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Cognitive Computing: Architecture, Technologies and Intelligent Applications

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ABSTRACT With the development of network-enabled sensors and artificial intelligence algorithms, various human-centered smart systems are proposed to provide services with higher quality, such as smart healthcare, affective interaction, and autonomous driving. Considering cognitive computing is an indispensable technology to develop these smart systems, this paper proposes human-centered computing assisted by cognitive computing and cloud computing. First, we provide a comprehensive investigation of cognitive computing, including its evolution from knowledge discovery, cognitive science, and big data. Then, the system architecture of cognitive computing is proposed, which consists of three critical technologies, i.e., networking (e.g., Internet of Things), analytics (e.g., reinforcement learning and deep learning), and cloud computing. Finally, it describes the representative applications of human-centered cognitive computing, including robot technology, emotional communication system, and medical cognitive system.

INDEX TERMS Cognitive computing, big data analysis, Internet of Things, cloud computing.

I. INTRODUCTION

In recent years, with the rapid development in computer software and hardware technologies, big data and the artificial intelligence (AI), cognitive computing has received considerable attention in both academic and industry. In the academic, the IEEE Technical Activity for cognitive computing defines it as "an interdisciplinary research and application field", which "uses methods from psychology, biology, signal processing, physics, information theory, mathematics, and statistics" in an attempt to construct "machines that will have reasoning abilities analogous to a human brain". In the industry, the IBM corporation developed the cognitive system, i.e., Waston, which could process and reason about natural language and learn from documents without supervision. Those works focus on strong AI, and the intelligence of these systems is based on the diverse data provided by cyberspace [1], [2].

However, modern cognitive computing still falls short of realizing human-like intelligence. Specifically, current technology advance on cognitive computing faces the following challenges:

- Most of the existing industrialized AI systems are still preliminary AI-based applications. Furthermore, a lot of applications based on neural network and deep-learning framework, such as Smart City [3]–[6], Smart Healthcare [7]–[9], Smart Home [10]–[12] and Smart Transportation [13], [14], have not yet extended sufficiently to the realm of spirit and does not focus on human-centered intrinsic information such as emotions and mentality.
- Without continuous provisionings of big data, knowledge is difficult to be sustainably discovered for the improvement of machine intelligence. Furthermore, the human expectation on the ability of machine is getting higher and higher. Therefore, it is significantly important whether the development of AI in later period will be able to break through the limitation of data.

Thus, in this paper, we propose a new human-centered computing with cognitive intelligence on cloud. As shown in Fig. 1, the human-centered cognitive cycle includes machine, cyberspace and human. The machine means hardware facilities such as computer network, devices for basic communication architecture, terminal devices and robots. While cyberspace means the space composed of information that is stored in virtual networks. This new paradigm of human-centered cognitive computing can interact human

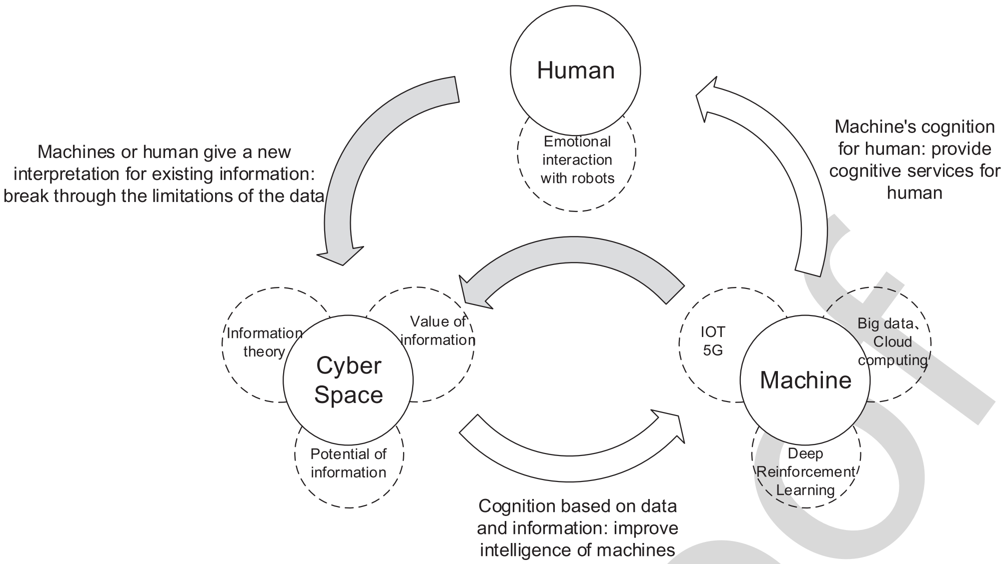

FIGURE 1. Human-centered cognitive cycle.

