A Comparative Analysis of the Cognitive Processes in Machine Translation and Human Translation

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Abstract: *The rapid development of artificial intelligence technology makes machine translation show its great advantages in translating multilingual information; yet there are no systematic explanations about the essential difference between them with regard to their cognitive levels. In this paper, we conduct in-depth analysis of the fundamental differences between the two at the level of cognitive mechanisms according to the framework of cognitive science. We find out that machine translation is based on computational models and data driven foundation showing the characteristics of formalized processing and probabilistic optimization while human translation relies on the complex cognitive system of the biological brain possessing advanced cognitive ability like contextual understanding, dynamic knowledge management and creative decision-making. Establishing a systematic comparative analysis framework, we analyze the essential differences from three aspects: language understanding, knowledge application and decision-making processing and propose a new model of human-machine collaborative translation based on cognitive complementarity. Our research will not only enrich our theoretical understanding of the cognitive process of translation, it provides an important basis for building an efficient human-machine collaborative translation system.*

Keywords: *Machine Translation; Human Translation; Cognitive Process; Cognitive Mechanisms; Human-Machine Collaboration; Comparative Analysis*

Introduction

With globalization and informatization being highly intertwined today's society, there is an explosion of demands for language services; although with the advancement of machine translation technology, the translation efficiency has been greatly improved, however, there is still a gap in quality between machine translation and human translation which needs to be explored deeply regarding their different cognitive mechanisms. Most existing works mainly optimize and improve on the technical level while lacking systematic and in-depth comparison about the internal processing mechanism of the two from the perspective of cognitive science. Such lack of theoretical research will limit the innovation of human-machine collaborative translation models and make it hard to effectively guide the quality improvement in translation practice. Thus, it is very meaningful both theoretically (deepening our understanding of the cognitive mechanisms of language processing), and practically (provide a scientific basis for overcoming the current bottleneck in translation technology development and build a new paradigm of human-machine collaboration) to explore the intrinsic differences and complementarity between machine translation and human translation from the perspective of cognitive process. In order to set up a systematic cognitive comparative framework so that we can reveal the essential difference between the two in key aspects like language understanding, knowledge application, and decision-making processing, thus provide new ideas and methods for promoting the development of translation theory and technology.

1. Exploration of the Cognitive Mechanisms of Machine Translation and Human Translation

1.1 The Cognitive Foundations and Processing Mechanisms of Machine Translation

The cognition basis for machine translation comes neither from the intelligence of a biological brain nor from computational linguistics and statistical models: it basically treats the source language text as a data sequence which can be mathematically modeled and realize mapping and conversion between symbols through complex algorithmic computations. Early rule-based machine translation system relies

upon grammatical dictionary and compilation of conversion rules by experts whose cognitive process simulates the derivation of formal logic so as to produce translations using symbolic operations and syntactic analysis[1].

On contrary, the mainstream neural machine translation relies on end-to-end distributed representations and probabilistic predictions as deep neural networks do. It trains massively trained corpora, learns complex associations/statistical patterns between linguistic symbols with multilayer networks, building up an implicit knowledge model including lexical, syntactic and shallow semantic information. Information flows through a black box from encoding to decoding: transform the source language sentence into a distributed representation in a high dimension vector space; generate words for the target language one after another according to the distribution representation and the previously generated text via the probability method. This is a data driven pattern recognition and probabilistic optimization process whose cognition has completely been constrained by the size and quality of training data.

1.2 The Cognitive Process and Mental Representation of Human Translation

The human translation cognition is a very dynamic intelligent behavior with many complex psychological activities: First, it involves deep reading and understanding of the source text that is not only decoding linguistic symbols, but also building up a mental model based on world knowledge and context information; Translators activate their linguistic schemata and conceptual structures from long-term memory to parse, filter and reconstruct textual information into an overall mental picture for the intention, emotional style and logical thread of the source text. In the transfer stage, translators' cognitive activity is not just code substitution, but cross-mapping (meaning negotiation and conceptual integration) between the bilingual mental lexicon and conceptual system. There are countless internal decision making and judgment involved in this process which requires solving the category gap and expressing conflict due to linguistic and cultural difference.

