Tracking Decision Makers under Uncertainty[†]

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Eye tracking is used to investigate the procedures that participants employ in choosing between two lotteries. Eye movement patterns in problems where the deliberation process is clearly identified are used to substantiate an interpretation of the results. The data provide little support for the hypothesis that decision makers rely exclusively upon an expected utility type of calculation. Instead eye patterns indicate that decision makers often compare prizes and probabilities separately. This is particularly true when the multiplication of sums and probabilities is laborious to compute. (JEL D81, D87)

How do people choose between lottery 1, which yields the prize $\$x_1$ with probability p_1, and lottery 2, which yields the prize $\$x_2$ with probability p_2? There are two types of procedures that come to mind:

Holistic (H-) procedures: In this type of procedure, the decision maker treats the alternatives holistically. For example, he evaluates the certainty equivalent of each of the alternatives and chooses the one with the higher certainty equivalence. Or, he computes the expectation of each of the two lotteries and chooses the one with the higher expectation. More generally, he might have functions g and v in mind and choose the lottery with the higher $g(p_i)v(x_i)$. A canonic formula for such a procedure would assume the existence of a function u such that lottery 1 is chosen if $u(x_1, p_1) > u(x_2, p_2)$.

Component (C-) procedures: The decision maker compares prizes and probabilities separately. In the case that one of the lotteries yields a larger prize with a higher probability, he will choose that lottery. Otherwise, he checks for similarity between the prizes and between the probabilities and uses that similarity to make the choice. If, for example, the prize $\$x_1$ is much larger than the prize $\$x_2$ and the probabilities are similar, even though p_2 is higher than p_1, he would choose lottery 1. A canonic procedure of this type would assume the existence of functions f, g, and h, such that lottery 1 is chosen if $h(f(x_1,x_2), g(p_1,p_2)) > 0$. The idea that the choice of an alternative is based, at least partially, on a comparison of components has appeared in the psychological literature (see, for example, Amos Tversky, Shmuel Sattath, and Paul Slovic 1988).

Our research is motivated by the bounded rationality approach to decision making which focuses on the choice procedures used by individuals. The classical economic approach attempted to explain choice behavior using only the observed choices. Contemporary research (especially in Psychology and Neuroeconomics) attempts to elicit information about choice procedures from observations of the decision maker during his deliberations (including, for example, eye movements and activity in various areas of the brain).

Whereas evidence for H-procedures supports theories that describe the decision maker as explicitly maximizing a utility function, evidence for C-procedures opens the door to other models (such as the one described in Rubinstein 1988) which require an explicit comparison of components and are not necessarily consistent with maximization of a well-defined preference relation. In this paper, we go no further than examining experimental data to find evidence for the use of C-procedures. We believe that experimental evidence as to how people choose between lotteries may change the way in which decision making under uncertainty is modeled; however, as always, the proof is in the pudding.

We attempt to uncover procedures used by decision makers by following their eye movements while they deliberate over a choice. This method was first used in research done in the 70s and was recently revisited.[1] Eye tracking complements another interesting approach which observes mouse movements using a program called MouseLab (see John W. Payne, James R. Bettman, and Eric J. Johnson 1993). In this approach, the participant accesses the information hidden behind boxes on the computer screen by moving the cursor over the boxes.[2] Particularly relevant for our purposes is Johnson, Michael Schulte-Mecklenbeck, and Martijn C. Willemsen (2008) who used MouseLab techniques to study the choice between gambling procedures. Both methods are attractive in that they are cheap to use and produce data that is straightforward to interpret (in contrast to methods that record signals from the brain). However, eye tracking has an advantage over MouseLab in that it records natural and unconscious movements while the need to move the mouse in MouseLab requires a somewhat less natural information acquisition strategy (see Gerald Lohse and Johnson 1996).