and machine at a deep algorithmic level using the data in cyber space. The two features of human-centered cognitive computing will not only result in the interaction among human, machine and cyberspace, but also break through the dependency of machine learning on data. Therefore, this new cognitive computing provides an effective pathway for machine to explore the internal needs of human and enable it to produce more profound understanding of cognition on human in order to provide more intelligent cognitive service for the user.

Specifically, the main contributions of this paper include:

- We propose a new human-centered cognitive computing architecture, which includes Internet of Things (IoT), big data analysis and cloud computing. Correspondingly, information collection, analysis and storage are supported.
- We give the enabling technologies in cognitive computing, which includes reinforcement learning and deep learning. Using these techniques, the machine has sufficiently discovered the value of existing cyberspace data. Furthermore, we introduce that if cognitive computing intends to further enhance machine intelligence, both existing data analysis and the innovative methods of breaking through the data limitation are required.
- We introduce three typical technologies to be integrated with human-centered cognitive computing, including robotics, emotional communication system and medical cognitive system. From these integrations, we expect that the data fusion and the interaction among human, machine and cyberspace enable the machine to provide more intelligent services to human.

The remainder of this article is organized as follows. Section II introduces the evolution of cognitive computing. The system architecture of cognitive computing are described in Section III, the key technologies of cognitive computing are presented in Section IV and the applications based on human-centered cognitive computing are illustrated in Section V. Finally, Section VI concludes this paper.

II. THE EVOLUTION OF COGNITIVE COMPUTING

In middle and later periods of the 20th century, the trend of behaviorism gradually declined. The rapid development of linguistics, information theory and data science as well as the popularization of computer technologies have brought an impressive and thought-provoking cognitive revolution. Cognitive Science has emerged, which is an interdisciplinary subject that studies the circulation and treatment of information in human brain. Cognitive scientists explore mental ability of human beings through observation on aspects such as language, perception, memory, attention, reasoning and emotion [15]. The cognitive process of human beings is mainly reflected on the following two stages. Firstly, people become aware of ambient physical environments through their own perceptive sense organs such as skin, eyes and ears, etc., by which the external information is obtained as input. Secondly, the input is transmitted to brain through nerves for complicated processing such as storage, analysis and learning. The processing results are fed back to various body parts through nervous system and then each part produces appropriate behavior response. Thus, a complete closed loop that covers decision-making and action is formed. Therefore, when a newborn is cognizing the world, constant communications with outer world are required to obtain various information on external environments. In the meantime, he or she gradually establishes his or her own cognitive system by using the obtained information and feedback. Since the cognitive system is extremely complex, it is essential to use the tools and the methods from various subjects, in order to conduct

