NEUROECONOMICS

Best to go with what you know?

Daeyeol Lee

In a changing world, how do we decide our best option? How do we settle between picking something familiar or trying out a new, possibly more rewarding, choice?

You step into a music store: how do you choose which CD to buy? If you pick something by your favourite composer, Schubert say, you know you will enjoy it. But you might want to expand your repertoire by trying a less familiar piece, for example Mahler's symphony No. 10. You might not like it; on the other hand, you might discover a new favourite. So how do you decide between sticking with what you know and like, and trying something more adventurous that might prove even more rewarding? On page 876 of this issue, Daw *et al.*[1] provide valuable insight into how people balance the two basic impulses of exploiting what they know and exploring new options.

Standard economic theories tend to assume that people always make the decision that gives them the greatest reward — in terms of its subjective value or utility to the person. In reality, however, people often do not know which option will produce the best outcome, as even familiar environments change continually, so decision-making strategies must be adjusted through experience[2]. In reinforcement-learning theories[3], estimates of future rewards expected from alternative actions are referred to as their value functions, and these must be updated appropriately to reflect the actual rewards. Choosing the action with the maximum value function is referred to as exploitation. Because value functions are only estimates of future rewards, however, it is often desirable to try out actions that might seem to have suboptimal value functions, and this is known as exploration.

To see how people deal with making decisions in changing circumstances, Daw *et al.*[1] asked their subjects to play a computer game where they could choose among four slot machines. Each machine was assigned a different payout level, and each time the subject played, the payout they received from their chosen machine was determined randomly on the basis of the mean and the standard deviation of the assigned payout. In addition, the mean payout of each slot machine drifted randomly over time, preventing the subjects from ever knowing accurately which slot machine would reward them the most.

Daw *et al.* considered the ways in which people might resolve the exploration–exploitation dilemma. One possibility, known as the ε-greedy rule, is to select the action with the maximum value function most of the time, but to choose randomly among the remaining options with a small probability (ε). Alternatively, people might explore more frequently if the differences among value functions of the various options are relatively small. This behaviour is described by the 'softmax' rule, which states that the probability of choosing a particular action is given by the Boltzmann distribution of the value functions (analogous to the Boltzmann distribution in physics that describes the behaviour of particles according to their energies).

To illustrate the difference between these two rules, let us consider the choice of Schubert versus Mahler, and imagine that the value function is higher for Schubert than for Mahler (shown by the light-blue area in Fig. 1). If there is no exploration, one would always choose Schubert, consistent with the utility maximization posited by standard economic theories. According to the ε-greedy rule, Mahler will be chosen occasionally (with probability ε). According to the softmax rule, the probability that less-preferred Mahler will be chosen depends on the difference in the value functions of these two composers, and increases as Mahler's value function becomes more similar to Schubert's.

