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Dual or unitary system? Two alternative models of decision making

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In recent years, a lively debate in neuroeconomics has focused on what appears to be a fundamental question: Is the brain a unitary or a dual system? We are still far from a consensus view. The accumulating evidence supports both sides of the debate. A reason for the difficulty in reaching a convincing solution is that we do not yet have a clear theoretical model for either position. Here I review the basic elements and potential building blocks for such theories, using sources in large measure from classical decision theory and game theory.

In recent years, a lively debate in neuroeconomics has focused on a fundamental question: Is the brain a unitary or a dual system? When facing a choice of an economic nature, we may formulate two hypotheses about how the final decision is made. According to one view, the brain acts as a unified system, in the role of information processor: This system elaborates the inputs provided by the description of the choices, and eventually produces a final decision. Different units may take part in the process, and each may provide separate elements for the evaluation of the available options. The activity of these elements is not controlled by any central unit, and coordination may require some way of integrating the inputs provided by the different units. No one of the units, however, can reach a decision on its own.

According to the alternative view, most of our choices, and all of the interesting ones, produce an internal conflict between two (or perhaps more) well-defined and complete preferences about the available outcomes. It may be useful to think of each such preference as a "self." The reason for this name is that each of these two selves could in principle reach a decision on its own, and from this point of view is very similar to an individual. When the potential choices of the two selves agree, the solution is naturally the commonly preferred choice. When they disagree, some way of resolving the conflict is necessary: For example, the intensity of the preference of each self may determine the option chosen, or a control unit may override the choice made by one of the units. Thus, an additional concept is needed to provide a prediction on the final outcome—for example, the Nash equilibrium concept.

After this brief review, the next section makes clear that a consensus view is still far from being achieved. The accumulating evidence supports both sides of the debate. A reason for the difficulty in reaching a convincing solution has been that we do not yet have a clear theoretical model of either of the positions. The purpose of this study is to review the basic elements and potential building blocks of such theories, using sources in large measure from classical decision theory and game theory.

Dual and Unitary Systems: Evidence

Three separate sets of experimental evidence have informed the ideas on this matter. If we focus only on economic choices that do not involve other individuals, three different environments have been considered.

Early and late rewards. The first environment involves choices among outcomes that occur at different points in time. For example, the subject has to choose between the payment of $10 today and the payment of $12 in a week. In this case, the two-selves hypothesis assumes a tension between short-run and long-run preferences. The short-run preference favors immediate rewards and is less sensitive to future ones. The long-run preference has opposite inclinations, and so is more able to trade off the advantages of payments at different points in time.

In brain-imaging studies, the hypothesis that two systems may be simultaneously active when the choice is made should be reflected in differential activation of distinguishable neural systems. This is, of course, a necessary condition; the fact that different systems are activated, however, is not by itself sufficient to prove the dual-system hypothesis. The short-run preference is assumed to be located in the limbic system, the long-run preference in the lateral prefrontal cortex. This prediction has been tested, and support for it was found by McClure, Laibson, Loewenstein, and Cohen (2004), for the case of monetary payments, and McClure, Ericson, Laibson, Loewenstein, and Cohen (2007), for the case of primary rewards. The strategy in these studies was to compare the brain activation for choices that included an immediate reward and for choices between delayed outcomes only. Areas more strongly activated in the former case should correspond to the short-run preference, whereas those ac-

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tivated in all choices should correspond to the long-run preference.

The opposite point of view, corresponding to the unified-system hypothesis, was presented and defended by Kable and Glimcher (2007). Their results showed that neural activity in ventral striatum, medial prefrontal cortex, and posterior cingulate cortex tracks the subjective value of monetary rewards. The subjective value to the subject is determined independently of the choices that are made. The unitary hypothesis is supported by the finding that the subjective value of rewards in time is represented in the human brain within regions that are independent of the date of the earlier payment. This study did not use choices including immediate payments; thus, further studies will be desirable that combine a focus on subjective value with choices that include an immediate reward.