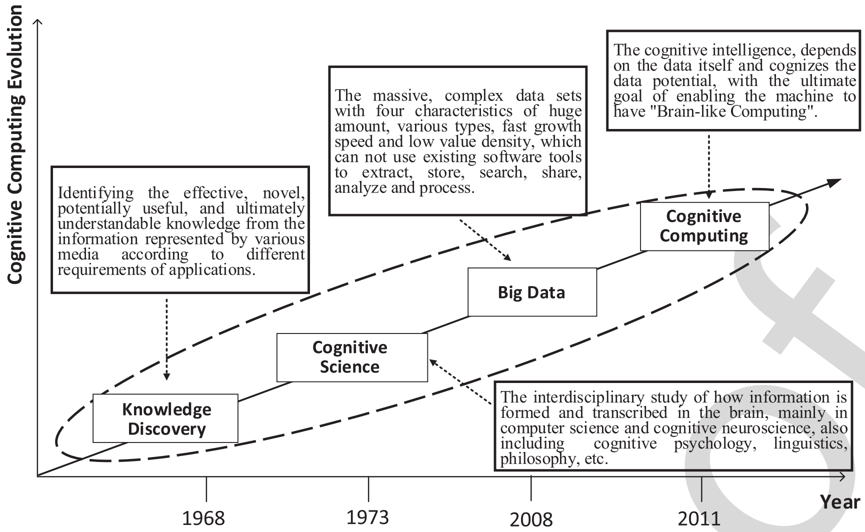

FIGURE 2. **The evolution of cognitive computing.**

multi-dimensional [16], all-around and in-depth studies for a better understand the cognitive system. Therefore, cognitive science crosses many subjects and research fields such as linguistics, psychology, AI, philosophy, neuroscience and anthropology. In a manner of speaking, the achievements obtained by researchers in the field of cognitive science up to now are closely related to interdisciplinary research methods.

Fig. 2 shows the evolution process of cognitive computing. Big data analysis and cognitive computing are two different technologies that are derived from data science. As for big data analysis, it is emphasized that the data processed should be characterized by the "5V" features of big data [17]. Cognitive computing focuses more on breakthrough in processing methods. In cognitive computing, the data processed are not necessarily big data. Just like human brain, the limited memory does not affect the cognition of image information. Actually, the image processing by human brain is extremely efficient. Cognitive computing tends to develop algorithms by utilizing the theories in cognitive science. Finally, it enables a machine to possess certain degree of brain-like cognitive intelligence [18]. Brain-like computing aims to enable the computers to understand and cognize the objective world from the perspective of human thinking. In order to understand the need of human beings, it is critical to strengthen the cognition of machine through cognitive computing [19]. Thus, the intelligence and decision-making ability of machine needs to be improved. Thereinto, especially in allusion to problems that involve complicated emotions and reasoning, cognitive computing will far exceed the traditional machine learning. When cognitive computing is embedded into IoT, the smart IoT system may assist human beings in decision-making and provide critical suggestions [1]. Cognitive technologies can also be integrated with information communication system in order to spawn novel cognitive radio networks [20]. For instance, in [21], Tian et al., propose the first application of multiple-input-multiple-output (MIMO) transmissions based on robust optimized cognitive radio to vehicular networks to enhance the performance of vehicular networks. If the data processed by cognitive computing are big data, then both cognitive computing and big data analysis are used at the same time.

III. COGNITIVE COMPUTING ARCHITECTURE

Fig. 3 shows the system architecture of cognitive computing. With the support of underlying technologies such as 5G network [22], robotics and deep learning along with IoT/cloud infrastructures, tasks involving human-machine interaction, voice recognition and computer vision will be implemented in a large scale. The upper applications supported can be health supervision, cognitive healthcare, smart city, smart transportation and scientific experiments. Thereinto, each layer in the system architecture is accompanied by corresponding technological challenges and system requirements. Therefore, the relevance between cognitive computing and each layer is studied and discussed in detail in this paper.

A. COGNITIVE COMPUTING AND INTERNET OF THINGS

It is clear from above-description that cognitive computing is based on information. Communication field emphasizes on transmission of information, while computer realm emphasizes on utilization of information. In actual cognitive computing applications, the information is mainly represented by data including various structured and unstructured data. The IoT [23] collects diverse real-time valuable information of objects' concerns in objective world, forms a giant network through Internet and realizes interconnection among massive sensing devices in order to make co-fusion between data world and physical world [24]. Currently, some advanced distributed information fusion technologies, such as [25], can also be employed to improve the accuracy of the sensed