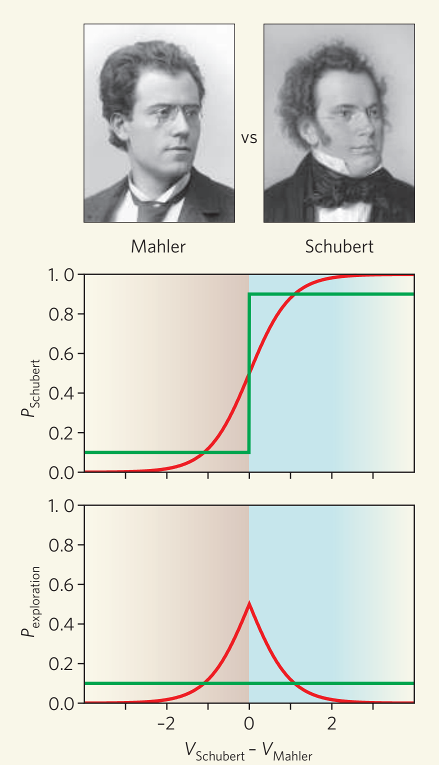

Figure 1 | The contribution of exploration to making a decision. The probability (P) of choosing a particular composer (for example, Schubert rather than Mahler) can be determined by the difference in the value functions between the two composers ($V_{\mathrm{Schubert}} - V_{\mathrm{Mahler}}$). According to the ε-greedy rule (green line), the choice to explore a less-favoured option is made randomly with some probability (ε; here $\varepsilon = 0.1$). By contrast, according to the softmax rule (red line), the probability of exploration increases gradually as the difference in the value functions approaches zero. Daw *et al.*[1] show that in their slot-machine game, subjects seemed to explore options according to the softmax rule.

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The results of Daw and colleagues showed that in their slot-machine game the softmax rule accounted for the pattern of exploration better than the ε-greedy rule. Yet another strategy of exploration in decision-making is to increase the probability of choosing a particular action according to the uncertainty of its outcome. Daw *et al.* found that applying this so-called 'exploration bonus' did not account for the data any better than the simple softmax rule. So it seems that the subjects did indeed explore according to the softmax rule.

To understand how the brain decides to explore, Daw *et al.* examined the activity in the subjects' brains during the slot-machine game using functional magnetic resonance imaging. Consistent with findings from previous studies, they found that several brain areas, such as the orbitofrontal cortex, displayed changes in activity that were related to the value functions of the chosen action[2]. More notably, having classified a subject's choice in each trial as exploitation or exploration, the authors looked for brain areas that showed increased activity associated with each choice. They did not find any areas that became more active during exploitation, but they did find that exploration was accompanied by stronger activation in the frontopolar cortex, a region considered important for the control of cognitive functions[4].

The findings of Daw *et al.* not only provide a unique insight into how we make decisions, but also raise many exciting questions for future research. For example, the randomness of the choice generated by the softmax rule can be specified by a parameter analogous to the temperature in the Boltzmann distribution. At a high 'temperature', all actions are chosen more or less randomly, whereas at a low 'temperature' preferred actions are chosen deterministically. Is it possible that the temperature parameter in the softmax rule decreases, and decision-makers explore less, as they get more familiar with a particular task? If so, what are the underlying neural mechanisms? Changes in the parameters of learning models, such as temperature, are known as meta-learning[5,6], and this process may be controlled by neuromodulators — chemicals such as noradrenaline and acetylcholine that affect the efficacy of other neurotransmitters[7,8]. But the precise roles of these neuromodulators in reinforcement learning and decision-making have still to be defined. As beautifully exemplified by Daw *et al.*[1], exploring these questions will require interdisciplinary approaches, in which the computational theories inspire and guide behavioural and neurobiological experiments. ■

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SOLID-STATE CHEMISTRY

A glass of carbon dioxide

Paul F. McMillan

Carbon is unusual in its family of elements because it has gaseous oxides. But under high pressure, carbon dioxide forms crystalline solids and can become a glass — so revealing the chemical family resemblance.

Everyone is familiar with the common forms of silicon dioxide (SiO_2, silica), such as the crystalline version known as quartz, the major component of sand. When melted and cooled rapidly, and usually mixed with metal oxides, sand forms silica-based glasses that we use to make many useful things, ranging from windows to champagne bottles. A glassy dioxide of germanium (GeO_2, germania) is also known, and is added to the kilometre-long silica glassy fibres used in optical telecommunications, to control their refractive index. Carbon belongs to the same family of elements as silicon and germanium, but carbon dioxide (CO_2, carbonia) glass has remained a theoretical possibility. On page 857 of this issue, however, Santoro and colleagues[1] show that carbonia glass can be made when a high-density form of solid CO_2 is melted and cooled under high-pressure conditions.

