A Brain Imaging Study of the Choice Procedure [1]

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Abstract

We study the behavior of subjects facing choices between certain, risky, partially ambiguous, and ambiguous lotteries in an experimentally controlled environment. Our observations are subjects' choice behavior, response times, and brain activations.

The choices of subjects are consistent with economic theories designed to predict these choices, namely theories modeling ambiguity aversion. The additional evidence we present supports a specific interpretation of the decision process that is implementing these choices. In particular it supports the conjecture that subjects face the choice task as an estimation of the value of the two lotteries; and that a measure of the difficulty of the choice provides an important explanatory variable (in addition to risk and ambiguity aversion) of the observed behavior. Further support for the interpretation of choice as cognitive task in our experiment comes from the observation that emotional factors seem to play a minor role. Specifically, the medial orbito frontal region and amygdala are not activated. Compared with the set of results organized in the Somatic Marker Hypothesis (Damasio [9], Bechara, Damasio and Damasio [1]), these results suggest that a static choice without learning and feedback on outcome is a task of a different nature than a choice with learning and feedback.

The brain imaging data suggest that the estimation is of an approximate nature when the choices involve ambiguous and risky lotteries, and requires mental faculties that are shared by all mammals and in particular are independent of language. The regions in the brain that are activated are located typically in parietal lobes, which are known to be involved in approximate calculations. Choices involving partial ambiguous lotteries produce in addition an activation of the frontal region, which indicates a different, more sophisticated cognitive process. The time to decide is shorter for arguably harder choices, a finding that suggests the need for new models of the allocation of effort in the choice process.

Keywords: Brain Imaging, Decision Theory, Ambiguity, Procedural Choice.

1 Introduction

The economic theory of decision making in the past fifty years has been based in large part on a method familiarly described as the “as if” method. We can describe its main prescription as stating that the realism of the model is irrelevant, and that a model is useful if, and only if, it gives correct predictions. An example of the application of the method is one way, possibly the weakest, to interpret the rationality assumption: subjects are not necessarily rational, but their behavior is the same “as if” subjects were rational individuals.

One way of interpreting the discipline of Decision Theory is in the light of this method. Decision Theory typically characterizes in terms of a set of axioms restricting admissible choices, a representation of the preference order in terms of some utility function. Any such representation can be interpreted as an “as if” construction. The subjects may be very unaware of the functional as well as of any auxiliary concept which is used in the representation (utility function over consequences, beliefs, and so on); still their behavior is completely described and predicted by the function.

The power of this method is the generality of the results: the method is appealing if the same “as if” model can be successfully applied to a variety of circumstances. If different models are needed to “predict” behavior in different circumstances, then the method may be no longer useful. The predictive power of the model is weakened by the introduction of a smaller set of axiomatic restrictions on the behavior: the set of admissible behavior is larger, but the predictions of the model are less specific. In recent work [1], the wide applicability of the expected utility model has been called into question. A remedy that has been adopted has produced a proliferation of numerous “as if” models, and a weakening of the predictive power that we mentioned earlier.

1.1 General aim of the research

The aim of the present research, stated briefly, is to replace the “as if” with the “how”: which implies a focus on the procedures adopted in the decision process. The use of the term procedure suggests a similarity with the method suggested by Herbert Simon. The similarity between the methodology of the research on Bounded Rationality and the one suggested here is the attention given to the process of deciding. The important difference between the two is our assumption that the neuronal structure of the brain is important in determining specifically the process by which a choice is made.

Because of this different way of posing the classical questions of Decision Theory,

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[1] The survey of Luce ([24]) is a thoughtful analysis of the developments in the last twenty years.

new answers to old questions may be found. In addition, new questions altogether may arise. For example: how much of a decision is a conscious and how much an unconscious process? How much of it is automatic and how much reflective? How much of our learning and knowledge and information processing is procedural? How much is explicit? And how will the answers to these new and different questions affect our understanding of behavior in decisions, economics, and games?

Finally, to new answers and new questions we add a new method, based on the interaction with Neuroscience, and a new tool, brain imaging, which has an important place in the present study.

The Principles of Functional Segregation

The technical details of the neuroimaging technique are discussed later. The preliminary, crucial step in the analysis is determining the physical locations of (networks of) activity in the brain that are associated with specific mental processes: in particular, in our case, those involved in decision processes. Since it may not be clear why economists should be interested in the location in the brain of the activity that corresponds to a task, we discuss here briefly the theoretical premises behind this step.

The connection between imaging studies and the analysis of choice is provided by the *Principle of Functional Segregation*, which we may simply state in a very weak form as "Not all functions of the brain are performed by the brain as a whole." A stronger conjecture is that different regions are associated with different functions. As such this is probably false. More likely, different networks of regions are activated for different functions, with overlaps over the regions used in different networks. The difficulty and the challenge in this research are precisely consequences of the lack of a one-to-one map from functions to regions.

Crude but strong evidence for the Principle of Functional Segregation is provided by patients with brain lesions who are able to perform some functions normally, but are impeded in others[2]. On the basis of this evidence in the past twenty years neuroscientists have constructed a first rough model of the functional structure of the brain. An example of such reconstruction is the (now classic) book by Shallice ([31]) and its model of the interaction between supervisory attention scheduling and the various schemata that direct behavior in routine situations. Although extremely useful as a first tool, the neuro psychology based on clinical evidence has two main limits. First, the regions of the brain that are affected by traumas, or strokes are obviously selected by accident, and not by scientific design. Second, by necessity subjects are not normal subjects.

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[2] The first to use this type of information to make inferences on the structure and functioning of the brain is Broca ([5])

Imaging techniques overcome both limits, allowing the researcher an overall view of the activity of the brain associated with different controlled experimental treatments.

1.2 Specific aims of the study

As we have mentioned, the aim is to identify and test a theory of how subjects reach their decisions. We think it is advisable, in this first phase of the research, to focus on the analysis of simple decisions, based on the choice between pairs of economic stimuli. Consequently, we chose a decision problem in line with the original Ellsberg's thought experiment ([15]). We did not expect the choice behavior of subjects to be different from that predicted by existing "as if" theories (of choice under risk and ambiguity). In fact, the analysis of the choice data in section below shows that they were not.