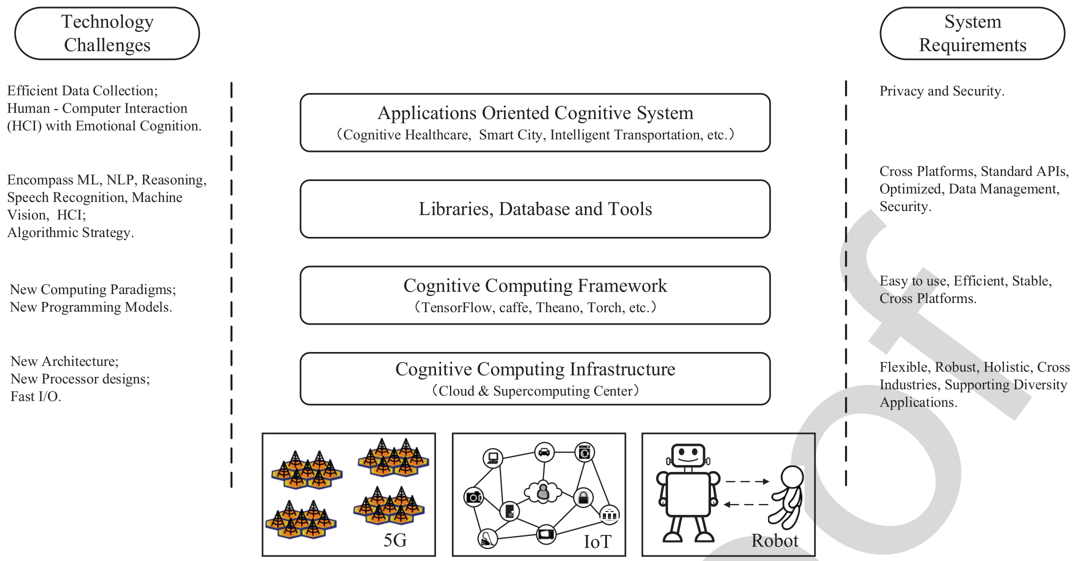

FIGURE 3. The system architecture of cognitive computing.

large-scale network information. The IoT firstly obtains information related to monitored objects through perception technologies such as RFID and wireless sensor, satellite positioning and positioning through WiFi and fingerprint. Secondly, it spreads relevant information in the network using various efficient means of communication and conducts sharing and integration. Finally, it conducts analysis and processing of information using the intelligent computing technologies such as cloud computing, machine learning and data mining to realize intelligentized decision-making and control in physical fusion system of information. The IoT realizes the perception and transmission of information. The popularization and extensive use of IoT will generate more and more data that will provide important information source for realization of cognitive computing. In turn, as a new type of computing mode, the cognitive computing will provide means of practice with higher and better energy efficiency for data perception and collection in IoT.

B. COGNITIVE COMPUTING AND BIG DATA ANALYSIS

The continuous increase of information and the constant improvement in computing power of machine are irreversible obvious in the era of big data [26]. Compared with the increase in traditional structured data, the increase in unstructured data such as data in social media and in mobile internet is evergrowing exponentially. Structured and unstructured data compose cognitive big data, the feature of which can be represented by 5V, i.e., volume (large volume), velocity (rapid change and high velocity), variety, value (value-oriented) and veracity. In the meantime, these features cause many problems during the analysis and processing of information. However, big data analysis and cognitive computing provide efficient solutions. We introduce the connection and differences between big data analysis and cognitive computing.

Cognitive computing mimics human senses. One connection between big data analysis and cognitive computing is human's big data thinking. The experience constantly accumulates during the life of human being. Once the information quantity of various experience become large, he or she may possess human's big data thinking, which is hierarchical as deep learning. The first level is the concern about the improvement in material life and environment. The second level is pursuing spiritual culture and the third level is concerned with the meaning of life. The amount of people in top level is the least. Currently, the thinking that is simulated by machine intelligence mainly focuses on first and second level to concern the living standard and the emotional state of human. The corresponding applications are: health monitoring, smart healthcare, smart home, smart city and emotional care [27]–[29]. The third level is further deep that concerns the meaning of life and puts forward personalized suggestions for development direction in the life of user to help the user realize happy but more meaningful life. It cannot be done by machines at present and is a great challenge in artificial intelligence in future. Under the circumstance where data set complies with features of big data, the most direct way to analyze and process the data is to adopt the existing method of machine learning [30]. However, data processing technique with "brain-like" computing is the key point for distinguishing the big data analysis from cognitive computing. The method that more emphasizes on potential of value for data should be employed in order to enable the machine to achieve the third level by cognizing the connotation of data and the image information contained in these data, and understanding the ambient information just as human being does.