I. The Research Concept

In our study, participants[3] were asked to respond to a sequence of simple virtual choice problems. The participants were paid only a show-up fee of $12. Participants were not paid for choices made. There is ample evidence that the lack of monetary incentives does not significantly affect participants' choices (see Camerer and Robin

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[1] Using early eye tracking techniques, J. Edward Russo and Larry D. Rosen (1975) studied multi-alternative choice while Russo and Barbara A. Dosher (1983) investigated multi-attribute binary choice. They concluded that feature-by-feature comparisons make up much of the decision procedure. More recently, Joseph Tao-yi Wang, Michael Spezio, and Colin F. Camerer (2010) investigated behavior in a sender-receiver game and Elena Reutskaja et al. (2011) studied choice of snack foods under time pressure and option overload.

[2] The site http://www.mouselabweb.org demonstrates the program and allows one to try it out.

[3] The participants (24 males and 23 females; average age of 27) all had normal or corrected-to-normal vision and were students (in fields other than economics) in Rehovot, Israel. Participants signed an informed consent form in accordance with the Declaration of Helsinki.
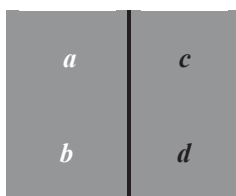
FIGURE 1. SCHEMATIC REPRESENTATION OF THE SCREEN SHOWN TO THE PARTICIPANTS

FIGURE 2. SCHEME FOR CHOICE UNDER UNCERTAINTY PROBLEMS

M. Hogarth 1999). In any case, note that we are interested only in the choice process that led participants to make their particular choices and not in the choice distributions themselves, which are reported only for the sake of completeness.

In each problem, a participant was asked to choose between two alternatives, Left (L) and Right (R), by clicking on the mouse. Each decision problem was presented on a separate screen (Figure 1), in which two parameters, a and b, describe the L alternative and two parameters, c and d, describe the R alternative.[4] No time restrictions were imposed on the participants and a typical median response time was eight seconds.

Our focus is on the case in which L is a lottery that yields \$$x_1$ with probability p_1 (and \$0 with probability $1 - p_1$) and R is the lottery yielding \$$x_2$ with probability p_2 (Figure 2).

We concentrate on comparing the intensity of horizontal and vertical eye movements. Our hypothesis is that decision makers who follow H-procedures will show intensive vertical eye movements while decision makers who follow C-procedures will show intensive horizontal eye movements.

II. The Method

An eye-tracking system[5] was used in order to continuously record a participant's point of gaze. Analyzing the huge amount of recorded data was not straightforward. We first transformed it into movies showing the path of eye movement on the screen.

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[4]We did not alternate the sides on which the alternatives are presented. In order to check whether presenting alternatives on the left side (white letters) or on the right side (black letters) makes any difference, we calculated the distribution of response time over all the problems for participants who chose L ($N = 902$) and participants who chose R ($N = 805$). We found that the average response times of the two groups were practically identical (5.81 sec and 5.75 sec; T-test p-value of 42.5 percent).

[5]We used a high-speed eye-tracking system (iView) made by SensoMotoric Instruments (SMI) which is based on an infrared light camera. It captures (at a sampling frequency of 240Hz or one sample every 4.2 milliseconds) a high-resolution image of the pupil and corneal reflection.

However, there were only a few cases in which the choice procedure was discernable from the movie (a sample movie can be watched at http://arielrubinstein.tau.ac.il/ABR09/). Thus, we needed to develop a measure of the intensity of horizontal and vertical movements.

We divided the screen into four quarters: Top left, top right, bottom left, and bottom right. Eye movements between two sections of the screen are classified into six categories: Left-vertical, right-vertical, top-horizontal, bottom-horizontal, descending-diagonal, and ascending-diagonal. For each problem and each participant, we calculated the proportion of time spent in each of the six categories of eye movements. Averaging over all participants produced a vector α on which our analysis is based.[6] (The six components of α sum up to 100 percent.)

We omitted any period of time for which the eye tracker did not identify the eye position, which was usually the result of blinking. In addition, in order to identify diagonal movements, which always pass briefly through another section of the screen, we omitted any period of time in which the participant's gaze stayed in a particular section for less than 100 milliseconds. Cases in which the above omissions exceeded 20 percent of the response time were excluded from the sample. The same participants responded to all of the problems. However, due to the need to eliminate answers for which the recorded data was not complete, the subset of participants for analysis differs somewhat from one question to the next.