A second element in our choice of design was the introduction of a *partially* ambiguous lottery. In a risky lottery the subject knows the objective probability of outcomes, in an ambiguous lottery he has no information on this objective probability. In a partially ambiguous he has *some* information. The partially ambiguous lottery is located, *from a choice theoretic point of view*, in an intermediate position between risky and ambiguous lottery. We will see, however, that from a procedural point of view it has a very specific nature. If the procedure is an important concern, the behavior of a subject facing a partially ambiguous lottery will be very different. The analysis of the data on response times and the imaging data confirm this conjecture as well.

1.3 Content of the paper

In section 2 we describe the experimental design. In section 3 we present and discuss the behavioral data. More precisely, in the subsection 3.1 we examine the choices made by the subjects in different conditions, while in subsection 3.2 we focus on the response time, namely the time used by the subject to reach each decision. In section 4 we present and interpret the brain-imaging data in the light of information available in the neuroscience literature on the significance of the different patterns and centers of neural activation. In section 5 we state out conclusions, and outline what we think should be done next.

2 Experimental Design

Subjects were instructed to make a sequence of choices between pairs of lotteries. The pairs are presented in groups of similar choices, and no feedback on the outcome is provided during the test. Outcomes and payments are determined at the end.

Lotteries

In the entire experiment, four different types of lotteries were used: certain (C), risky (R), partially ambiguous (PA) and ambiguous (A). Subjects were informed that those lotteries would eventually be implemented by the draw of a ball, which could be blue or red, out of an urn which contained in every case 180 balls, with a number of balls of each color consistent with the probability described by the lottery. Overall subjects had to make 96 choices. The actual payments were decided at the end of the experiment: First, 4 out of the 96 choices were randomly selected according to a uniform distribution. We then checked which of the two lotteries in these choices the subject had selected, filled a real urn with balls in the proportions stated in those lotteries, and asked the subject to pick one of the balls, while keeping the urn above his/her head. The subject was then paid the total of the payments for the four choices.

The pair of lotteries in each choice was presented on a screen, indicating the number of balls for each color and the amount in dollars that each color would pay. The only exception was the certain lottery, for which the screen simply indicated a fixed amount in dollars. Subjects knew that the urn contained in all cases 180 balls in total. In the risky lottery they knew that the urn contained an equal number (90) of balls of each color; for the ambiguous lottery no information on the number of balls of either color was given (although the amount in dollars for each color was clearly indicated). The urn for the partially ambiguous lottery reported that 10 balls of each color would be in the urn, while the color of the remaining 160 would be unspecified.

Choices

A distinction between main lottery and reference lottery in a choice pair is useful. The main lottery is one out of the set of risky, partially ambiguous and ambiguous. One may think of this set as presenting an increasing amount of ambiguity: from no ambiguity in the risky lottery to full ambiguity in the ambiguous one. This main lottery is to be compared to the reference lottery, one out of the set of risky or certain. We used all possible combinations of main and reference lotteries to obtain six types of choices, the *conditions* in our experiment. Each condition will be denoted by its pair of lotteries: for example, the condition PAC is given by the choice between a partially ambiguous lottery, PA (the main lottery), and a certain lottery, C (the reference lottery). The condition AR is given by the choice that between an ambiguous and a risky lottery, and so on. Overall we had three condition where R is the reference lottery (the R-conditions

RR, PAR, AR) and three where C is the reference lottery (the C-conditions RC, PAC, AC). The names “main” and “reference lottery” are used here for expository purposes only: these names were never used in the experiment, and neither were the labels certain, risky, partially ambiguous and ambiguous.

The specific values of the lotteries

A detailed description of the different lotteries is provided in the appendix, section 7. Here we point out some specific feature of the set of choices we used, because understanding them is essential in the interpretation of the results.

In the C condition subjects are comparing a certain amount (ranging from a minimum of 10 dollars to a maximum of 50) with either a risky, partially ambiguous, or ambiguous lottery. In the R condition the reference lottery is a risky, rather than certain, lottery: this choice may appear more difficult, but it is not necessarily so in the specific setup we adopted. The reference lottery in fact *dominates* the main lottery, in a sense that we are going to make precise. In the RR choice, the dominance is simply given by the fact that the main lottery is a mean-preserving (variance-increasing) spread of the reference lottery. For example: with an equal probability for each type of ball, the main lottery has outcomes $(64, 0)$, while the reference lottery has outcomes $(60, 4)$. In the AR and PAR conditions, the negative effect of ambiguity compounds that of risk. For example, the reference lottery has a fifty-fifty probability on the outcome $(60, 4)$ while the main lottery has a fifty-fifty probability on the outcome $(64, 0)$ for red and blue balls respectively, with the proportion of red and blue unspecified.

The joint effect of risk and ambiguity should make the choice of the main lottery inferior to a subject who is risk and ambiguity averse. In addition this comparison should involve simple qualitative reasoning, rather than quantitative comparisons. The choice in the C conditions, on the other hand, involves a quantitative comparison, since an estimate of the value of the main lottery has to be compared with a certain, but varying amount of the C lottery. As we are going to see, this prediction holds.

Time sequence

Each subject experienced the six conditions (RC, PAC, AC, RR, PAR and AR) that we have just described, plus two with Eyes Closed Rest (ECR). The conditions and the set of choices in each condition were the same for each subject. The order in which the conditions were presented was determined randomly and independently for each subject. Also the order of different choices was selected randomly and independently for each subject.

Imaging technique

The imaging study was conducted with PET (Positron Emission Tomography). General information on the technique is given in the appendix (section 8). PET was used together with a tracer (H215O) to estimate regional Cerebral Blood Flow ($rCBF$) which is a standard indicator for brain activity. The $rCBF$ was estimated from tissue radioactivity (after correction with measured two-dimensional attenuation) using a Siemens ECAT 953B scanner (Knoxville, TN USA) with septae retracted, i.e., three-dimensional acquisition (Silbersweig, Stern, Frith et al., 1993). An arm vein was used for access. The participant's head position was stabilized with a vacuum-molded pillow. A slow-bolus of H215O was injected intravenously (9.25 MBA or 0.25 mCi/KGB initially, infused at a constant speed over 30 s). Data acquisition (correcting for random decay and electronic dead time only) commenced upon arrival of activity into the head as evidenced by consistently rising true counts. Each experimental scan of 90 seconds contained data from one type of lottery, e.g., CGS or RG. The interval between scans was about 10 minutes. Images were reconstructed by filtered back projection including non-orthogonal angles to a final image resolution of 10 mm full-width at half-maximum.