One differences between big data analysis and cognitive computing is data size. The big data analysis in allusion to some data set is not necessarily cognitive computing. The thinking of big data emphasizes on mining the value and obtaining the insight from large volume of data. Without large volume of data as base, the accuracy and the reliability of prediction cannot be guaranteed. Considering the accumulation of data in volume in cognitive computing does not mean relying on data size. Based on cognition and judgement like human brain, the cognitive computing tries to solve the problems of fuzziness and uncertainty in biological system. Thus realizes various degrees of processes such as cognition, memory, learning, thinking and problem solving. For example, in real life, a child only needs a few times to learn to know a person. Although, the data size is not large enough but the cognitive computing can still be employed to process the data. As for common people and domain experts, it is assumed that the data are identical but the profundity of knowledge obtained by common people may differ from that obtained by domain experts. Since the height of thinking is different, the angle to interpret the data may also be different. The machine can mine more hidden meaning from limited data using cognitive computing [31].

Furthermore, the combination of cognitive computing and big data will bring ''win-win'' benefits. The cognitive computing is inspired by learning process of human. Human beings only require a very short period of time to cognize an image and after that they can easily distinguish cat from dog and etc. The traditional big data can achieve this simple function of human after large amount of training. For example, though ''Google Photos'' can distinguish cat from dog by learning a lot of pictures [32]. However, it cannot recognize the different varieties of cat. In addition, there is big redundancy for numerous volumes of data and these data will occupy massive storage space. The cognitive computing prefers utilization of a pathway that is more light and convenient than big data analysis. It mines universality and value of data and after acquiring cognitive intelligence, it makes the big data analysis to not only utilize ''brute computing force''. Before the era of big data, the cognitive computing had not been sufficiently studied. At present, the rise of AI and the support of sufficient computing resources on cloud provide advantages for development of cognitive computing [33] and make it possible for machine to interpret and mine the implication of data from angle of cognizing internal needs of user.

C. COGNITIVE COMPUTING AND CLOUD COMPUTING

Cloud computing virtualizes the computing, storage and band width. Thus, it reduces the deployment cost for software services and provides support for industrialization as well as promotion of application cognitive computing [34]. Moreover, the strong computing and storage capacity of cloud computing provide dynamical, flexible, virtual, shared and efficient computing resource services to cognitive computing [35].

For large amount of data information generated in real life, after big data analysis is conducted on platform of cloud computing, the technologies such as machine learning are adopted to conduct mining for data and the results are applied in different fields. The different categories of information correspond to different processing technologies. For example, the literal information and the pictorial information correspond to natural language processing and machine vision, respectively. The cognitive service of IBM for language and cognitive computing application of Google emphasize on realization of brain-like cognition and judgement by deploying cloud service model to provide accurate assistance in decision-making. Cloud computing and IoT provide cognitive computing with software and hardware basis [36], while big data analysis provides methods and thinking for discovering and recognizing new opportunity and new value in data.

IV. ENABLING TECHNOLOGIES IN COGNITIVE COMPUTING

In this section, we introduce the enabling technologies which include reinforcement learning and deep learning. The reinforcement learning can learn from the environment and reflects on behavior. The deep learning can learn high levels of features. We will give a detailed description.

A. COGNITIVE COMPUTING AND REINFORCEMENT LEARNING

The traditional machine learning methods can divided into supervised learning and unsupervised learning. In those methods, the machines train those model with data that are often in fixed format and machines complete tasks such as regression, classification and aggregation. However, the information that can be received by the machines is limited. It is difficult for machines to learn information in nonlinear case because they can only conduct prediction according to the received information. Moreover, the tag for same data can be different in different conditions, which means that the usability of information learned by machines is different for different users. Traditional supervised learning and unsupervised learning are based on closed training with data input. These traditional learning methods are unable to meet the requirements of sustainable improvement in intelligence of machine. Therefore, reinforcement learning has become a hot research branch in the field of machine learning.