High α-values for the two vertical eye movements will imply that participants' choices were largely based on relating to each alternative as a unit and comparing them as such. High α-values for the horizontal eye movements will indicate that participants based their decisions heavily on comparing each of the features of the alternatives separately.

We suspected that the α-values are sensitive to variation in the level of difficulty in understanding the question's parameters (e.g., if one of the parameters takes a long time to read, this will lengthen the duration of the movement into and out of that section of the screen). Therefore, we also produced a similar vector β for the number of transitions in each type of eye movement. We found that the two measures produced almost identical results.[7]

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[6] Given a choice problem, the exact calculation of the vector α is done as follows:

(i) For each participant i, let 0 be the point in time at which the problem is first presented and T be the point in time at which the participant clicked on the mouse.

(ii) Denote the transition times between sections of the screen by: $t_1, t_2, \ldots, t_k, \ldots, t_n$.

(iii) Divide the segment of time $[0, T]$ into n intervals:

$$[0, (t_1 + t_2)/2], [(t_1 + t_2)/2, (t_2 + t_3)/2], \ldots, [(t_{n-1} + t_n)/2, T].$$

Credit the duration of the kth interval ($k = 1, \ldots, n$) to the total for the type of eye movement that occurred at tk.

(iv) Divide the time credited to each type of eye movement by the total of all the eye movements to obtain a vector $\alpha(i)$ (for participant i), which consists of six numbers representing the proportion of time spent in each type of movement.

(v) Average the vectors $\alpha(i)$ over all participants. Denote the vector of averages as α.

[7] Russo and Rosen (1975) and Russo and Dosher (1983) based their analysis on counting movements from one section of the screen, X, to another, Y, and back to X. In contrast, we base our analysis on counting movements from X to Y even if there is no return to X. In problems where the response time is relatively long, the two approaches yield the same qualitative results. In problems where the response time is relatively short, their method does not yield sufficient data to make significant inferences.

TABLE 1

The lotteries		α-values					
L	R	(pictogram 1)	(pictogram 2)	(pictogram 3)	(pictogram 4)	(pictogram 5)	(pictogram 6)
Panel A							
U1 $3,000	$4,000	**24%**	**23%**	18%	28%	4%	3%
0.15	0.11	(2%)	(2%)	(2%)	(2%)	(1%)	(1%)
U2 $1,700	$1,300	**20%**	**25%**	25%	23%	4%	2%
0.4	0.5	(2%)	(3%)	(2%)	(2%)	(1%)	(1%)
U3 $637	$549	17%	18%	**29%**	**30%**	2%	4%
0.649	0.732	(2%)	(2%)	(2%)	(2%)	(1%)	(1%)
U4 $13,600	$15,500	16%	18%	**33%**	**28%**	4%	2%
0.31	0.27	(2%)	(2%)	(2%)	(2%)	(1%)	(1%)

	N	Percent of choices	
		L	R
Panel B			
U1	35	60%	40%
U2	35	51%	49%
U3	41	41%	59%
U4	35	37%	63%

Notes: Panel A: α-values in lottery choice problems (estimates standard deviations are in parentheses, bold percentages emphasize the difference in α-values between a problem in which the expected payoff calculation is easy and one in which it is difficult). Panel B: the number of participants (N) with eye-tracking data covering at least 80 percent of the response time and their final decisions.

III. Results

The basic results are presented in Table 1, which shows the α-values in four lottery choice problems.

Our first conclusion is drawn from the comparison of problems U1–U2 and problems U3–U4 which differ in the difficulty of calculating the expectation. For U3–U4 (which involves a difficult calculation) the average proportion of horizontal movements is 59–61 percent as compared to only 45–47 percent for U1–U2 (which involves an easy calculation). We infer that when the expectation calculation is relatively difficult participants tend to use a C-procedure.[8]

Our main interest is in the procedure used in problems like U1 and U2. In order to interpret the results, we compared them to results in two other types of problems in which the deliberation process is transparent.