Implementation

The original sample was composed of 12 young healthy right-handed individuals, chosen among those answering a public announcement posted on campus. One of the subjects had to be excluded from the sample after post experiment interviews determined a state of depression; for a second the data on scanning were lost for technical reasons. So the data in this study refer to the sub-sample of 10 individuals.

Subjects came in separately, on different days. We first paid each subject 50 dollars in cash. This show-up award was never at risk during the experiment. We then read the instructions. The instructions were very detailed; we also asked the subjects to answer short quiz questions during the presentation to check their understanding. Detailed and careful instructions were intended to make the subject familiar with the four different types of lotteries and the six different conditions. We presented a set of examples, and asked the subject to choose among the lotteries in the example. We were also trying to familiarize them with the method of expressing the choice, a click on the left or right button of a mouse.

After the instructions, the subjects were moved and were positioned in a scanner.

Choices were made while the brain activity of the subject was scanned. We had 15 choices for each R-condition and 17 choices for each C-condition, for a total of 96 choices per subject. A choice appeared on the screen, and subjects had six seconds to decide. The time interval between choices was fixed, and independent from the moment in which the choice was made. A pause of two seconds would follow the end of each choice, and then the next choice would be displayed on the screen (so the overall time interval between choices was eight seconds). The time interval between the different conditions varied between two to four minutes, since a new condition could begin only when the scanner was ready for the next analysis. The entire experiment lasted approximately two hours.

3 Behavioral data

3.1 Choices

The C-condition

The observed choice in the C-condition tends to follow a rather regular cut-off policy. Each subject chooses the R, PA or A lottery rather than the C when the certain amount is below a threshold (which varies with the subject), and switches to the C lottery when the threshold is passed.

Estimates of the cutoff point are in the table 1 below [3]. The cutoff value is chosen for each subject to minimize the number of deviations, for that subject, of the observed choices from the cutoff policy [4].

Table 2 shows that subjects [5] are consistent in their choices, and the instances of

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[3] Some of the data are missing because either the subject did not choose in the amount of time available, or because of an error in recording the answer, for subject number 71.

[4] More precisely, the cutoff has been determined according to the following rule. A c-policy is the policy of choosing the C lottery if its value is larger or equal to c. For each of the possible values of c, determine the number of deviations from the c-policy in the observed choices of the subject. Choose the c that minimizes the number of deviations. If the value of this c is among the values at which the subject expressed indifference, choose the middle if the number of such values is odd, and the next one in ascending order if the number is even.

[5] Subjects are indicated by the classification number in data archive of the Veterans Affairs Medical Center. A $*$ denotes missing data.

Table 1: Summary statistics for the cutoff in the C-condition

Variable	Obs	Mean	Std. Err.	95% conf. int.
AC cutoff	170	22.7	.439	[21.83, 23.56]
PAC cutoff	165	21.7	.3769	[20.95, 22.44]
RC cutoff	153	28.11	.217	[27.68, 28.54]

deviations from the policy that is implicitly described by the cutoff are small in number.

The bottom row of the table 2 reports the differences in the value of the cutoff for PAC and AC conditions. The differences are zero or small: this indicates that the choices of the same subject are consistent across conditions. The "Mean value" column of Table 1 and the last row of Table 2 shows that the values of the cutoffs in the two conditions PAC and AC are similar.

Table 2: Choices in the C-condition

Subject	27	29	40	44	52	53	55	59	68	71	average
Cutoff in RC	25	25	25	33	31	30	28	28	28	*	28.11
Deviations from cutoff	0	0	0	2	3	3	3	0	1	*	1.33
Cutoff in PAC	20	25	15	32	20	30	20	20	15	25	21.7
Deviations from cutoff	0	0	0	1	2	0	2	1	0	0	0.6
Cutoff in AC	20	20	15	31	30	28	20	28	15	20	22.7
Deviations from cutoff	0	0	0	2	0	0	0	0	0	1	.3
PAC-AC	0	5	0	1	-10	-3	0	-8	0	5	-1

The R-condition

Table 3 reports the number of times each subject chose the risky reference lottery in the R-condition.

Subjects chose the more risky lottery (the lottery with the greater spread) the most frequently (but still only 14.7 per cent of the times) in RR, and with a lower frequency in PAR and AR (approximately the same in the two conditions).

Table 3: Choices of the reference lottery in the R-condition

Subject	27	29	40	44	52	53	55	59	68	71	total	percent
RR	0	4	0	3	0	6	1	6	2	*	22	14.7
PAR	1	0	0	4	0	1	1	4	1	0	12	8
AR	1	2	0	2	2	3	1	3	0	0	14	9.3

Summary of the analysis of choices

Overall, the observed choices of the subjects are those predicted by widely accepted theories of choice in risky and ambiguous environments. Between two lotteries, where one is a mean-preserving spread of the other, the subjects chose consistently and almost exclusively the lottery with smaller variance. Subjects are ambiguity averse. This is hard to detect in the R-condition where the choice is already almost entirely of the lottery with smaller variance. But in the C-condition, the mean cutoff is six to seven dollars higher when the main lottery is R than it is when the main lottery is A or PA (see table 1).

3.2 Response Times

The *response time* (*RT*) is the length of the time interval between the moment in which the stimulus (the two lotteries) appears on the screen and the moment in which the subject clicks on the mouse making the choice. The Tables 4 and 5 present the first surprise. They show the average response time, taken over subjects and different choices in the same condition, together with some summary statistics [6].

Table 4: Average response times (RT) in the R condition

Variable	Obs	Mean	Std. Err.	[95% conf. interval]
RT in AR	147	2776.95	87.24	[2604.52, 2949.37]
RT in PAR	165	2741.74	94.58	[2554.85, 2928.64]
RT in RR	148	2723.27	92.00	[2541.45, 2905.10]

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[6] The number of observations is different across conditions. This happens for two reasons. First, some of the observations were lost for technical reasons. Second, the number of choices in the R conditions were 15, and they were 17 in the C condition

The response time is approximately half of a second (that is, 25 per cent) longer in the R-conditions than in the C-conditions. In the first class of choices the time taken to decide is something around half a second, over two to three seconds typically necessary, more than in the latter class (the C conditions).