Risky and ambiguous choices. The second environment involves choices under uncertainty. In a typical experimental design, the subject has to choose between two *lotteries*, where a lottery is a promise to pay a specified amount that depends on the realization of a random outcome. The crucial difference stems from the nature of the uncertainty. In a risky lottery, the probability of each outcome is explicitly and clearly specified to the subject. In an ambiguous lottery, these probabilities are not specified explicitly, but instead are left to the subject to evaluate. In addition, the environment defining the probability is sufficiently unfamiliar to the subjects that they can only evaluate it imprecisely, and will naturally not be confident of their own belief.

In this case, the two selves are assumed to operate independently on risky and ambiguous choices. The different neural structures involved are regions that have been found to be active in the processing of such emotions as fear (the amygdala). The dual-system view was presented and defended by Hsu, Bhatt, Adolphs, Tranel, and Camerer (2005), and the unified-system view by Levy, Rustichini, and Glimcher (2007).

Gains and losses. The third environment also involves choices under uncertainty, but this time the crucial difference concerns not the probability but the outcomes. Here, the two selves in the dual-system hypothesis have different attitudes toward gains and losses. Examples of such dual systems were presented by Breiter, Aharon, Kahneman, Dale, and Shizgal (2001), Kahn et al. (2002), Dickhaut et al. (2003), Kuhnen and Knutson (2005), and Knutson, Taylor, Kaufman, Peterson, and Glover (2005). The unified-system point of view was presented by Tom, Fox, Trepel, and Poldrack (2007).

Cognitive skills and preferences. The puzzle has been made more interesting in the recent past by a set of experimental findings that relate choice to cognitive skills. The question that these experiments were addressing was natural, given the premises we have seen so far. Independently of whether one adopts the unitary or the dual-self model, a natural conjecture is that cognitive skills affect economic choices.

For example, if one accepts the premises that an impulsive self strongly prefers the immediate delivery of a reward to a later delivery and that self-control is necessary to override this temptation, then, if higher cognitive skills are associated with stronger self-control, such skills should correspond to more effective self-regulation. Thus, higher cognitive skills should be associated with less-impatient choices and more willingness to postpone consumption.

A similar conclusion, however, would follow from a unitary model, in which the emphasis is on choice as information processing: A later payment is more complex to analyze than a present one, and people typically dislike options that they cannot clearly understand. Thus, everything else being equal, a subject who is higher in cognitive skills should be more inclined to choose the later payment than a subject with lower skills would be.

Behavioral findings. The leading hypothesis, supported by experimental test, of Mischel, Shoda, and Rodriguez (1989) links self-control and preferences: Self-control within the child in choices between immediate and future rewards predicts cognitive and social competence in the adolescent.

How cognitive skills affect choices in other environments—for example, choice under uncertainty—is less clear. An individual more inclined to save than to consume today might be considered more likely to avoid risky choice and to display more prudent behavior when choosing under uncertainty. The experimental findings (Benjamin, Brown, & Shapiro, 2006; Burks et al., 2007; Burks, Carpenter, Götte, & Rustichini, 2008; Dohmen, Falk, Huffman, & Sunde, 2007) show just the opposite: Subjects with higher cognitive skills are also generally more willing to take calculated risks.

The relationship between cognitive skills and risk taking is complex and imposes restrictions on the theories that try to explain it. This effect is not monotonic: If one looks at the mean intelligence quotient (IQ) according to categories of risk-seeking behavior, the highest mean is reached just below risk neutrality. Also, the effect is different when losses are involved; in this case, subjects with lower IQ are more risk seeking. In both cases, higher-IQ subjects are closer to the risk neutrality benchmark. The common link with cognitive skills induces a correlation among preferences. Subjects displaying higher patience in intertemporal choices are also more risk-taking.

The finding that cognitive skills affect economic behavior extends to behavior in games: Subjects with higher cognitive skills are found to have a stronger awareness of the social implications of their actions. They are more generous and cooperative, but also are more willing to retaliate when they observe negative behavior directed at them. Although the latter evidence is indirectly related to our general topic of decision making, it confirms the general hypothesis that the effect of general cognitive ability extends its influence to more general decision making, beyond single-player economic choice.