In D1 and D2, participants were asked to indicate which difference is larger ($a-b$ or $c-d$). Results are summarized in Table 2.

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[8] In order to check whether some participants present a consistent tendency for either the horizontal (H) or vertical (V) eye movements, we ranked the participants (for each question separately) according to the relative portion of the vertical movements from the overall horizontal and vertical movements ($V/(V + H)$). We calculated the Spearman rank correlation matrix between the different questions for the 27 participants for which we have reliable measures for all of U1–U4. We found that participants had correlated rankings in 4 out of 6 pairs of questions $\rho(U1, U2) = 0.29$; $\rho(U2, U3) = 0.39$; $\rho(U2, U4) = 0.41$; $\rho(U3, U4) = 0.42$; correlation was significant at the 5 percent level). Similar results were obtained for the diagonal questions U5–U8. This implies some consistent tendency in eye movements. However, we didn't find correlation between eye-movement tendencies and the decisions that were made.

TABLE 2

The differences			α-values					
	L = a − b	R = c − d	⋮ ⋯	⋯ ⋮	•—• ••	•• ••	╲	╱
Panel A								
D1	251	187	38%	44%	13%	3%	2%	1%
	222	153	(2%)	(2%)	(1%)	(1%)	(1%)	(0.3%)
D2	983,462	983,501	18%	22%	35%	20%	3%	3%
	718,509	718,499	(3%)	(2%)	(3%)	(2%)	(1%)	(1%)

		N	Percent of choices	
			L	R
Panel B				
D1		38	24%	76%
D2		37	22%	78%

Notes: Panel A: α-values for problems in which differences were compared. Panel B: number of participants and their decisions.
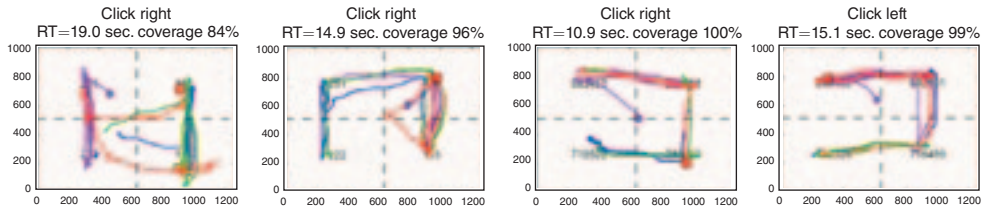

FIGURE 3. EYE MOVEMENTS FOR TWO PARTICIPANTS WHILE RESPONDING TO D1 (*left two boxes*) AND D2 (*right two boxes*)

In D1, the most straightforward procedure involves computing the differences using vertical eye movements. And indeed, vertical eye movements accounted for 82 percent of the time spent on this problem. In D2, the easiest way of making the choice is to calculate horizontal differences and indeed the share of vertical eye movements declined to 40 percent. Figure 3 presents the eye movements of two typical participants; both of them used vertical eye movements almost exclusively in D1 while in D2 horizontal eye movements dominated.

In T1, T2, and T3, participants were asked to choose between receiving a sum of money on a particular date and a different sum of money on another date. The results are summarized in Table 3.

In this case, it is hard to imagine that any of the participants made a "present-value-like" computation which would have involved vertical eye movements. Indeed, we found that 2/3 of eye movements were horizontal. Thus, participants clearly used a C-procedure; in other words, they based their decisions on comparing sums of money and delivery dates separately.

We are now ready to compare the eye movements in problems U1 and U2 with those observed in problems involving the comparison of differences (D1 and D2) and time preferences (T1, T2, T3). For convenience, in Figure 4 we present the α-values of the participants in problem U1 alongside their α-values in D1 and T3.