Carbon, silicon and germanium are the first three members of group IV of the periodic table, which also includes the heavier elements tin and lead. These last two elements form both monoxides and dioxides, which have been used as pigments since ancient times[2]. In contrast, only the dioxides of silicon and germanium occur as stable solids. Once we reach carbon, the lightest member of the series, we find that both carbon monoxide and carbon dioxide are stable molecules, but these exist as gases at ambient temperature and pressure. As we rise up a group of the periodic table, such anomalous jumps in the properties of compounds formed from the elements of that group often occur. Smooth changes in chemical and physical properties are generally observed among the heavier members of the group, but the lightest element behaves quite differently.

Carbon dioxide is a linear molecule with strong carbon–oxygen double bonds. Freezing or high-pressure treatment condenses this gas into solid forms, in which the molecules remain intact, even under extreme pressurization to 80 GPa at ambient temperature[3]. Recently, however, experiments showed that under simultaneous high-pressure and high-temperature conditions, CO_2 molecules undergo bond-breaking and re-formation reactions, producing a three-dimensional network of polymerized tetrahedral CO_4 units. This network is analogous to the crystalline silica structures found in minerals such as cristobalite, tridymite or quartz[4,5], although it reverts to solids containing CO_2 molecules at pressures below 1 GPa. Other nitrogen- and oxygen-containing molecules also undergo solid-state chemistry at high pressure[6]. These results have generated great excitement among chemists.

The newly prepared materials might have useful properties for technological applications. Studies on the polymeric, silica-like form of CO_2 suggest that it is 'super-hard' and that it is an optically nonlinear material — for example, it causes doubling of the frequency of light from a laser[4,5]. The discovery also has implications for geochemistry, because the conditions found in Earth's mantle could induce the formation of these newly discovered forms of carbon oxides. Incorporation of CO_2 into solid-state compounds formed under high temperature and pressure may even lead to methods for disposal of this environmentally problematic gas.

So, a crystalline silica-like form of CO_2 has been made, but how about a glassy version? Enter Santoro and colleagues[1], who have prepared a dense, polymeric amorphous form of this compound that is analogous to silica- and germania-based glasses. They did this by compressing molecular solid CO_2 to pressures of 40–65 GPa with heating, then cooling it to ambient temperature. Their result is at least as exciting as the discovery of the polymeric crystalline carbon dioxide solid, and the chemistry of carbonia-based glasses is now open for exploration.

So far, glassy carbonia is like its crystalline equivalent in that it is not yet recoverable to ambient conditions, preventing further study of its physical properties. During decompression from the conditions under which it is formed, the glass transforms back to an amorphous version of molecular solid CO_2. Developing carbonia glasses that can be recovered to ambient conditions will be one of the first challenges for future research.

These results[1] have implications for liquid-state physics, and inform us about the conditions under which CO_2 undergoes various phase transitions, including melting[7]. There has been much discussion of the newly recognized phenomenon of polyamorphism — the ability of a material to exist in several different amorphous forms — and of phase transitions between distinct liquid states of a single substance. These are driven by density or entropy changes between glassy or liquid forms at constant chemical composition[8]. It has been suggested that such transitions occur for many liquids and glasses, including water, silica and germania. The observation by Santoro *et al.*[1] that, upon decompression, glassy carbonia transforms from a dense amorphous solid containing networks of single bonds, to an amorphous solid containing molecular CO_2, represents a dramatic example of polyamorphic behaviour, analogous to that observed for amorphous silicon or liquid phosphorus[9,10]. It follows that anomalies are to be expected in the melting behaviour of crystalline CO_2 solids, or that a phase transition may occur in the liquid state at high pressure, between the molecular and the polymeric forms.

The discovery of mineral-like polymeric and ionic solids that form at high pressure, based on the light elements carbon, oxygen and nitrogen, opens up a new area in solid-state chemistry. Carbonia-based minerals and glasses could give rise to useful technological materials, if we can recover them to ambient conditions. These findings will also help set the rules for understanding structure, bonding and thermodynamic properties as we move our experiments into the high-pressure, high-temperature conditions mimicking those deep inside planetary interiors. ■

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