Reinforcement learning is quite similar to the learning process of human. Let's take the case where a child learns to speak as an example. When a child is to learn a word, usually an adult would repeatedly read that word, pointing at something represented by that word or doing the action represented by that word. If the child's understanding is wrong due to incorrect judgement, the adult would conduct correction. Once the child gets it right, the adult would give reward. The ambient environment is also a very important factor during the learning process of human. Reinforcement learning takes the example by this point and it can learns from the environment and reflects on behavior. A set of reward mechanism is established, i.e., certain reward is given when some behavior is good for objective and certain punishment is exerted on the contrary. During the process toward the objective, there are multiple choices. Therefore, the decision at each time is not necessarily the optimum, but it must be good for the machine to gain more reward. Let's take AlphaGo [37] as an example. After absorbing millions of games of chess for deep learning, it plays chess with itself by reinforcement learning and in its strategy, each choice is not necessarily the optimum step like deep learning at that step, but the step that is most likely to cause final win as per global planning. In this process, the machine is not only dependent on past experience but would also try new paths to maximize the target reward. Just like drawing learning, extemporaneous play would be added once the basic skills are mastered. Data are generated in the process of attempts of machine, the final objective is not regression, classification or aggregation but maximum reward. With this purpose, both successful and unsuccessful attempts are meaningful for the machine. It would learn from experience in previous attempts at each subsequent step.

However, if a machine only communicates with itself, then its cognition is not satisfactory. This is just like for a child, it would be difficult to learn to speak without communicating with others. Therefore, if a learning system carries out its idea irrespective of external circumstances, it is not a good cognitive system. So, a cognitive system should conduct communication directly with human. However, if a person is specially assigned to conduct communication with a machine, it would consume a lot of time and manpower. Fortunately, the crowdsourcing method can make the communication between machine and human natural. A typical case is the game Foldit. In this game, a target protein is given, the players conduct assembling with various amino acids until the complete body of this piece of protein is pieced together. The players volunteer to participate in the assembling process of amino acids. Furthermore, if there are enough players, the collective intelligence of this crowd of unprofessional players will surpass that of a few professionals. This method can be used to improve the intelligence of machine in some application fields by allowing the users to unconsciously communicate with machine through customized cognitive computing software. The diverse information provided by the users who participate in crowdsourcing unconsciously also remits the rely of cognitive learning on data and a new kind of data processing method is provided at the same time.

B. COGNITIVE COMPUTING AND DEEP LEARNING

1) RATIONAL METHOD AND PERCEPTUAL METHOD

The cerebral cortex of human is divided into two hemispheres that have different functions. As for most people, the left brain is responsible for language, ideas, logic, etc. While the right brain is responsible for visual thinking and emotions. People with a developed left brain usually bear strong logicality and are more rational (e.g., scientist). While people with a developed right brain usually have strong creativity, are good at cognition on space and object shapes (e.g., artist). Therefore, the thinking mode of human is divided into logical thinking and visual thinking. According to different abstraction in content of thinking, the method for human to recognize the natural world is divided into: rational method and perceptual method.

The rational method is based on strict concept and definition, while the perceptual method is certain mapping relation established between input and output. How human brain realizes the information coding, processing and storage for 100 billion of nerve cells is still unknown. However, the thinking method of human brain can be simulated in cognitive system through data analysis. The manual feature design method are strictly defined. This method can be viewed as a kind of rational method, i.e., it simulates logical thinking ability of human. The feature learning method is to learn the mapping relation between input and output. It is a kind of perceptual method, i.e., it simulates the ability of visual thinking of human.

As shown in Fig. 4, rational and perceptual methods are adopted separately to determine a quadrangle is a square. The rational analytic method is used to detect the features of a square, to determine if there are four right angles and to decide whether the lengths of four sides are identical or not, as shown in Fig. 4 (a). This method requires the understanding of concepts of angle, right angle, side and length of side. If a picture of square is shown to a child and he or she is told that it is a square, after several times of learning, that child can recognize a square accurately, as shown in Fig. 4 (b). In fact, the child does not know the concept of side or angle but he or she can still recognize a square. The method where the child recognizes a square is perceptual method or intuition. In fact, after several practices, the child learns the mapping relation between the figure of square and the concept of square. Recognizing a square with rational method requires seeking image features, manual feature design can be viewed as simulation of this method. When a child learns to recognize a square, perceptual method is employed to establish the mapping relation between figure and concept, learning features with deep learning model can be viewed as simulation of this method.