Table 5: Average response times (RT) in the C conditions

Variable	Obs	Mean	Std. Err.	[95% conf. interval]
RT in AC	170	1947.60	65.98	[1817.34, 2077.85]
RT in PAC	165	2196.72	76.32	[2046.01, 2347.42]
RT in RC	153	2534.43	84.38	[2367.70, 2701.16]

Among the C-conditions, the fastest decisions are made in the AC and PAC conditions. The slowest decision are made in the corresponding R-conditions, namely AR and PAR. This disparity in response time suggests that subjects approached the two conditions with different mental processes.

Difficult decisions and Learning

Several factors may affect the length of time a subject uses before making a choice. Some insight into the determinants of this time (and hence on the decision process itself) can be obtained by a simple regression. A detailed report of these results is presented in the appendix, sections 6.1 and 6.2.

Learning in C. Consider first the C-conditions. We use two variables. The variable *discut* is defined as the absolute value of the difference between the value of the certain lottery and the cutoff point that we have estimated for the subject. When the distance is very small, the subject is probably almost indifferent between the two alternatives, so the decision, in terms of the utility to the subject, is less important. On the other hand, the conclusion that he is indifferent is the outcome of a real life decision process, rather than its starting point. To reach this outcome, the subject might need less time when the value of the certain lottery is farther from the cutoff point, since in this case even an approximate estimate of the value of the main lottery will suffice. A procedural model of choice would predict that the response time increases, as the certain value gets closer to the cutoff.

A second variable is the integer valued *order*, describing the order in which the choice has been presented to the subject in the same condition. If some form of learning takes place, then the response time will fall as the subject is facing choices that are becoming familiar.

The coefficient for the distance from the cutoff point (*discut*) is significant in the three C conditions, and has a negative sign. This is the sign one expects if the task of deciding involves in substantial way a comparison of two quantities, in our case the value of the certain lottery and some estimate of the value of the main lottery. This is in agreement with the findings in purely cognitive studies. A strong non-linearity, with the response time increasingly in steep way as the term of comparisons are closer is well documented in cognitive psychology and neuro psychology (see for instance [28]).

There are some interesting differences among conditions. Both *discut* and *order* have significant coefficients in the regression for the PAC condition. The coefficient for the variable *discut* is -51 *msc* per dollar, (with a p-value < 0.0001), the coefficient for the *order* variable is -26 per unit (p-value < 0.039). There is on the other hand no significant difference in the latter coefficient if one estimates separately the initial and later choices. This indicates a regular, progressive learning, rather than a two stages process, with an initial stage where subjects decide a policy in the form of a cutoff and a second stage in which they simply implement the policy. The *discut* variable has a significant coefficient in the AC and RC conditions as well; but the coefficient in AC is significantly smaller than in the PAC condition. The *order* variable is less significant, or insignificant, in the RC and AC cases respectively.

Learning in R. Here we consider three variables. The first is *value*, the expected value of the reference lottery, which ranged in the experiment between 30 and 40. The second is *order*, with the same meaning as in the previous section. The third and last is *variance*, a dummy variable with values $-1, 0, 1$ indicating the low, medium and high variance in the reference lottery. Only the variable *variance* is significant, at least in the PAR and in the RR condition. The lack of learning is in agreement with the idea that the conditions where R is the reference lottery are easier; it makes however the length of the response time in these very conditions even more surprising.

What operations do the subjects do?

The average value of the response time and the way it changes over the course of the trial can give some information on the type of operations subjects are performing. It is useful to compare our data with those for subjects performing a "pure" cognitive task.

In [33], the authors conduct a careful study of the response time for addition of two digit integer numbers [7]. They studied both approximate and exact operations. In the exact addition treatment subjects had to decide between the right answer and a distractor where the tens place was increased or decreased by 1. In the approximate addition treatment the problem was the same, but the candidate answers were multiples of 10, with the most distant answer 30 units more distant than the value closest to the correct answer. The average response time in both cases is (before training) between 4 and 4.5 seconds, a quantity much larger than we observe [8].

The coefficient for the variable *discut* is large when compared to estimates of the effect of the difficulty of the problem induced by the proximity of the quantities to be compared. Consider for instance the finding in [28]. In that study subjects had to perform a numerical comparison task: specifically, they had to decide whether a visually presented number was larger or smaller than a fixed reference number, 65. The *numerical distance effect* [9], namely the effect of the distance from 65 of the number presented to subjects on their response time was estimated. The average response time was 600 *msc* for far numbers, slightly larger for moderately distant numbers, and 700 *msc* for the close numbers [10]

4 Imaging results and analysis

4.1 Technical Premise

We present the basic concepts necessary to understand the brain images. A more detailed explanation of the PET technique and of the statistical analysis underlying the study is

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[7] For example, in the exact addition treatment, the subjects had to add a first addend, which was ranging from 22 to 86 to a second addend ranging from 18 to 86 with the sum ranging from 18 to 86.

[8] No specific details are given in the study, but it seems that subjects had no time constraint.

[9] This effect is defined and discussed in detail in [12]. A second effect, the *number size effect*, was also documented in [12]: for equal numerical distance, the discrimination of two numbers worsens as their numerical size increases.

[10] Numbers close to 65 were in the intervals 60-64 and 66-69; numbers moderately distant 50-59 and 70-79; numbers far 30-49 and 80-99. These times are much shorter than we observed: but the task of these subjects was a simple comparison of two numbers.

given in the appendix.

A point in the brain is defined by a triple of (x, y, z) coordinates, with x the coordinate in the right to left direction, y the coordinate in the front to back direction, and z in the top to bottom direction. A positive x value denotes a position on the right; a positive y in the anterior part and a positive z a position in the top part of the brain. The origin of this system of coordinates is roughly in the middle of the brain. Together, the triple (x, y, z) defines a point in a standardized three-dimensional model of the brain. The very small volume of brain around each such point is called a *voxel*.

Our observations are N vectors of $rCBF$, one for each point (x, y, z) in the brain of each of the N subjects. As different subjects have brains of different shape and size one of the first steps in data reduction to map the observations for the different subjects into a single standardized brain.

