dissemination of spoken language accelerate the demise of regional dialects and less widely spoken languages? Written contracts today have greater legal standing than verbal ones. Will that distinction persist in a world in which spoken and written words have equal permanence? How can we harness this new technology to accelerate access to new knowledge, and what would be the implications of the resulting compression of innovation cycles?

Our parents complained that our generation relied on calculators rather than learning arithmetic. Will we complain when our grandchildren rely on speech-enabled systems rather than learning to read and write? Near-universal literacy has been one of humankind's greatest accomplishments, with 82% of the world's adult population now able to read and write. But it was the ephemeral nature of speech that gave rise to the imperative for literacy, and it is intriguing to imagine what will happen as that imperative abates. In Plato's *Phaedrus*, the Pharaoh Thamus says of writing, "If men learn this, it will implant forgetfulness in their souls: They will cease to exercise memory because they rely on that which is written" (*6*). Plato could not anticipate all the ways in which writing would be used for so much more than merely to augment memory—from an Internet that transports ideas through time and space, to great works of literature that transport our imagination to places that do not exist. What would a modern-day Plato have to say about the rise of speech to stand alongside writing as a cornerstone for our society? Our generation will unlock the full potential of the spoken word, but it may fall to our children, and to their children, to learn how best to use that gift.

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ECONOMICS

Can Neural Data Improve Economics?

Researchers are exploring how neurobiology can guide economic experiments and refine economic models.

Eric Maskin

Modern neuroimaging techniques—functional magnetic resonance imaging (fMRI), positron emission tomography scans, and so on—allow us to peer inside the brain and see what is going on when experimental subjects make economic decisions such as how to bid in auctions. The data on, say, dopamine release in the nucleus accumbens, or—as Delgado *et al.* (*1*) report on page 1849 of this issue—blood oxygen in the striatum, are certainly fascinating in their own right. But can they improve our understanding of economic behavior?

Opinions diverge on this question. Neuroeconomists Camerer *et al*. recently predicted that "We will eventually be able to replace the simple mathematical ideas that have been used in economics with more neurally-detailed descriptions" (*2*). By contrast, economic theorists Gul and Pesendorfer maintain that neuroscience evidence is irrelevant to economics because "the latter makes no assumptions and draws no conclusions about the physiology of the brain" (*3*). Limited to current practice in economics, the Gul-Pesendorfer assertion is correct. In a standard economic model, a decision-maker is confronted with several options, and the purpose of the exercise is to predict which one the subject will select. The model assumes and asserts nothing about the subject's brain states, nor is there any call for it to do so as long as the prediction is accurate. But predictions based on standard choice models are sometimes far from satisfactory, and so in principle, we might improve matters by allowing predicted behavior in the model to depend not only on the economic options but also on neurophysiological information.

Buying behavior. Why do people overbid for items at auction?

So far, the field of neuroeconomics has not developed such an expanded model. Moreover, even when it does so, there are knotty problems of obtrusiveness and privacy to be resolved before one could perform brain scans outside the laboratory. The field has been moving quickly enough so that there is cause for optimism that all this will ultimately transpire, but integrating neural information into everyday economics is probably a good many years off.

What can be done with brain scans before that happy time? One possibility advocated by Delgado *et al*. is to use them for discriminating among standard economic models, in which neurophysiological variables (such as changes in blood oxygen levels) do not appear. Most puzzling economic phenomena admit quite a few conceivable alternative explanations, and neural data can streamline the process of finding the best one—suggesting follow-up experiments or new hypotheses. The authors use this approach to try to illuminate subjects' behavior in high-bid auction experiments. While they are probably right about how neural data can be useful, their application of this principle to auctions does not seem entirely successful.

In a high-bid auction, each potential buyer for the item being sold makes a sealed bid (i.e., quotes an amount of money without disclosing that amount to the other buyers). The buyer making the highest bid wins the item

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and pays the seller that bid. High-bid auctions call for strategic behavior by buyers. If the item is worth *v* to a buyer, she will bid strictly less than *v*, because bidding her actual valuation would gain her nothing: She would get something worth *v* but also pay *v*. How much she "shades" her bid—that is, bidding below what the item is worth to her—will depend on what she expects others will do. Game theory predicts that each buyer will bid so as to maximize her expected payoff, given that all other buyers do the same. The result is what is called an equilibrium.