2) COGNITIVE COMPUTING AND IMAGE UNDERSTANDING

If machine is going to solve problems in real world, the best way is to simulate the thinking mode of human brain. In cognitive system, the features can either be extracted from original data for classification and prediction model using the method of manual feature design to simulate the logical thinking ability of human brain or can be learned through deep learning to simulate the ability of visual thinking of human brain. As the computer applications are getting more sophisticated, the researchers are realizing that many problems in real world that are easy to understand by human beings are difficult to describe with rational method making the rational analytic method ineffective or completely impossible for computers. In other words, the effective data features cannot be designed with manual feature design method and it is quite difficult for computer to realize the feature expression.

Image feature extraction is the base for understanding the image irrespective of application (e.g., image

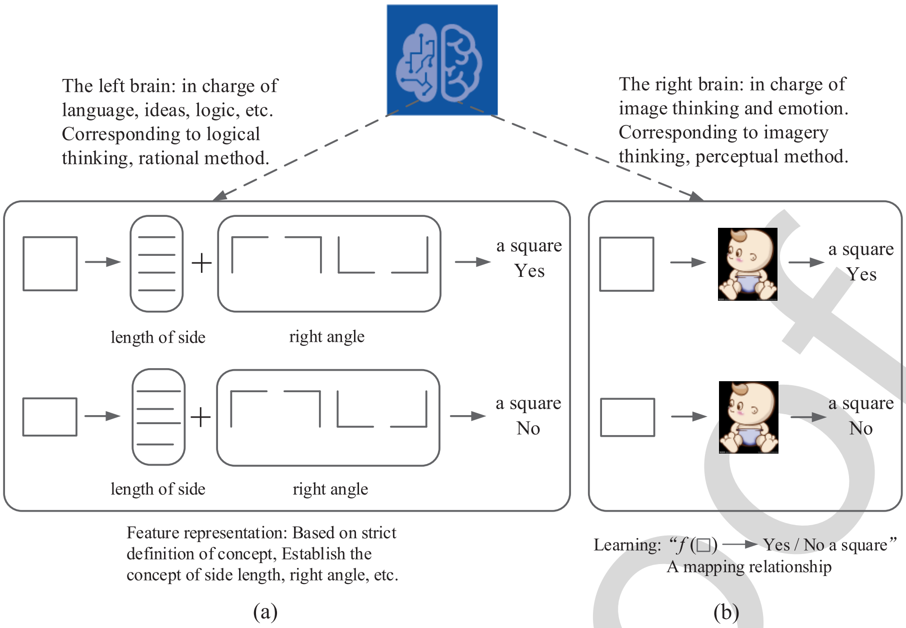

FIGURE 4. Perceptual and rational method to recognize a square. (a) Rational method. (b) Perceptual method.

classification and image retrieval). Let's take face recognition as an example. There are two methods for feature extraction in face images: manual feature design and feature learning. In manual feature design method, the computer simulates the rational method for recognition and determines which features (e.g., shape of nose, eyes, eyebrow and mouth) on human face can be used for distinction. The feature design and the feature extraction [38] become quite difficult due to factors such as expression, making up, beard, glasses, change in illumination and photographing angle. However, when a human being conducts face recognition, he or she seldom considers specific features in the image, instead, he or she makes judgement totally by virtue of intuition. The expression, illumination, photographing angle and glasses in the pictures would not influence the recognition effects at all [39]. It can be paraphrased that the mapping relation between the input (i.e., pictures of a person) and the output (i.e., who is that person) is established with this recognition method of human by virtue of intuition. When image classification is conducted with deep learning, the perceptual method of human for image recognition is simulated. The mapping relation between the images and the classification results is obtained through learning a large amount of image data, i.e., the feature expression of input images is obtained and used for classification. The classification results for input image can be obtained when a mapping relation obtained through training is utilized [28], [40] .

