"I see myself more as a problem creator than as a problem solver."

Making invisible problems visible

In order to explain cognition, scientists need to look not only *inside* the brain, but also *outside* the brain. That's the view of computational cognitive scientist Iris van Rooij.

What enables us as to employ our cognitive capacities? This is the fundamental question that cognitive scientist Iris van Rooij – leader of the Computational Cognitive Science group at the Donders Institute – poses. She investigates this question in relation to computational models that can be used to develop artificial intelligence, i.e. smart robots and virtual agents. She believes that humans do not owe their remarkable cognitive capacities to the biological and chemical stuff that their brains are made of. In her view, the same functional properties can – at least in principle – be mimicked by artificial 'agents' as well.

Van Rooij: "I'm particularly interested in cognitive capacities that are extremely hard for machines, such as developing what we call common sense. This is illustrated, for instance, by meanings that cannot be expressed literally or put into words. For example, when we talk with each other, you know that I know certain things and I know that you know

The limits of computation
Thinking naively, you might expect that if you were able to bring enough computer power to bear, you could solve any mathematical problem that has a finite number of solutions. However, this is not the case. Even if you could calculate using all the atoms in the universe, and even if you had done that from the nanosecond when the universe began, it would still be impossible to calculate all solutions to certain types of problems. In mathematics these are called NP-hard, i.e. the hardest problems in the class *nondeterministic polynomial time*. Unfortunately, such problems are very common in everyday life. The best-known NP-problem is the 'travelling salesman' problem. A travelling salesman has to find the shortest route to allow him to visit a given number of cities. The number of possible routes explodes very rapidly as the number of cities increases. For fifty cities there are more than 10^{62} possible routes (that's a 1 followed by 62 zeroes). Even with a trillion super-powerful computers, it would take more than the lifetime of the universe to check out all potential routes. Many computational-level theories of cognition are equivalent to NP-hard problems, including those related to vision, planning, learning a language, decision-making, categorizing and making analogies. For cognitive scientists the 'grand challenge' is to explain how the brain nevertheless manages to solve such problems, even though they seem to be intractable from a computational point of view.

certain things. Each of us uses this knowledge to read things, as we put it, 'between the lines'. This capacity goes way beyond what artificial intelligence systems are currently able to do."

Fundamental problems

Cognitive capacities require an explanation at three levels, she explains, referring to the seminal work by the British neuroscientist and psychologist David Marr. The first explanation is provided at the computational level. That's the 'what' question: what precisely is the problem that the cognitive process attempts to solve? For example, mapping from the sensory input on the retina to a three-dimensional visual representation of the world. The answer to this question can be formulated in the form of a mathematical function that maps an input to an output. Then, there's the explanation at the algorithmic level. That's the 'how' question. Given the function at the computational level, how does this form of mapping work? Which algorithm can be used? The third part of the explanation of cognitive capacity lies at the level of implementation. How is the mapping achieved physically? It can be done in a biological way, but also in a non-biological way, for example in a computer.

"My research, which focuses on the computational level, is largely meta-theoretical," explains Van Rooij. "I explore ways of modelling cognition. So my approach is applicable to all types of cognitive models, no matter whether they are neural networks, Bayesian models, dynamical systems, or whatever else. Too often there are discussions about which of these models is better, whereas I see fundamental problems in all of these models."

Van Rooij applies her thinking to a wide variety of areas: from learning and communication to sense of agency and self-awareness. Many models of these cognitive capacities are computationally intractable. In mathematics such problems are known as NP-hard problems (see boxed text above). Van Rooij: "Scientists have very different explanations for why some problems are so hard computationally. Some claim that optimizing makes problems hard, while others argue that it's the large search space that causes problems to become so intractable. Still others think approximation makes problems easier. However, I argue that none of these classical approaches are useful."

Structure in the world

How is it then that the brain is able to rapidly solve cognitive problems that seem to be computationally intractable?

In Van Rooij's opinion, the only possible answer is that the mathematical function used to map an input to an output over-generalizes. "I believe that the brain only computes on a particular subset of the input domain that is relevant to the way we function in the world. Therefore, to explain cognition, cognitive scientists not only need to look inside the brain, but also outside. We need to take the structures in the world into account, and not just the physical structures, but also the social and cultural structures. We need to understand *that* brain in *that* organism in *that* particular world."

"I believe my main contribution is to make invisible problems visible," says Van Rooij. "Not everyone finds this helpful, but luckily some of my colleagues do." Within the Donders Institute she works together with, among others, Ivan Toni on the puzzle of communication. Together they use a digital board game to study human communication. Two players can move figures on a virtual board and they are not allowed to communicate with each other except by moving these figures. Van Rooij: "It turns out that different pairs of players develop different strategies to communicate during the game. I have shown that the communication problem they solve together is computationally even more challenging than an NP-hard problem. This insight helps explain why it's so hard to build a form of artificial intelligence that can play the game." With a big smile she adds: "In science, helping not only means solving problems, it can also be about *identifying* the right problems. In fact, I see myself more as a problem *creator* than as a problem *solver*."

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