Cognitive load, transcranial magnetic stimulation (TMS), and transcranial direct current stimulation (tDCS). A test of the general hypothesis that cognitive skills affect preferences has been provided by experiments in which the cognitive skills are modified, either by nonintrusive methods, such as cognitive loads and distractors, or by more intrusive procedures, such as TMS. Examples of the use of cognitive loads are in Shiv and

Fedorikhin (1999), Ward and Mann (2000), and Benjamin et al. (2006); in these articles, the result seems to be that impulsive choice is strengthened by cognitive load.

The connection between these results and the rest of the evidence is not yet clear. For example, in Knoch et al. (2006), subjects were asked to choose between two lotteries, one of which—call it *X*—was more risky than the other—call it *Y*. Say the *X* lottery has outcome *x* with probability *p*, and outcome $-x$ otherwise; the *Y* lottery has outcome $-y$ with probability *p*, and outcome *y* otherwise, with $y > x$. For example, if $p = 5/6$, $x = 20$, and $y = 80$, lottery *X* pays \$20 with probability 5/6 and −\$20 with probability 1/6. Lottery *Y*, on the other hand, pays −\$80 with probability 5/6 and \$80 with probability 1/6. Lottery *X* has a positive, and lottery *Y* a negative, expected value. Lottery *X* also has a smaller variance. The only redeeming quality of lottery *Y* is that it has a larger maximum payment; this fact was particularly salient in the presentation of the lotteries used in Knoch et al.'s experiment, in which only the positive payment was displayed.

Subjects received repetitive TMS (rTMS) on the right or the left dorsolateral prefrontal cortex (DLPFC), or a sham treatment. Subjects who were treated in the right DLPFC chose the *Y* lottery about 20% of the time, as opposed to slightly less than 10% of the time for the other two groups. The difference was significant, so the impairment produced by the rTMS on the right DLPFC produced more risky behavior. The difference in the effects of the right and left treatments indicated a likely right lateralization of some important component of the decision process. Similar results were found with a different method, tDCS (Fecteau et al., 2007), for ambiguous choices.

Dual-Self Models

As was mentioned earlier, a multiple-selves model predicts that the brain-activity and behavioral correlates of economic choices are the output of conflicts between different neural circuits, each of them, in some sense, pursuing an independent and potentially conflicting aim. Early presentations of the dual-self idea can be found in Strotz (1955), Pollack (1968), and Phelps and Pollack (1968), within economics, and Mischel et al. (1989), within psychology.

Time inconsistency. Strotz (1956) and later Pollack (1968) focused on the phenomenon of *time inconsistency*. That is, when planning at time 0, a decision maker might and should plan ahead and choose what to do not only in the current period, but also in future ones. This is a necessary prerequisite for good planning: For example, a decision to save today cannot be effective if the decision maker does not also plan when and how much to spend in consumption in the future. So, a plan made today is both a choice of action today and a sequence of choices in future days, to be executed when the time comes. A decision maker is time-inconsistent if the action planned at time 0 for a future period is different from the one actually chosen during that period; in other words, the choices made in the future are different from those that form part of the earlier plan.

Time inconsistency can be interpreted naturally as the behavioral manifestation of a conflict between two selves: one inclined to consume more today, the other inclined to save for the future. Pollack (1968) and Phelps and Pollack (1968) noted that a decision maker who discounts the future in a way different from exponential discounting may exhibit time inconsistency. For example, suppose that the decision maker values the utilities at future times according to the sequence

$$(1, \beta\delta, \beta\delta^2, \ldots, \beta\delta^t, \ldots).$$

Exponential discounting occurs when $\beta = 1$. When the decision maker makes a plan at time 1, the trade-off between consumption at times 2 and 3 is given by the ratio of the two factors, which is δ. The trade-off between times 1 and 2 is instead $\beta\delta$. Only when $\beta = 1$ are the ratios the same between times 1 and 2 and times 2 and 3.

