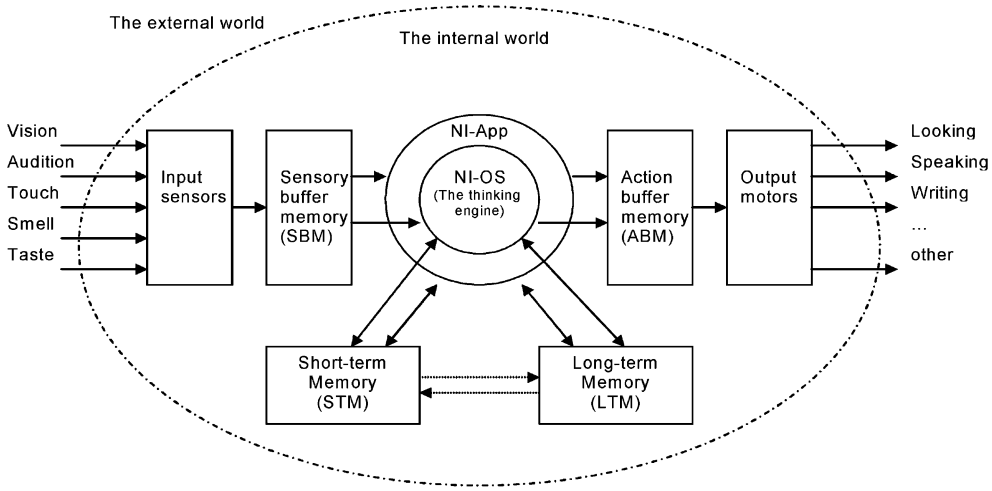

Fig. 7. Functional model of the brain.

domain that consists of a set of rules and practices, an individual who makes a novel variation in the contents of the domain, and a field that consists of experts who act as gatekeepers to the domain and decide which novel variation is worth adding to it [2].

Definition 6.14: Analogy is a higher CP of the brain at the higher cognitive layer that identifies similarity of the same relations between different domains or systems and/or examines that if two things agree in certain respects then they probably agree in others.

Analogy is a mapping process that identifies relation(s) in which people understand one situation in terms of another. Analogy can be used as mental model for understanding new domains, explaining new phenomena, capturing significant parallels across different situations, describing new concepts, and discovering new relations.

Definition 6.15: Planning is a higher CP of the brain at the higher cognitive layer that generates abstract representations of future actions, statuses, or paths to achieving a given goal, based on current information.

Many planning techniques are formulated as search problems. The outcome of planning is usually a set of actions, with temporal and other constraints on them, for execution by some agents. One of the major planning techniques is goal-directed problem solving. When a plan is executed, finding differences between goal and current states becomes a dynamic and real-time process.

Definition 6.16: Quantification is a higher CP of the brain at the higher cognitive layer that measures and specifies the quantity of an object or attribute by using a quantifier such as all, some, most, and none, or by using a more exact rational measurement scale.

The restricting role of the noun property distinguishes natural languages from first-order logic, in which its quantifiers are limited to every object $(\forall x)$ and some object $(\exists x)$, and forces logical forms to vary considerably and nonuniformly from the natural sentence they represent.

IV. Interactions Among the CPs of the LRMB Reference Model

According to the LRMB, as described in Section II and explained in Section III, the CPs of the brain can be categorized into six layers and then two subsystems. The subconscious subsystem of the brain (NI-OS) is inherited and fixed; while the conscious subsystem (NI-App) is acquired and highly plastic. It is noteworthy that the subconscious life functions determine the majority of human behaviors and CPs and this might be overlooked in psychology and cognitive science [11], [21], [23]. Although Sigmund Freud focused on the psychological effects of sex-related desires of human beings [3], he probably over simplified a whole set of other subconscious life functions as identified in Table I [21]. Therefore, a study on the subconscious behaviors of the brain and their mechanisms may be the key to understand how the brain works.

In examining the relationship between the subconscious and conscious layers of the brain, it is found that their relationship can be analogized as that of the operating system and applications in a computing system, particularly a real-time system. Cognitive informatics studies the brain and the NI as a real-time information processing system. The cognitive model of the brain NI-Sys can be described as a real-time intelligent system with a predetermined operating system (thinking engine) NI-OS and a set of acquired life applications NI-App.

The basic characteristic of the brain is information processing. The brain may be stimulated by external and internal information, which can be classified as follows:

1) willingness driven (internal events such as goals, motivation, and emotions);
2) event driven (external events);
3) time driven (mainly external events triggered by an external clock).

The functional model of the brain is illustrated in Fig. 7, which encompasses the natural intelligence system (NI-Sys),

LTM, STM, SBM (connected with a set of sensors), and ABM (connected with a set of motor drivers). In Fig. 7, the kernel of the brain is the NI-OS in a narrow sense, which is the thinking engine of the brain. While, in a broad sense, NI-OS encompasses all memories, sensors, and action motors as described in Figs. 1 and 7.

NI-Sys functions as parallel interactions between NI-OS and NI-App. NI-Sys can response to event-driven, time-driven, and willingness-driven information. The relationship between NI-OS and NI-App is illustrated in Fig. 1. The Layers 1–4 life functions in Fig. 1 belong to NI-OS, and the Layers 5 and 6 life functions are a part of NI-App.

NI-Sys interacts with LTM and STM in a bidirectional way and forms the basic functionality of the brain as a real-time thinking organ. STM provides working space for the NI-Sys and LTM stores cumulated information (knowledge). However, it is noteworthy that the wired and usually subconscious procedures known as skills are stored in ABM.