Forming the target texts in its final stage requires a creative reconstruction according to the target-language norms and communicative purposes. In order to ensure equivalence of the target text with the source one from different aspects (meaning, function, style), the translator should balance between an automatic process of language generation and conscious monitoring and evaluation. This cognitive flow goes via higher level psychological functions like: perception, memory, thinking, decision-making, creation - it is characterized by initiative, flexibility, purposeness.

1.3 Construction of a Comparative Framework for Cognitive Mechanisms

To build up a comparison framework between the cognitive mechanism of machine translation with human translation we need to analyze systematically their difference about processing units, knowledge sources, and operational nature on different aspects: regarding processing units, machine translation uses locally co-occurring word sequences or sentences as basic units; its operations rely upon statistical association at the surface level; human translation uses meaning proposition and the discourse as a whole as processing units; its operations rely upon deep conceptual and intentional analysis. The knowledge of machine translation comes from closed, annotated training datasets, whose knowledge can be represented as neural network parameters which are hard to interpret; the knowledge of human translation comes from open, constantly updated personal experience and sociocultural practice, whose knowledge is stored in abstract conceptual systems and schematic structures.

As regards its operation: The core of machine translation is mathematical pattern matching and probabilistic computation (pursuing formal statistical optimality), while the core of human translation is understanding, reasoning and creating (pursuing dynamic equivalence in communicative function). From these kinds of comparison we are able to witness that machine translation simulates the fast, automatic shallow information processing mode in human cognition but human translation has the slow, controlled deep meaning processing capability. Fundamental mechanistic differences lay down a theoretical basis on how to understand the capability boundaries and complementarity between them as well as pointing out the direction for further exploration of possible pathways towards human-machine collaboration[2].

2. Analysis of the Differences and Complementarity in the Cognitive Processes of Machine Translation and Human Translation

2.1 Main Dimensions of Differences in Cognitive Processes

2.1.1 The Opposition Between Formalization and Contextualization in the Dimension of Language Understanding

The cognition of machine translation depends upon its formalized processing. Mapping linguistic elements into a high-dimensional vector space to compute allows it to achieve surface-level understanding by statistical regularity. Its way of processing is just a probabilistic reconstruction of language patterns; it does not grasp the deep semantics and contextual association of the text. The cognitive features of human translation are very contextualized: they can make use of their rich world knowledge and contextual information to build up a complete mental representation. There is a deep understanding about implicit meaning, emotional coloring and cultural connotations with respect to complex linguistic phenomena -- which is a cognitive level difficult to be reached by existing machine systems.

2.1.2 The Divide Between Static Implicitness and Dynamic Explicitness in the Dimension of Knowledge Application

Knowledge System of Machine Translation: Static The knowledge structure of machine translation is fixed by the parameters of a trained model, which presents as a closed mode for knowledge retrieval at application stage. This implicit knowledge system is hard to be updated in real-time and dynamically expanding. Different from human translation having been constructed based on an explicit knowledge management system; translators can flexibly calling up both declarative and procedural knowledge and do targeted knowledge integration according to their tasks' demands. Translators have great ability in knowledge updating and adapting when facing knowledge blind spots[3].

2.1.3 The Coexistence of Probabilistic Optimization and Constraint Trade-offs in the Dimension of Decision-Making Processing

The basic principle of machine translation decisions is essentially an optimization based on probabilistic models that chooses the most statistical optimal translation sequence by algorithmic calculations. The decision making in machine translation is linear and deterministic; whereas human translation decision making involves complex trade-off under various constraints with comprehensive consideration from different aspects such as text fidelity, reader acceptance, style requirement and time cost. A translator's decision is a "satisficing solution" which seeks solutions within a certain cognitive context, reflecting the dialectical and flexible nature of human cognition.

2.2 The Sources and Manifestations of the Differences

2.2.1 The Computational Nature and Biological Nature of Intelligent Carriers

Roots of the cognitive differences are inherent difference between intelligent carriers: Machine translation is based on formal computation that displays its intelligence through data-driven pattern recognition ability. The computational intelligence possesses only efficiency and consistency without any real understanding nor creativity whatsoever. Human translation depends on biological nervous system with higher cognitive functions like perception, consciousness and metacognition which can do deep reasoning and possess emotional resonance -- this is a core advantage for coping with complicated tasks (e.g., literary translation).