The statistical test estimates the probability that the different levels of $rCBF$ in two conditions (for instance, in the PAC and the AC condition) at a specific point labeled by a triple (x, y, z) is different from zero. It is possible that two different conditions have a $rCBF$ significantly different from the ECR condition, but also that the levels are so similar that the difference is not significant. The Z score is the statistic we use to report the probability that the difference is different from zero. The test is based on the assumption of normality and independence of the error, even in voxels that are very close.

There is a Z score for each voxel. The data can be more easily interpreted if a map of the difference score is presented in a picture [11]

The images in the figures present the Z score for each voxel, associating different colors to different scores. First, in color only the voxels where the value of the Z score is above 2 are shown in color. A green color denotes a value between 2 and 3, yellow between 3 and 4, red between 4 and 5. All regions with value above 5 are white in color. In the images, the top part of each section corresponds to the front (rostral) part of the brain, the left part to the *right* part of the brain.

The values of the three coordinates are given here in millimeters (mm). The images show horizontal (also called transversal) sections of the standard brain, with the Z scores overlaid in color. The sections begin with the top and descend to the bottom. The numbers report the value of the z section, in mm. The standard model of the brain is that reported in the Talairach and Tournoux [34] atlas.

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[11] Colors are essential for the interpretation of the images, so a color printer is necessary. A copy of the images can be downloaded at
http://www.econ.umn.edu/ arust/neuroecon.html

4.2 The evidence from brain images

4.2.1 Overview

The activation is mostly in cortical areas, particularly frontal and parietal. There is no significant activation of areas (like the medial orbito frontal, or in general orbito frontal, and the limbic system, in particular the amygdala) that have been associated with the effect of emotions on decision making. The significance of this finding is discussed in detail in the section 5.4. The images support the idea that the procedure selecting the choice is mostly of a cognitive nature, possibly involving some approximate computation (this hypothesis is discussed in detail in the section 5.2.1).

The R and C conditions are qualitatively different: the R conditions have modest activation compared to the C conditions. This finding supports the conjecture that the process involved in the choice in R conditions is simpler than the one in the C condition. These issues are discussed in detail in section 4.2.2.

Among the C conditions, the AC and RC differ from the PAC. The first have activations concentrated in parietal areas. The PAC condition has activations of the parietal and frontal areas. So the PAC condition stands in a special role. In fact, the subtraction $PAC - RC$ seems a weaker version of the $PAC - AC$. This is particularly surprising in view of two facts. First, considered as a decision problem, the difference between the AC condition and the PAC condition seems very small. The decision maker is told that the number of the two types of ball can be anywhere in the interval $[0, 180]$, while in the second it can be anywhere in the interval $[10, 170]$, a difference which seems minor. Second, two sets of behavioral data suggest a similarity between PAC and AC as compared to RC. The cutoff point is in all subjects very close in the first two, and rather different from the last. Also, the response times in the PAC and AC are similar, and different from the RC condition.

4.2.2 C condition *versus* R condition

The most active contrasts are in the C conditions. The R condition is comparatively weaker. This is particularly true if one considers the difference between the various treatments and the ECR condition[12]. Among the C conditions, the most active is PAC. Similarly, among the R conditions the most active is PAR.

A large active region common to many of the differences between the C condition

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[12] See [18] for a recent illuminating discussion of the role and interpretation of the "baseline" conditions in brain imaging

and the ECR is in the occipital lobe, lingual gyrus, with a peak around $(1, -75, 3)$. This region is for example active in $PAC - ECR$, $RC - ECR$. Interestingly, it is considerably less active in $AC - ECR$. This is the primary visual cortex (V1). The activity is due to increased visual attention. The higher activity in the C condition is indirect evidence that this task induces a relatively greater amount of visual scanning the main lottery for the purpose of defining the cutoff that is subsequently compared to the (degenerate) constant lottery.

4.2.3 The PAC condition

The two differences $PAC - AC$ and $PAC - RC$ have similar patterns. The main areas of activation in the two differences $PAC - AC$ are:

1. in the right frontal lobe, middle frontal gyrus, with peak at $(42, 50, -2)$, with a Z score 4.59;
2. in the parietal lobe: in the subgyrus, with two peaks: one at $(25, -55, 42)$, with a Z score 4.42, and the other at $(34, -55, 33)$, with a Z score 4.11; also in the parietal lobe, precuneus, with peak at $(1, -37, 42)$, with a Z score 3.89;
3. an occipital lobe, lingual gyrus, with peak at $(-15, -91, -14)$, with a Z score 4.1;
4. left frontal lobe, with peak at $(-15, -13, 63)$ with a Z score $= 4.1$

The frontal and occipital activations have a weaker mirror image in the opposite hemisphere.

The region of activation in the difference $PAC - RC$ are similar to the previous ones. More specifically the most active areas are:

1. a region in the frontal lobe, lower than in $PAC - AC$, with a peak at coordinates $(46, 39, -9)$, with a Z score 4.46;
2. a region in the occipital lobe, with a peak at $(-10, -91, -14)$, with a Z score 4.37.
3. a region in the parietal lobe, precuneus, at $(15, -42, 50)$, with a Z score 4.11;

In contrast, it is clear from the tables for the $AC - RC$ and $RC - AC$ that there is little differential activation in these two cases.

In summary, the PAC condition stands in a special state compared to the AC and RC conditions. This finding stands in surprising contrast with the reasonable idea that a partially ambiguous lottery is an intermediate state between a totally ambiguous and a risky lottery. But it is consistent with the idea that the PAC condition is a novel experience for our subjects.

4.2.4 Frontal areas

There seems to be no strong activation of the higher frontal regions. More precisely, there is no difference displaying a strong and significant level of frontal activation in the levels above $z = 11$ mm. With one exception that we discuss later, this is also true in the differences $PAC - AC$ and $PAC - RC$. In the first case the frontal activation we have already reported is in the z interval between $+11$ and -11 mm. The same area is found in the difference $RC - AC$, but not in the $PAC - RC$ difference.

The partial exception we mentioned in the $PAC - AC$ treatment is the region in the superior frontal gyrus, in the left frontal lobe reported earlier (peak at $(-15, -13, 63)$). A similar activation is in the $PAC - RC$ difference. In this case the peak is at $(-12, -8, 61)$, in the medial frontal gyrus of the left frontal lobe. The z coordinate is -4.7 mm, which is the highest in this difference.