Table 3

α-values					
Panel A					
T1	16%	15%	24%	39%	3%	4%
	(1%)	(1%)	(1%)	(2%)	(1%)	(1%)
T2	13%	14%	36%	30%	5%	2%
	(1%)	(2%)	(2%)	(2%)	(1%)	(1%)
T3	13%	14%	25%	42%	3%	2%
	(2%)	(2%)	(3%)	(2%)	(1%)	(1%)

	The alternatives			Percent of choices	
	L	R	N	L	R
Panel B					
T1	$351.02	$348.23	39	92%	8%
	On 20-Jun-2009	On 12-Jul-2009			
T2	$467:39	$467.00	38	58%	42%
	On 17-Dec-2009	On 16-Dec-2009			
T3	$500.00	$508.00	39	74%	26%
	On 13-Jan-2009	On 13-Apr-2009			

Notes: Panel A: α-values for time preference problems. Panel B: number of participants and their decisions. Experiments took place during June–September 2008.

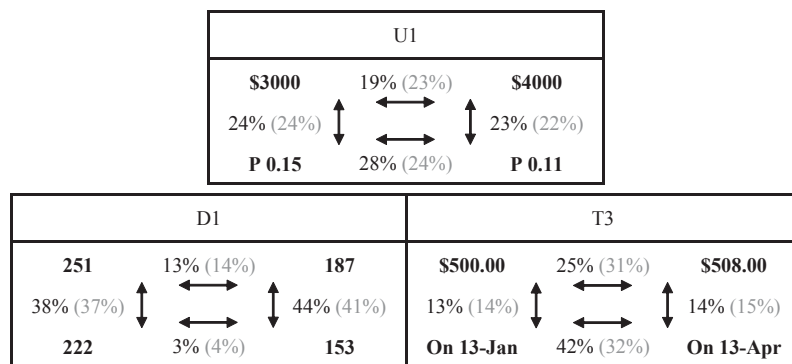Figure 4. α's (and β's) for Participants in U1, D1, and T3

We find that α-values in U1 and U2 fell in between those of the other two problems. The proportion of vertical eye movements in the problems involving choice under uncertainty were well below those in a problem like D1 and well above those in problems involving time preferences, such at T3, in which it is clear that participants use a C-procedure. In each of these problems, the distribution of the frequency of horizontal movements is relatively concentrated around the average.[9] Therefore,

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[9] The distribution of the horizontal movements shows a single peak with standard deviation of 13 percent.

x_1	With probability p_2
With probability p_1	x_2

FIGURE 5. CHOICE UNDER UNCERTAINTY PROBLEM: DIAGONAL LAYOUT

TABLE 4

	The lotteries		α-values					
	L	R						
Panel A								
U5	$5,000	0.11	21%	21%	16%	10%	9%	23%
	0.16	$7,000	(2%)	(2%)	(2%)	(1%)	(1%)	(3%)
U6	$2,468	0.53	19%	22%	16%	8%	14%	21%
	0.26	$1,234	(2%)	(2%)	(2%)	(1%)	(2%)	(3%)
U7	$4,947	0.638	17%	17%	12%	8%	23%	24%
	0.64	$4,952	(2%)	(2%)	(2%)	(1%)	(2%)	(2%)
U8	$621	0.82	16%	19%	13%	10%	19%	23%
	0.87	$652	(1%)	(2%)	(2%)	(1%)	(2%)	(2%)

			Percent of choices	
		N	L	R
Panel B				
U5		37	57%	43%
U6		36	6%	94%
U7		38	61%	39%
U8		38	68%	32%

Notes: Panel A: α-values in lottery choice problems with diagonal layout. Panel B: number of participants and their decisions.

we conclude that most participants in the lottery problems U1 and U2 use procedures that are largely, but not solely, based on the comparison of components.

In another group of problems, we switched the locations of the probability and the dollar amount on the right side of the screen (see Figure 5).

In all the problems apart from those in this group, the α-values of the diagonal movements were negligible. In contrast, diagonal movements were used intensively here (see Table 4).

IV. Conclusion

The aim of this study was to use eye tracking in order to shed light on the procedures used by decision makers in the context of decision making under uncertainty. We conclude that when the numbers which specify the prices and probabilities of two lotteries made the expectation calculation difficult, they rely almost exclusively on separate comparisons of prizes and probabilities. In the other cases, it appears that they are involved in a hybrid of C- and H-procedures.

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