In one of the Delgado *et al*. experiments, there are two buyers, whose assigned valuations for the item being sold are drawn independently from a uniform distribution on the numbers between 0 and 100. If the buyers are risk-neutral—that is, if a buyer's expected payoff is her net gain from winning (valuation minus bid) times the probability of winning—then in equilibrium, the buyer will bid half her valuation. However, Delgado *et al*. found—as have many other similar experiments—that subjects generally bid more than this: They "overbid."

Delgado *et al*. discuss two standard explanations for overbidding. One is that subjects are risk-averse rather than risk-neutral—they strictly prefer the expectation of a monetary gamble to the gamble itself. The other is that they get an extra psychic benefit from beating out another buyer. What the authors do not mention, however, is that both hypotheses are now considered somewhat dubious: Recent experimental evidence seems in conflict with each of them (*4*). Thus, it is welcome that Delgado *et al*. propose their own explanation, based on fMRI studies they performed.

Unfortunately, it is not completely clear what this new hypothesis is. The fMRI data show that subjects experience a lower blood oxygen level in the striatum in response to losing an auction, but no significant change in reaction to winning one. The authors interpret this result as suggesting that subjects experience "fear of losing" and that this fear accounts for their overbidding. But actually modeling fear explicitly—making it precise—does not seem straightforward.

A natural modeling device would be simply to subtract something from the subject's payoff when she loses. However, such a modification would not accord with the authors' findings in their subsequent experiment. In the follow-up, there were two treatments: one in which a subject is initially given a bonus sum of money *S* but told that she has to return it if she loses the auction; the other in which the subject is promised that if she wins she will get *S*. The two treatments are, *ex post*, identical: In both cases, the subject ends up with the bonus if and only if she wins. However, in practice, subjects bid more in the former treatment than the latter. Such behavior sharply contradicts the "payment subtraction" hypothesis, under which behavior in the two treatments would be the same. Moreover, it seems difficult to find a natural alternative formulation of the "fear of losing" idea that explains the results simultaneously from both Delgado *et al*. experiments. Even so, there is a well-known principle that could account for the behavioral discrepancy between the two treatments in the follow-up experiment: the "endowment" effect (*5*). When a subject is given a bonus *S* at the outset, she may become possessive and so move more aggressively to retain it than she would act to obtain a contingent bonus at the end of the experiment.

As for why subjects overbid, perhaps the answer is that high-bid auctions are just too complex for a typical buyer to analyze completely systematically. The buyer will easily see that she has to shade her bid (bid strictly below *v*) to get a positive payoff. Still, she won't want to shade too much because shading reduces her probability of winning. A simple rule of thumb would be to shade just a little. But this leads immediately to overbidding, because risk-neutral equilibrium bidding entails a great deal of shading: A buyer will bid only one-half her valuation.

In short, Delgado *et al*.'s discovery of a dip in striatal blood oxygen levels when buyers lose in an auction is an intriguing neurophysiological finding, although it is not so clear that it has yet led to a better economic model of buyers' behavior. Still, the philosophy of Delgado *et al*.—that neural findings show great potential for improving economic analysis—is one that should be endorsed, well before the time when neuroscience and economics become one.

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CHEMISTRY

Nonlinear Thinking About Molecular Energy Transfer

Richard M. Stratt

Although solvent molecules move about randomly in a liquid, an experiment showed that changing their initial arrangement affected the rate of a chemical process.

In the movies, nobody cares what the extras are doing or saying, but you would notice if they were missing. Chemical reactions in solution are similar. The solvent molecules need to be there to ferry energy into and out of the reacting molecules, but when chemists study how molecules change into one another in chemical reactions, solvent molecules barely show up in the credits. In fact, the working hypothesis of most studies of chemical reactions run in solution is that the details of how the reaction funnels energy into the solvent tend to average out: The ability to transfer energy depends on the solution's friction (its intrinsic ability to absorb energy), not on precisely how the energy is donated. This notion, which sanctions not having to remeasure or recalculate results with every tiny shift in reaction conditions, receives its justification from linear response theory, an idea that is used in many fields to understand complex systems. Thus, the observation that linear response does not always work as expected, as Bragg *et al*. (*1*) demonstrate on page 1817 of this issue for the simplest chemical reaction—shifting an electron—is striking.

A basic tenet of linear response theory is that the energy flow in macroscopic systems is proportional to whatever causes it, with the proportionality constant a measure of the relevant friction. Linear response theory accounts for current being proportional to voltage in Ohm's law, for example (with the resistance a constant, reflecting the constancy of the friction) (*2*). However, in more recent

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