Particularly the Pre-frontal cortex (PFC) does appear prominently among the regions that are activated. The PFC [13] is associated with planning, namely the ability to organize cognitive behavior in time and space [14].

4.2.5 Orbito frontal ventromedial areas

There seems to be no strong activation of the ventromedial sections of the frontal lobes, that is, in areas known to mediate the processing of somatic and emotional reactions. A partial exception is an area that appears the $RR - PAR$ difference; the peak is at $(6, 19, -18)$, right cerebrum, frontal lobe, medial frontal gyrus. The score is $Z = -3.47$, $p < 0.00027$. This is the only significant exception: the relative activations in $AC - AR$ at $(1, 32, -22)$ and in $RC - RR$ at $(-1, 8, -18)$ are probably artifacts, since they are at the extreme outer boundary of the brain.

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[13] This is the pole of the frontal lobe. It corresponds to the Brodmann areas 9, 10, 11.

[14] This is by now a classic finding. It has first been suggested by lesion studies (see for example the early studies of Shallice ([32]). These early results have been confirmed by brain-imaging studies. For this, see for example [35], [21], [22]. But the literature on this is very large: a useful review is in Cabeza *et alii*, [7]. Owen (1997) ([26]) offers a detailed review of definition and properties of planning ability in human subjects.

5 Conclusions

We collect the different observations that are particularly significant (in the section 5.1), and provide a provisional interpretation of the results (in the section 5.2.)

5.1 Summary

1. In their choices, subjects behave as predicted by models of risk and ambiguity aversion; their ambiguity aversion is consistent across the PAC and AC conditions;
2. The time to decide is shorter in the C type conditions, and among those the minimum is in the PAC and AC condition;
3. Learning occurs in the PAC condition, less so in the other two C conditions, and is almost absent in the R conditions;
4. A larger distance from the cutoff point of the certain value makes the decision faster in the PAC condition;
5. The regions with most intense activation are observed in the C type conditions, and particularly in the difference between PAC and AC;
6. There is a low activation of ventromedial regions;
7. There is a low activation of the high frontal and pre-frontal regions;
8. The only important frontal activation is in the PAC condition;
9. There is a large activation in the parietal regions in the C conditions.

5.2 Interpretations

5.2.1 Qualitative and quantitative comparisons

As we have already mentioned, the valuation in the R condition seems to be of a qualitative, and easier, nature. This is confirmed by the data on choice and by the imaging data. The data on response times are harder to assess: they are longer for the R condition, but in the C condition only one of the two lotteries (the one which is not certain) needs to be evaluated. The various C conditions are not uniformly harder. However, the *procedural* difficulty of the choice seems to be the dominant factor. The PA ambiguous lottery may appear, from several natural points of view, in an intermediate position between the risky and the ambiguous one. For instance, consider the amount of information available to the decision maker. There is only one possible composition of the urn in the risky lottery; in the partially ambiguous one, there is a set of possible compositions, and in the ambiguous one there is an even larger set. Or consider the point of view of a decision maker who is evaluating lotteries according to the multiple priors model ([17]). The worst case in the risky lottery is better than it is in the partially ambiguous one, and this is in turn better than it is in the ambiguous one. These different views are not contradicted by the choice data: but they are contradicted by the response time and imaging data.

5.2.2 Conscious and unconscious estimates

The procedure we have outlined may not be consciously followed by the subjects. There is however a substantial difference in the response time in our experiment (always less than three seconds) and that observed in simple computational problems (for example in the studies by Dehaene and co-authors already cited). This difference suggests that the procedure in our study does not involve explicit calculations and may be partially automatic. We consider this issue important because automatic processes need not be mediated by consciousness. As a consequence, they are likely to produce relatively inflexible behaviors that differ from the repertoire produced by conscious or planned thought. Clearly more research is needed in this arena.

5.2.3 Approximate and exact estimates

The evidence we have presented suggests that subjects develop their decision process trying to provide some quantitative estimate of the lotteries, but that these estimates are approximate rather than exact. This conclusion is suggested first by the short response time, particularly short in the harder tasks and is supported by the observation that the computational aspects of the estimates used in the decision are located in the parietal, rather than frontal lobe.

This statement is significant and informative only if there is a qualitative difference between the exact and approximate processes; for example if there is a difference in the cerebral networks activated in the two types of processing. This is precisely the conclusion that a set of recent studies suggests; in particular, a set of studies by Dehaene and different co-authors (see [10], [13]; also see [29], [20]).

The studies argue for the existence of a specialization for processing *approximate* numerical quantities that is common to humans and animals, particularly mammals: see for instance [11] for a review of these findings [15]. Subsequent work by the same team (see [12]) has supported these findings with brain-imaging techniques. In addition, exact and approximate processing are associated with activity in different cerebral locations. For example in [13] the authors note that

> ..the bilateral parietal lobe showed greater activation for approximation than for exact calculation. The active areas occupied the banks of the left and right intra parietal sulci, extending anteriorly to the depth of the post central sulcus and laterally into the inferior parietal lobule... Activation was also found during approximation in the right precuneus, left and right pre central sulci..[p. 971]

These two regions also relate differently to language centers. In behavioral and brain-imaging studies exact calculations are shown to be language dependent, while approximations rely on a visuo-spatial cerebral network (see [33] and [13] [16]).

5.2.4 The partial ambiguous lottery

As we have seen, the PAC condition has a comparatively strong activation of the frontal lobe, which extends over a large part of the middle frontal gyrus. This is one of the findings that sets the PAC condition apart from the others, including the AC and RC. There are two possible interpretations of this difference. The first is that some exact calculation is taking place when subjects are considering a partially ambiguous lottery. This is partially in agreement with the finding of [13], but is not entirely convincing in

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[15] For instance, in [13] the authors state that

> Within the domain of elementary arithmetic, current cognitive models postulate at least two representational formats for number: a language-based format is used to store tables of exact arithmetic, and a language-independent representation of number magnitude, akin to a mental “number line”.