If $\beta < 1$, however, when the second period comes, the trade-off between the present and the future changes to $\beta\delta$, and consequently the choices differ from those planned earlier. The factor β measures the degree of the inconsistency and suggests the degree of underlying conflict between the two selves: It indicates that the benefits from all future consumptions are uniformly reduced by β. When tomorrow becomes today, all consumptions but the current one are reduced by β, and the valuation of future benefits is always biased in favor of present consumption.

Time inconsistency represents a problem because, with no further specifications, the theory does not predict behavior. Phelps and Pollack (1968) proposed a solution, by considering the problem as a game between the decision makers at each point in time. Each of these decision makers (or selves) chooses a saving rate—that is, a linear function from available income to amount saved. The equilibrium vector of choices satisfies the Nash equilibrium condition that the choice described at the equilibrium is the optimal one if the other choices are taken as given. The solution has been applied to a conflict between selves (instead of a conflict between generations, as in Phelps & Pollack, 1968) by Laibson (1997).

Temptation. The introduction of game theoretic concepts in the field of decision making has been considered an unnecessary complication by some theorists, who view as undesirable the use of a conceptual structure designed to analyze multisubject interactions to study a single-subject problem. For example, multisubject concepts bring to the analysis problems, such as a multiplicity of equilibria, that weaken the predictive power of the theory.

These theorists have suggested the use of cleaner axiomatic models based on a more sophisticated object of choice: menus (Dekel, Lipman, & Rustichini, 2001, in press; Gul & Pesendorfer, 2001). Every choice we make typically implies a different set of choices available for us in the future, which we might call a *menu*. For example, when we choose one restaurant instead of another, we are literally choosing a menu. When we decide the amount we save today, we decide the menu of consumptions available tomorrow. The freedom to choose at later dates provided by a menu may reveal something important about the decision maker. For example, if a decision maker always likes larger menus, this reveals a preference for flexibility. But if the decision maker sometimes chooses a smaller menu rather than a larger one, when both are available at the same cost, this reveals a preference for commitment, which may be induced by the awareness that new options might be tempting in the future. Hence, the conscious choice of a smaller menu reveals that the subject is exercising self-control. This idea is the basic element in the simple model that I will use later to present a unified approach to dual-system theory in different environments.

Self-control. In psychology, Mischel et al. (1989) introduced the idea that a difference in the behavior of children who face the temptation of an immediate consumption reveals deep character differences in the children. Mischel et al. measured individual differences in self-control among children by offering them treats and then leaving the room; the children had the option of waiting to the end of a period and getting the most preferred object, or calling the experimenter back before the end and getting the least preferred one. Mischel et al. found that differences in this preference were already clear in the preschool years and were enduring: The 4-year-old children who were able to delay gratification more effectively achieved higher school performance in later years and were better able to cope with frustration and stress.

A model with short- and long-run selves. A simple model of the dual-system theory was presented by Fudenberg and Levine (2006; see also Bernheim & Rangel, 2004; Loewenstein & O'Donoghue, 2007). As an introduction to the main idea in this model, consider a simple consumption-and-saving problem: An individual lives for infinitely many days, earns every day a given amount of wealth, and has to decide how much to consume and how much to save. The wealth saved produces an additional amount of wealth (e.g., through interest) and carries over to the next day. The individual likes consumption and does not derive any intrinsic pleasure from saving, although he or she may want to save in order to increase future consumption. How does this individual decide on the amount to consume each day?

In Fudenberg and Levine (2006), this decision is the result of a game played between a long-run self (LRS) and the sum of the utilities of all of the short-run selves (SRSs): In this game, future utility is discounted.

The choice in a period is made by the SRS in that day, and no one else. The only way the LRS can affect choices is through self-control. By paying the appropriate amount, the LRS can make sure that any specific action the LRS desires is finally chosen by the SRS. However, this is a psychological effort that is costly to exercise: The cost to implement an action a is proportional to the temptation, which is the difference between the maximum utility the SRS could derive from a free choice of action (with no self-control) and the utility derived from action a. The utility that both the LRS and the SRSs experience is the net utility, including this cost. How does such an individual choose?