V. APPLICATION OF COGNITIVE COMPUTING

A. COGNITIVE COMPUTING AND ROBOT TECHNOLOGY

Robots were born in the middle of the 20th century. With the development of more than half a century, robot technology has profoundly influenced the production mode and life style of human. This technology has become an important symbol to measure the level of scientific technological innovation and high-end manufacturing of a country. "Making a man-like robot" has been a great desire of human beings for thousands of years. However, the current relationship between human and robot is still the relationship between utilizing and being utilized, and between replacing and being replaced. The new trend in social development indicates that the new generation of robot system will simulate human beings from more aspects in future, especially, there should be a kind of partnership relation where robots and humans coexist in harmony and make their respective advantages complementary to each other. The co-fusion with human beings is an important feature for new generation of robots.

B. EMOTIONAL COMMUNICATION SYSTEM

Currently, the world is interconnected through internet, mobile phones and countless objects. The seamless fusion of physical world and cyber world has become the trend in development of future network [41]. The material life today is increasingly abundant and people have started to transfer the focus of attention from physical world to spiritual world. For example, the traditional Smart Home 1.0 only realizes energy saving through networking of machine to machine (M2M) and makes it convenient for a human being to remotely control the electric appliances. However, after the addition of cognition on human by machine, the traditional smart home evolves into Smart Home 2.0 [42]. The Smart Home 2.0 is a new generation of smart home system and integrates Smart Home 1.0 and emotion cognition. It is an intelligent system that integrates user, intelligent application, green plants and indoor environment. The system combines smart home and indoor green plants to provide intelligent cognitive services for perception and regulation on emotions of indoor users. It is able to perceive the emotions of user and adjust the environment accordingly.

Emotions of human beings gradually become a direct reference index for spiritual world. Thus, emotion cognition is an important application of cognitive computing. Furthermore, this is a new human-machine interaction technology. Currently, the human-machine interaction system available often means human-machine interaction supported in visual distance environment (i.e., within the view of each other). However, most of human-to-human or human-to-robot interactions are not in the mode of visual distance. In order to break through the limitation in traditional human-machine interaction system, we introduces a kind of emotional communication system not based on mode of visual distance [27]. In this system, the remote communication mode is not video or voice call on mobile phone, but the communication medium discussed in the paper is pillow robot. This cognitive system has a lots of applications, for example, there is an autistic child who is at home alone and his or her mother went on a long-term business trip. The emotion of this child is quite passive that significantly influences the physical and the psychological health of the child. At the moment, the child longs for the concern of his or her mother and it is not only a paragraph of mother's voice in the call, the child also longs for true emotional comfort in sense of touch as if the mother is with him or her. In emotional communication system not based on mode of visual distance, emotion is firstly defined as a kind of multimedia data that is similar to voice and video. Emotional information can not only be recognized but can also be transmitted in long distance. In the meantime, an emotional communication protocol is proposed by the system considering the real-time requirements and ensuring the reliability of emotional communication.

C. MEDICAL COGNITIVE SYSTEM

With economic development and environmental changes in human society, the morbidity of chronic diseases is constantly increasing and chronic diseases have become the greatest threat to human health. As for medical professionals, a medical cognitive system can be utilized to assist in diagnosis and to make decision using various types of data and contents in order to take appropriate operation. In medical system, the risk is quite high if correct data relation and mode are not found [28]. If the important information is ignored or misunderstood, then the patient can suffer long-term injury and even death. The multidisciplinary fusion of technologies such as machine learning, AI and natural language processing can enable the cognitive computing to determine the mode and the relation of a disease from data. All different data points should be analyzed comprehensively to help the medical experts in learning, until the final accurate solution is found. In cognitive system, the cooperation between human and machine is intrinsic, which is able to ensure that medical institutions obtain more values from data and solve complicated problems [43], [44].

VI. CONCLUSION

In this paper, we first introduced the evolution of cognitive computing from four aspects, i.e., knowledge discovery, cognitive science, big data and cognitive computing. Then, the cognitive computing system architecture is proposed which consists of three parts, i.e., IoT, big data analysis and cloud computing. Furthermore, we introduce the enabling technologies in cognitive computing including reinforcement learning and deep learning. Finally, the representative applications of cognitive computing are illustrated from three scenarios, i.e., robot technology, emotion communication system and medical cognitive system.

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