2.2.2 The Divide Between Patterned and Creative Processing Capabilities

Specifically about its processing ability: Machine translation is good at processed, patterned language – it translates normative texts like technical documents very well. But for creative use of language (literary rhetoric or poetic expressions) machine systems are inadequate. The whole process from language conversion to artistic recreation by humans was done via aesthetic judgment and linguistic creativity which demonstrated a unique creative processing capability.

2.2.3 A Comparison Between Mechanical Rigidity and Flexible Agency in Contextual Adaptability

The machine translation have great shortcomings on contextual adaptability: their processing units are generally at the sentence level not able to grasp the whole structure of a discourse. The mechanical processing mode results in obvious deficiency for stylistic consistency and emotional coherence.

Human translation can build up a global cognitive schema such that every local choice will be coordinated with the overall context, which has excellent macro-contextual adaptability[4].

2.3 Potential Areas and Value of Complementarity

2.3.1 Task Division Based on Cognitive Load Theory

Cognitive load theory suggests that machine translation takes over external cognitive load during the translation process by automating foundational work which frees up a lot of cognitive resources for translators: by dividing the labor, they focus on dealing with complex segments requiring high-level cognitive processing and therefore have an optimal allocation of overall cognitive resources. Dividing cognition between humans and machines opens new opportunities to improve translation efficiency and quality.

2.3.2 The Iterative Optimization Model of Human-Machine Collaboration

Complementarity between humans and machines can be seen from their dynamic iterative optimization process that form a collaborative closed loop of "machine pre-translation–human fine editing" which creates a virtuous cycle of continuous improvement: translators' revision behaviors provide high-quality feedback data for machine systems promoting the continuous optimization of models; this collaboration not only improves current translation quality, but it also give an impetus for the long-term evolution of machine systems.

2.3.3 Moving Toward a Paradigm Reconstruction of New Translation Capabilities

Deep human-machine collaboration changes the translation competence system. The future professional translators require metacognitive abilities based on human-machine collaboration – diagnosing machine translation output, doing in-depth editing, doing pre-translation preprocessing etc., emphasizing the understanding and integration of both cognitive systems is the key for achieving the maximum value from human-machine collaboration. Paradigm shift toward such a new capability enhances individual translation effectiveness as well as promotes cognitive upgrading of the whole translation industry.

3. Research on Human-Machine Collaborative Translation Models Based on the Complementarity of Cognitive Processes

3.1 The Theoretical Foundations of Human-Machine Collaborative Translation

Building up a human-machine collaborative translation model is not merely a superposition of technologies, but rests upon the cross-disciplinary integration of a series of theories that strongly supports its rationality and necessity. A key theoretical foundation lies in the perspective of cognitive ecology: Cognition does not exist only inside an individual's brain, but spreads throughout the whole system consisting of individuals, tools and the environment[5].

We believe that machine translation plays the role of expanding the frontier of human cognition within the translator's cognitive ecology: taking over the subtask with high load but low creativity from humans; another important theoretical basis is the theory of cognitive coupling in human-machine interaction on how human intelligence and artificial intelligence form a tight feedback loop when collaborating. In ideal case, if coupled together, the computational capability of the machine and the judgment ability of the human will be able to interact in real-time where the fast output of the machine becomes an input for the human's decision making and the immediate correction given by the human becomes a supervisory signal for the machine's next round of learning so they become a constantly-evolving intelligent joint system.

Furthermore, activity theory illuminates the division of labor and roles within collaboration systems; emphasizing the role of tool mediation in human activities toward goal achievement and interaction between people and communities constrained by rules. Both these theories make us conclude that perhaps the best translation system is not an autonomous artificial intelligence but a collaboratively designed system which achieves deep integration of the cognitive strengths of both humans and machines.