Time preferences. Let us begin with choice of payments over time. We denote by ($\$x$, t) the promise to pay the amount $\$x$ to the subject, t days in the future. Consider the choice between a payment today and a larger payment later—for instance, the choice between ($10, 0) and ($12, 7). The SRS will choose the payment today, independently of the size of the future payment, because this money increases the consumption that is feasible today, and hence the SRS's utility, whereas the future payment has no effect on current consumption.

The LRS instead will consider and compare the beneficial effects on the utilities of the self today and of the self in a week. In general, if the future payment is sufficiently larger than the payment today, the LRS will want the future payment for the good of the future SRSs and will choose to exercise self-control. Since self-control is costly, the choice will be biased in the direction of the taste for current consumption of the current SRS: The subject's choice will be made with less patience than it would be if the LRS had full control of the choice with no cost. Now consider instead the choice between two payments, both occurring in the future, such as ($10, 30) and ($12, 37). In this choice, the SRS has no interest at stake, so the choice can in effect be made by the LRS with no payment of self-control costs. Thus, this choice of the individual will appear to be motivated by a greater degree of patience.

In summary, the choice between $10 earlier and $12 a week later is reversed when the earlier payment occurs today, as opposed to when it occurs in a month, and this reversal occurs because the SRS is dominant in the first choice, but the LRS is dominant in the second.

Risk preferences. Suppose that the LRS has decided the amount of self-control and the SRS is left with an amount of money (pocket cash) to spend. Since the SRS is only interested in the present consumption, the plan is to spend all of the money.

Now suppose that our individual is offered a lottery. The individual can either accept the lottery, and pay the loss or cash the wins, or stay with the current amount of money. Suppose, too, that the LRS gets to make the choice of accepting or rejecting the lottery. How will this choice be made? The LRS will look forward and consider the possible actions that could be taken once the outcome of the lottery is revealed, when the LRS will again have the opportunity to plan and to exercise self-control, if needed.

Before we proceed, a brief reminder about the effect of wealth on risk aversion is necessary. The outcome of a lottery is added to the wealth that was available to the individual before the lottery. The same individual (with a given utility function) will look at these outcomes differently, depending on the amount of wealth available. If the amount is small, a loss might push the individual's wealth to very low, undesirable levels. This possibility will weigh heavily in the decision, and the individual will try to avoid it. The same individual facing the same loss with a higher level of wealth will find this occurrence not so undesirable, and thus will be more inclined to risk a loss for the benefits of a win. In summary, the same individual will be more risk averse with a smaller than with a larger amount of initial wealth.

Suppose that the amount at stake is small in comparison with total savings and pocket money. In the case of a win, a new intervention of the LRS will not be needed, and the individual will consume the entire cash available. In this case, the payment from the lottery will be evaluated from the point of view of the small wealth represented by the pocket cash plus the win, and so the individual will behave in a more risk-averse way.

Suppose instead that the amount at stake is large. Now the potential beneficial effect on future selves from an additional amount saved out of the lottery gain is important enough to warrant an intervention of the LRS, who will then exercise self-control and consume in that period less than the total new amount. The gain from the lottery is now considered from the point of view of the total wealth, a larger amount, and so the individual will behave in a less risk-averse way.

In summary, the dual-self model predicts very risk-averse behavior from subjects for small amounts, which does not translate into a similar risk aversion for larger stakes (as predicted, e.g., in the calibration theorem of Rabin, 2000).

Cognitive skills and preferences. In this dual-system model, cognitive skills affect choice by affecting the ability to exercise self-control: Better cognitive skills allow better self-control. In the specific Fudenberg and Levine (2006) model, this principle can be formulated by assigning a lower cost of self-control to individuals with higher cognitive skills, or alternatively a larger range and effectiveness of the self-control mechanism. The effect of higher cognitive skills on choices is now easy to see if we consider two extreme cases. Take two individuals with the same utility over consumption and the same underlying time preference, but with different costs of self-control: The first has zero cost, and the second has infinite cost. The first is as patient as the LRS optimal planner would be if allowed to choose directly. The second, on the other hand, chooses to immediately consume all that is available. The intermediate cases of self-control give the appropriate intermediate cases in choice.