It is noteworthy that although the thinking engine NI-Sys is considered the center of the NI, the memories are essential to enable the NI-Sys to function properly and to keep temporary and stable results retained and retrievable. Thus, in a broad sense, the NI-Sys includes not only NI-OS and NI-App, but also LTM, STM, SBM, ABM, as well as the perceptual sensors and action motors.

NI-Sys communicates with the external world through inputs and outputs (I/Os). The former are sensorial information, including vision, audition, touch, smell, and taste. The latter are actions and behaviors of life functions, such as looking, speaking, writing, and driving. The actions and behaviors generated in the brain, either from NI-OS or NI-App, are buffered in the ABM before they are executed and outputted to implement the predetermined behaviors. ABM plays an important role in the brain to plan and implement human behaviors [21]. However, it was overlooked in the literature of neuropsychology and cognition science [8], [10], [21].

Unlike a computer, the brain works in two approaches: the internal willingness-driven processes (in NI-OS) and the external event- and time-driven processes (in NI-App). The external information and events are the major sources that drive the brain, particularly for NI-App functions. In this case, the brain may be perceived as a passive system, at least when it is conscious, which is controlled and driven by external information. Even the internal willingness, such as goals, motivations, and emotions, may be considered as derived information based on originally external information with very long-range feedback.

V. Conclusion

This paper has developed the LRMB to explain the fundamental cognitive mechanisms and processes of the NI. The paper has identified 37 CPs at six layers known as the layers of sensation, memory, perception, action, meta-, and higher cognitive layers. All CPs related to the six layers have been described and integrated into the comprehensive and coherent reference model of LRMB. Complex and instant intelligent behaviors of the brain and mind have been reduced to the combinations of the six-layer CPs. Therefore, LRMB has provided a unified framework for explaining a wide range of cognitive and psychological phenomena of the nature intelligence. On the basis of LRMB, a variety of life functions and CPs have been formally and rigorously described. Case studies on the comprehension, decision making, and problem solving processes have extended LRMB to detailed mathematical models of individual CPs with rigorous descriptions using RTPA. The open framework of LRMB has made future extension and refinement possible for accommodating new CPs of the brain and mind.

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Yingxu Wang (M'97–SM'04) received the B.S. degree in electrical engineering from Shanghai Tiedao University, Shanghai, China, in 1983, and the Ph.D. degree in software engineering from Nottingham Trent University, Nottingham, U.K., in 1997.

Since 1994, he has been a Full Professor at Lanzhou Tiedao University, Lanzhou, China. In 1995, he was a Visiting Professor in the Computing Laboratory, Oxford University, U.K. He is currently a Full Professor of Cognitive Informatics and Software Engineering and the Director of Theoretical and Empirical Software Engineering Research Center (TESERC), University of Calgary, Calgary, AB, Canada, since 2000. He has accomplished a number of EU, Canadian, and industry-funded research projects as Principal Investigator and/or Coordinator, and has published over 260 papers and six books in software engineering and cognitive informatics.

Dr. Wang is a Fellow of WIF, a Senior Member of IEEE with the Societies of Computer, SMC, and Communications, and a member of ACM, ISO/IEC JTC1, and the Canadian Advisory Committee (CAC) for ISO. He is the founder and Steering Committee Chair of the Annual IEEE International Conference on Cognitive Informatics (ICCI). He is the Editor-in-Chief of the *International Journal of Cognitive Informatics and Natural Intelligence* (IJCI&NI), Editor-in-Chief of the World Scientific Book Series on Cognitive Informatics, and Editor of the CRC Book Series in Software Engineering. He was the Chairman of the Computer Chapter of IEEE Sweden during 1999–2000. He has served on numerous editorial boards and program committees, and as guest editors for a number of academic journals. He has won dozens of Research Achievement, Best Paper, and Teaching Awards in the last 25 years, particularly the IBC 21st Century Award for Achievement in recognition of outstanding contribution in the field of Cognitive Informatics and Software Science. He is a Professional Engineer of Canada.

Ying Wang received the B.H.Sc. (honors) degree in medical science from the Xian Medical University, Xian, China, in 1984, and the diploma in medical psychology from the Institute of Psychology, Chinese Academy of Sciences, Beijing, in 1997.

She is the Director Doctor and the Deputy Head of the Department of Gynecology, the Fourth City Hospital, Xian. Currently, she serves on the editorial boards of the *Chinese Journal of Contemporary Western and Traditional Medicine*, books on Chinese Medicine and Clinical Practice, and Chinese Medical Practice in Base Units. She has published more than 50 papers.

Ms. Wang is a senior member of the Chinese Societies of Medical Science, Medical Psychology, and Cancer Studies. She is the recipient of a number of Surgery Innovation and Best Paper Awards in the last 20 years.

Shushma Patel received the Ph.D. degree in medical science from the Faculty of Medicine, University of London, London, U.K.

She is a Principal Lecturer in the Information Systems, London South Bank University, London. Her research interests include cognitive informatics, medical informatics, information systems, and organizational behavior. She has published extensively in these areas.

Dr. Patel has Chaired, organized, and been a Program Committee Member for several International Conferences.

Dilip Patel received the M.S. degree from Open University, Milton Keynes, U.K., and Ph.D. degree from London South Bank University, London, U.K., in 1990 and 1996, respectively, both in computer science.

He is a Professor of the Information Systems, London South Bank University. His research interests include cognitive informatics, object technology, databases, and distributed systems. He has attracted research funding and published extensively in these areas.

Dr. Patel has organized several international conferences in object technology and cognitive informatics and has presented, by invitation, many keynote speeches at major conferences.