[16] In the [33] study, subjects were familiar with the two languages (Russian and English). They were trained to execute mathematical tasks either approximately or exactly. The performance after training improved, so training was effective. The crucial test however is the performance on new tests. When tested on the problems to be solved exactly, the performance was significantly better when the test was administered in the same language in which it had been taught, independently of whether it was English or Russian. On the contrary, the performance on approximate tests was independent of the language. In the words of the authors:

> a specific, natural language contributes to the representation of large, exact numbers but not to the approximate number representation that humans share with other mammals. Language appears to play a role in learning about exact numbers in a variety of contexts..

view of the short response time in this condition. A second interpretation appears more convincing on the basis of the evidence we have presented so far: more general higher cognitive functions are involved over the course of the trial, trying to define a satisfactory method to evaluate the PA lottery. Again, further research is necessary here.

The response times

Let us recall the two facts that stand out. First, the response times are longer in the R than in the C set of conditions. Second, among the type C conditions, the response time is shortest for the PAC condition. On first sight, these facts seem to contradict directly the two conjectures that the choices in the C conditions are harder, and that among them the PAC condition is the hardest. If this is the case, then why don't the subjects take more time in examining the more complex choices, and seem to do the opposite?

Let us consider the argument more closely. It is based on an implicit assumption that the allocation of attentional effort is in some way optimal, and that subjects make a single decision at the beginning of the choice process on the amount of effort to be devoted to the decision.

The first assumption is reasonable, but its implications are richer than the simple monotonicity giving longer time for harder problems, unless one assumes also that the attentional effort is costless. If it is not, then the cost of the effort, which may be different in different conditions, is compared with its effectiveness. The data on activation seem to indicate that the effort in the C conditions is more intense, perhaps more unpleasant. It is possible that this effort is also less effective that in the R condition.

The second assumption on the other hand, is clearly false: subjects monitor their own decision process, and probably get a feedback on the effectiveness of their thinking process. This is a common assumption in models of attention (see for example [6], where the attention produces a sharpening of the information, until the subject decides that it is optimal to decide.)

If we put all these arguments together, we conclude that in a realistic model of optimal allocation of attention and estimation, the time actually devoted to the choice in hard conditions might be shorter.

5.3 The choice procedure

The results we have reported strongly suggest that a computational model of decisions might give a more accurate model of the behavior of decision makers.

The nature of the procedure

Here is procedure which gives an account of the observed behavior of subjects in the C condition. In all three cases (whether the main lottery is R, or PA, or A), the subjects are comparing the certain value with some estimate of the value of the main lottery. When this lottery is R the estimate is in substance a sum of the two outcomes, perhaps followed by a simple division. In the A case, the subject considers the best and worst outcome possible. In the best outcome, all balls are of the "good " color (the one that gives the largest payoff), and in the worst outcome they are all of the "bad" color. In both cases, the corresponding lottery is degenerate, giving a certain amount equal to the prize associated with the only type of ball existing in the urn. So it is easy to estimate. The situation is more difficult to evaluate in the PA condition. In this case the same process of reduction to the best and worst case yields two non-degenerate (true) lotteries: one with the good outcome having probability $\frac{1}{18}$, the other with probability $\frac{17}{18}$.

We are of course assuming that there is a similarity in the behavior of subjects in laboratory, possibly an artificial environment, and in real life environments where economic decisions are made. The difficulty is of course to determine which features are going to be preserved and which are more likely to depend on the specific environment in which the choice is made. The hypothesis that we suggest here is that the reduction of the process to more directly observable variables (like brain activation) can make the verification of this transferability hypothesis easier. A methodological observation is important. Some of the crucial evidence that we have derived from existing literature, particularly in the neuroscience literature, is obtained on the basis of experiments designed to explain behavior that is not economic behavior. For example, the evidence on the dual nature of exact and approximate computations was designed to explain different arithmetical and mathematical abilities. The analysis of choice behavior that combines insights and methods from neuroscience and the conceptual structure of decision theory will have to provide its own, specifically conceived and designed, set of experimental evidence.

Finally we note that in our experiment the choices are similar to those predicted by the economic theory. This is not necessarily going to happen in general. As the choices become more complex, the constraints on the procedure delivering the choice become increasingly important, and affect in a systematic way the decision itself.

5.4 The Somatic Marker Hypothesis

The interpretation we have provided views the process of choice essentially as a cognitive process. This view contrasts with an interpretation suggested in the last decade, and based largely on neuro psychological and clinical observations, that "decision making is a process guided by emotions" ([2]).

This latter interpretation is centered around the Somatic Marker Hypothesis (SMH: [9], [8]). The initial insight for this hypothesis is provided by William James' theory of emotions. Let us first distinguish between *emotion* as the set of somatic reactions induced by an outside event (like the appearance of a snake) and *feeling* as the subjective perception of the events (both external to the subject and internal to the subject, as are the somatic reactions). In James' theory, the feeling is induced by the somatic reaction to outside events: in his beautiful expression, we are sad because we cry, we do not cry because we are sad [17]. The SMH extends this idea to decision making. According to the hypothesis, "an emotional (that is, somatic) mechanism rapidly signals the prospective consequences of an action, and accordingly assists in the selection of an advantageous response option." ([2], page 4)

The centers in the brain where such response is located are the orbito-frontal cortex and the amygdala. As we have seen, neither of these two centers is activated in our subjects. These two regions are routinely observed in studies conducted with the same scanner and techniques, so the failure to observe is almost certainly due to a lack of activation [18].

The SMH has been tested in a standard laboratory experimental setup, in particular in the Card Deck Test (see [1]). In this test, subjects choose one deck of cards out of a set of four for a number of periods (usually one hundred). After they choose a deck they pick the top card, and a monetary amount associated to each card, which can be positive (gain) or negative (loss), is revealed. Normal subjects tend to choose, after an initial number of periods, decks that have positive expected return, even if the positive amounts are smaller. Patients with lesions in the orbito frontal region or in the

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[17] More precisely:

> [..] the more rational statement is that we feel sorry because we cry, angry because we strike, afraid because we tremble, and not that we cry, strike, or tremble, because we are sorry, angry, or fearful, as the case may be. ([19])

[18] For example an orbito frontal activation appears clearly in the study [14], conducted with the same devices and techniques. In the images of the present study, a clear example of a ventromedial orbitofrontal activation can be found in any of the subtractions from ECR of any of the conditions. A particularly clear instance is for example in the $ECR-AR$ subtraction, between the vertical coordinates 0 to -13 (see the set of images ECR in http://www.econ.umn.edu/ arust/neuroecon.html.) A comparative activation of this region in the ECR condition is a standard finding, although not yet well understood.

amygdala [19] tend to choose, even in the later periods, deck that have larger positive amounts but compensated by even larger negative returns, so that the expected return for the deck is negative. These results support the hypothesis that the orbito frontal cortex and amygdala are involved in decision processes. The results are confirmed by imaging studies (see for example ([25])).