Unitary-System Models

The key idea of dual-system models is the conflict between the two selves; in unitary models of decision making, the idea instead is that choice is information processing. Obviously, the hard part of the task for a unitary model is to specify a model of decision making and then to show how it can provide an explanation of possibly paradoxical behavior in different environments. In addition, the model will have to provide an explanation of the connection between cognitive skills and choices, with the restrictions imposed by the experimental findings illustrated earlier.

The starting point of this exposition is the notion of order.

Orders. The notion of order is perhaps familiar: A set has total order if, for any two options x and y, a decision maker can always decide whether he or she strictly prefers x to y, or vice versa, or is indifferent between the two. Note that the order has two constituents: the strict preference relation and the indifference relation.

The strict preference is transitive: If x is strictly preferred to y and y is strictly preferred to z, then x is strictly preferred to z. The indifference relation is reflexive (x is indifferent to x) and symmetric (if x is indifferent to y, then y is indifferent to x). The indifference relation is also transitive: If x is indifferent to y and y is indifferent to z, then x is indifferent to z. This last condition is probably the most unlikely from the empirical point of view.

Nontransitive indifference. A classic example can illustrate the motivation for this key idea. Suppose you like your coffee with sugar. You are first asked to choose between two cups, one with one grain of sugar and the other with no sugar at all. You will not perceive any difference in taste when you take sips from the two, so you will be indifferent. Then you are asked to choose between a cup with two grains and a cup with one grain; the outcome will be the same. In any binary choice between a cup with n grains and a cup with $n + 1$ grains, you will be indifferent, up to a value N, your ideal amount of sugar. But if someone asks you to choose between a cup with 0 and one with N grains of sugar, you will prefer the second one. Here, the indifference relation is not transitive (Armstrong, 1939): The fact that you are indifferent between option n and option $n + 1$ for every n from 0 to N does not imply that you are indifferent between option 0 and option N.

The reason for the lack of transitivity is clear: Our senses and perception have limited discriminatory power, and each of us is characterized by a *just noticeable difference* (JND). We perceive a difference between two stimuli only when the difference is larger than this threshold. The JND is typically different among individuals, and can be taken as a good measure of an individual's discriminatory ability. This idea can be extended from sensory perception to the cognitive judgment that is involved in the evaluation of economic options at the moment of choice.

Semiorders. The concept of semiorder (introduced by Luce, 1956) is the appropriate generalization if one does not want to assume that the indifference order is transitive. An individual who has a semiorder can still decide, facing any pair x and y, whether one of the two options, and which, is strictly preferred, or whether he or she is indifferent. The strict preference relation is transitive, and the indifference relation is reflexive and symmetric. However, unlike with the total order described above, the indifference relation is not transitive. What produces this difference?

Going back to the simple example, suppose that the decision maker has to choose between pairs of options from the set x_0, x_1, and x_2 (zero, one, and two lumps of sugar in the coffee, respectively). He or she claims to be indifferent between x_0 and x_1 and between x_1 and x_2, but definitely prefers x_2 to x_0. This can be interpreted as the result of two separate factors: The individual truly prefers x_2 to x_1 to x_0 (but does not acknowledge the fact), and so has a true utility of, say, $u(xi) = i$. The available discriminatory power, however, does not allow the perception of a difference in utility smaller than 2. The combination of the true underlying utility with the coarseness of the discriminatory power produces the pattern of choices described.

Luce's (1956) theorem states that this decomposition into two factors is general: Take an individual who does not exhibit a total order on options, but just a semiorder. We can think of this individual's choices as resulting from the combination of a deep but unconscious utility and poor discriminatory power. If the individual could perceive the differences among the utilities of the different options according to the true utility, he or she would display a total order on the options—in particular, a transitive indifference. Under the effect of poor discriminatory power, though, only a difference larger than a minimum threshold is perceptible; x can be preferred to y only when the difference in utility between the two is larger than some minimum value. When this is not the case, the subject is indifferent. The theorem shows that from a pattern of choices, we can elicit precisely both the unconscious utility and the discriminatory power.