3.2 Design Principles of the Collaborative Model

In order for the human-machine collaborative translation model to work well and truly realize cognitive complementarity, it needs to abide by some basic principles based on cognitive processes as the core. The foremost one is the human-centered principle, i.e., designing the entire system with an emphasis on enhancing and empowering translators instead of replacing them: the function of machine translation should be designed as a "cognitive collaborator" committing itself to reduce translators' cognitive load and direct their attentional resources towards those complex decision-making segments which need human wisdom most.

Secondly: Principle of dynamic cognitive coupling extends beyond a linear "pre-processing–post-editing" workflow by enabling real-time, bidirectional intelligent interactions (i.e., dynamically adjust support strategies based on translators' behaviors such as pauses, revisions, and queries—e.g., provide alternative translations if translators hesitate or issue risk warnings upon detecting potential cultural conflicts so that we can achieve responsive cognitive collaborations) in system design.

Third: Principle of interface cognitive transparency – The user interface and interaction logic within the collaborative system must completely show the "cognitive state" of the machine together with the reasons for its decisions. It may visualize the confidence of key parts of the translation; it provides probability ranking of alternatives translations or even explaining the core source-language segments that have been used as basis for a specific translation choice. Translators will then understand easily how the machine operates, find out exactly where there are problems so they can use their superior cognitive abilities efficiently at the most important quality control links.

3.3 Implementation Paths and Effect Evaluation

Transformation from theory to practice requires an implementation path in steps and a multidimensional effect evaluation system for verification and leading the development of the collaborative model: we can start from task-oriented refined division of labor – different levels of human-machine collaboration workflows are predefined according to the type, complexity, and quality requirement of the texts; a "machine translation plus lightweight post-editing" model suits informative and highly patterned texts whereas a "machine assistance (such as terminology bases and translation memory) plus human-led creation" model suits those with high creativity and high precision requirements[6].

Most advanced path: build up embedded intelligent assistance tools; decompose machine capabilities in microservices which seamlessly integrating into the translator's working environment (real-time quality checking, context-aware terminology recommendation, style consistency verification), such that machine assistance contextualized running through the whole cognitive process of translation rather than only one post-process. Topmost level path: building up an adaptive learning collaborative system: analyzing a specific translator's revision patterns, preferences, and finally adopted translations, it will constantly learn and personalizes its output strategies and assistance content for long-term adaptation and co-evolution with a specific translator's cognitive style.

In order to evaluate effects, we have to go beyond traditional single automatic evaluation metrics of translation quality; build up an overall evaluation matrix of cognitive effectiveness and product quality that combines not just process indicators (focuses on the impact of the collaborative model on the cognitive process of translation) such as behavior data analysis with eye-tracking or keystroke logging analyzing change in translator's cognitive load, task completion efficiency, and decision-making focus, but also outcome indicators (besides traditional fluency/fidelity assessments): translation creativity and cultural appropriateness. Only multidimensional evaluation can comprehensively and objectively evaluate the human-machine collaborative translation model if it really achieve optimization of cognitive processes and value-added of final output to provide scientific guidance for its iteration and development.

Conclusion

Through systematic comparison on the cognitive processes of machine translation and human translation, we found out the essential differences between them from the aspects of cognitive foundation, processing mechanism and decision-making mode. Machine translation that possesses the characteristics of formalized processing and probabilistic optimization is able to rapidly process

standardized texts; while human translation possessing the characteristics of contextual understanding, dynamic knowledge management and creative decision-making capability has irreplaceable value when it comes to deeply processing complex linguistic phenomena. Human-machine collaborative translation model based on cognitive complementarity realizes an optimal allocation of cognitive resources at three levels: task division, iterative optimization and system integration. Some directions to explore in our future work such as developing more adaptive intelligent assistance systems, exploring the neural mechanisms of translation cognition, establishing a more complete evaluation system about human-machine collaboration effect. We also need pay attention to innovation in the translation education system, cultivate translators' human-machine collaboration capabilities, promote the transformation and upgrade of the translation industry in the era of artificial intelligence. These research directions will help us realize the deep integration of human intelligence and machine intelligence, and establish a new pattern improving both translation quality and efficiency coordinately.

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