Dimensions of choice. A concept like semiorder can explain why people are more indecisive than might seem reasonable, but it cannot explain any paradoxical behavior. To do this, we must make the model richer. Let us begin with the observation that options are typically characterized by several dimensions. For example, a specific food can be described by its taste and its nutritional value. Similarly, a lottery is described by the amount of money you can win in each event and each event's probability.

Individuals make choices by aggregating this rich set of characteristics into a single value. However, this aggregation is difficult, particularly when the characteristics are numerous and different. Individuals may therefore proceed by considering each characteristic separately, thus decomposing the original complex problem into several simpler ones.

One procedure to accomplish this decomposition seems natural (Rubinstein, 1988, 2003) and can be illustrated by the choice among payments over time. Recall that (x, t) is the promise of a payment x at time t. In the choice between (x, t) and (y, s), the subject may begin by considering each coordinate separately. If he or she finds that $x > y$ and $t < s$, the choice is clearly in favor of (x, t). If the values s and t are different, but the difference is not large enough to be noticeable, the comparison between x and y becomes the decisive factor. Saying that a difference is "not large enough to be noticeable" of course introduces an indifference relation between probability values. This relation is typically not transitive: Small, hard-to-notice differences may add up until they become noticeable. Now we can apply the conceptual structure we have seen before to the comparison that the decision maker applies with each coordinate. If the subject's power to discriminate the characteristics is not perfect, this procedure may produce paradoxical behavior such as we have seen in the earlier examples.

Time preferences. Consider a subject who picks (\$10, 0)—that is, \$10 immediately—over (\$12, 7)—\$12 in a week. If this subject's utility is both separable and discounted exponentially, this means that

$$\delta^0 u(10) > \delta^7 u(12),$$

which implies that

$$\delta^{30} u(10) > \delta^{37} u(12),$$

and therefore he or she should also choose (\$10, 30) over (\$12, 37). However, subjects typically reverse their choices and choose (\$12, 37) over (\$10, 30).

This can be explained by the difficulty in integrating the time of payment and the amount paid into a single choice. In the choice between (\$10, 0) and (\$12, 7), time 0 (payment is immediate) is perceived as very different from time 7, so time becomes the dominant consideration, and this tilts the balance in favor of the first option. However, in the choice between (\$10, 30) and (\$12, 37), the dates 30 and 37 days in the future are not perceived as very different (although the length of the interval between the two is 7 days, just as before), and now the fact that the amount \$12 is larger than \$10 becomes the decisive factor.

Risk preferences. Consider now choices under uncertainty. Here, the focus is on lotteries that give some positive amount of dollars x with some probability p, or \$0 otherwise. We can completely describe these lotteries with the pair (x, p), so the decision maker needs to consider two coordinates, given by the amount paid and the probability of payment. This choice is now very similar to the choice among payments over time. Let us see how this procedure can explain, for example, Allais's paradox.

When asked to choose between $L_1 = (\$3{,}000, 1)$ and $L_2 = (\$4{,}000, .8)$, subjects typically choose L_1 over L_2. Now consider the two composite lotteries that give you L_1 (or, respectively, L_2) with probability .25, and \$0 with probability .75. Call these lotteries L_3 and L_4. In view of the description just given, it seems natural to predict that the decision maker will ignore the event occurring with probability .75, since it is the same in both cases, and will therefore prefer L_3 to L_4 if and only if L_1 was preferred to L_2.

However, if we compute the probability over outcomes, we see that $L_3 = (\$3{,}000, .25)$ and $L_4 = (\$4{,}000, .20)$. Now the common observation is that subjects who chose L_1 over L_2 also now choose L_4 over L_3, thereby contradicting what would seem natural to expect.

The explanation of this fact may be that when a subject compares (\$3,000, 1) with (\$4,000, .8), the probability 1 is perceived as very different from .8, and the subject does not want to risk losing everything. However, when comparing (\$3,000, .25) and (\$4,000, .20), the difference between .25 and .20 is not noticeable, so the comparison between \$3,000 and \$4,000 becomes the dominant factor.

Cognitive skills and preferences. How do cognitive skills affect choices in this model? A dependent variable that is natural to consider first is the coarseness of the indifference relation. Take, for any value, the set of all other values that the subject does not perfectly discriminate from it. For example, take for any probability p the set of probabilities that the individual does not distinguish from p. We can compare two individuals by looking at these sets for each of them. If, for any such p, this set is larger for the first individual than it is for the second, we say that the former has coarser perception, or information processing, than does the latter.

A natural assumption is that individuals with lower cognitive skills have coarser information processing. For this reason, their choices will be different from those of individuals with higher cognitive function, even if their underlying "deep" preference is the same. Suppose, for instance, that two decision makers are asked to make several choices. All of the choices involve the same lottery (x, p) and degenerate lotteries $(y, 1)$, which pay an amount y with certainty. The value of y varies in the different choices.

The two decision makers have identical utilities but different information processing abilities: For both, the "deep" utility of a sure payment y^* is the same as that of the lottery (x, p). The first decision maker has extremely accurate judgment, and so chooses the lottery when $y < y^*$, or the sure payment otherwise. The second decision maker's judgment is not as accurate as the first's. When the difference in utility between the sure payment and the lottery is below the JND, the second decision maker can only choose randomly. The choices of the two decision makers are therefore different, since for some values below y^* the second chooses the sure payment, and for some values above the threshold chooses the lottery instead.

This model predicts a difference in the pattern of choices of two decision makers with different cognitive abilities, but only because processing is more noisy for the coarser decision maker. The experimental evidence (see Burks et al., 2007) supports this result: For example, lower IQ scores are associated with larger numbers of inconsistencies in decision making. The same experimental evidence, however, suggests that the effect of different cognitive skills is deeper, because it introduces a systematic bias—for example, making individuals with higher cognitive ability more patient and more willing to take risks. A satisfactory theory of this difference is the subject of current research.

Conclusions

This article has reviewed the available theories of decision making, derived from a long tradition in economic theory, and in particular, decision theory. A discussion of the possible neural basis underlying either the information processing in the unitary model or the conflicting selves in the dual-self model would be the next natural step, but such a discussion was not part of the intent here.

The two views each have natural strengths and weaknesses. The unitary view has the natural advantage of parsimonious explanation; Occam's razor works in its favor. The discipline imposed by the assumption of a single decision-making unit, on the other hand, makes explanation of inconsistencies in the data harder to achieve. The most promising direction for the theoretical research on the unitary model seems a satisfactory model of the effect of cognitive skills on preferences.

The dual-self model, on the other hand, naturally fits observations in which the patterns of decision appear inconsistent. Time inconsistency in choice is the first and most natural example. This inconsistency is easily explained if different selves take control in different circumstances.

The main difficulty for the dual model is that, at the moment, different theories and different models have been developed for each choice environment. The different paradigms seem to correspond to deeply different intuitive ideas about the selves that are in conflict. For example, the self that biases decision over time in favor of present rewards is motivated by impulsive behavior, whereas the self that is activated by ambiguous choices seems to be motivated by fear. Clearly, a theory that invokes different pairs of selves for each different environment is not satisfactory. The Fudenberg and Levine (2006) model is the best attempt available to provide a unified theory of the dual-self model across different environments. Still, even with this model the results probably depend on the specific details of a particular instantiation. The robustness of the link between the theory and experiments is still to be seen.

Research into this topic is active, and probably the most useful contributions will come from experimental tests of the connection between cognitive skills and preferences. The most useful of the experiments will be those that test the two theories directly. Some of the evidence currently available goes in the right direction but still does not provide a satisfactory answer. For example, the results of Knoch et al.'s (2006) experiment seem compatible with both models. A dual-self interpretation suggests that a self attracted by high rewards (but not mindful of their probability) is free to operate in subjects with rTMS in the DLPFC. A unitary model would simply observe that when information processing is impaired, a simple judgment based on the partial information that is more salient (the higher reward of the more risky lottery) would bias choice in the direction of the risky lottery. Ultimately, the two models may not even be mutually exclusive, so the truth might be found in a rich integration of the two.

AUTHOR NOTE

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