There are several differences between the two experimental setups that can explain this difference. First of all, our subjects do not receive any information on the consequences of their choices (no feedback), so they do not experience gain or losses during the experiment. Second, our subjects do not learn anything about the distribution of the outcomes in addition to what they know at the beginning of the experiment. In contrast in the Card Deck Test subjects experience incremental learning: they are informed of the outcome in each period, and can use this information in the following choices. Finally, our subjects have only gains, while subjects in the Card Deck test have gains and losses. It is interesting to note that in the study [14] with a structure similar to the present study, but with losses, an orbito frontal activation appears in the comparison between gain and losses.

So a possible explanation of the qualitative difference between our results and those supporting the SMH (particularly the lack of activation of the limbic regions) is that we study specifically choice, rather than learning and choice.

5.5 Reward anticipation and outcome

Very similar differences appear between the setup of our study and recent studies focusing on the neuroanatomical and neuro chemical mechanisms underlying the evaluation of rewards, and in particular on the separation between expectancy and experience of reward and loss (see [4], but also [3]), or reward anticipation and the reward outcome (see [23]).

In these studies, the experimental sessions consist of a sequence of trials, where subject observe a cue that may signal, depending on the cue, the delivery of a reward, or the lack of reward (or of a loss). Immediately after the arrival of the cue and possibly of their response, subjects know whether a reward is given in that trial. Different regions are activated in the different cases (with Nucleus Accumbens, Ventromedial Frontal Cortex and Orbito Frontal Cortex the main regions in the various cases). These studies provide the foundation for a mechanistic explanation of the processes that go from delivery of reward or lack thereof, to the subject's evaluation of the outcome, but they are not a study of the process leading to choice.

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[19] See Figure 4, page 12 of [2].

Further studies, with a careful analysis of brain activations, are needed to test the hypothesis that choice separated from immediate reward requires different brain processes, and to understand where emotions enter into the decision process. It seems however that the black box of the decision process is beginning to be yield.

6 Appendix: Regression tables

6.1 Regression on Response times for the C condition

Table A1: Response time for AC on discut and order

Variable	Coeff.	Std.Err.	t	$P > t$	95% conf.int.
discut	-34.68	7.77	-4.46	0.000	[-50.03, -19.32]
order	-3.91	12.68	-0.31	0.758	[-28.95, 21.12]
constant	2411.67	165.70	14.55	0.000	[2084.53, 2738.81]

Table A2: Response time for PAC on discut and order

Variable	Coeff.	Std.Err.	t	$P > t$	95% conf.int.
discut	-56.71	8.44	-6.71	0.000	[-73.39, -40.03]
order	-20.99	13.46	-1.56	0.121	[-47.58, 5.59]
cons	3106.25	172.11	18.05	0.000	[2790.70, 3417.4]

Table A3: Response time for RC on discut and order

Variable	Coeff.	Std.Err.	t	$P > t$	95% conf.int.
discut	-53.61	12.61	-4.25	0.000	[-78.53, -28.69]
order	-29.35	16.28	-1.80	0.074	[-61.53, 2.82]
constant	3286.75	188.70	17.42	0.000	[2913.89, 3659.62]

6.2 Regression on Response times for the R condition

Table A4: Response time for AR on value, order and variance

Variable	Coeff.	Std.Err.	t	$P > t$	95% conf.int.
value	4.24	12.04	0.35	0.725	[-19.58, 28.07]
order	-11.01	20.51	-0.54	0.592	[-51.60, 29.58]
variance	219.26	108.28	2.02	0.045	[5.005, 433.51]
constant	2470.72	890.28	2.78	0.006	[709.15, 4232.29]

Table A5: Response time for PAR on value, order and variance

Variable	Coeff.	Std.Err.	t	$P > t$	95% conf.int.
value	21.98	12.89	1.700	0.091	[-3.53, 47.49]
order	-1.21	22.02	-0.06	0.956	[-44.78, 42.36]
variance	311.23	117.17	2.66	0.009	[79.42, 543.04]
constant	1333.62	917.55	1.457	0.147	[-481.52,3148.77]

Table A6: Response time for RR on value, order and variance

Variable	Coeff.	Std.Err.	t	$P > t$	95% conf.int.
value	12.46	13.22	0.94	0.348	[-13.69, 38.62]
order	-8.48	22.70	-0.37	0.709	[-53.41, 36.44]
variance	251.10	120.21	2.09	0.039	[13.26,488.94]
constant	1915.64	968.55	1.98	0.050	[-.667,3831.95]

7 Appendix: The lotteries

Lotteries were all built on the basis of an urn containing 180 balls overall, that could be either red or blue. The different lotteries were described by different proportion, different information and different value associated with each ball. In all treatments, the color of the ball with the high value outcome changed over the different choices in that treatment.

Reference lotteries

The certain lottery C was a degenerate lottery: a single value would appear on the screen, ranging from a minimum of 10 to a maximum of 50 [20].

In the risky lottery R the urn had 90 blue, 90 red balls; the outcomes had expected values ranging from 30 to 40 [21]. For each of the different expected values, we had three different lotteries, with different variance. For instance for the expected value 40 we had (80, 0), (58, 12) and (48, 32) as possible outcomes.

Main lotteries

In the R lottery, the urn had 90 blue, 90 red balls, and the monetary amounts were fixed to be $(60, 10)$.

In the partially ambiguous lotteries (PA), 10 balls were assigned to be red and 10 blue, while the others were of an unspecified color. In the ambiguous lotteries (A) none of the balls had a color assigned.

In the PAC condition, the amounts were fixed to be $(60, 10)$; only the attribution to one or the other of the colors was changed. The same values, $(60, 10)$ were used for the A lotteries in the AC condition. In the PAR and AR conditions, the PA and A lotteries had a simple outcome structure: five different pairs of outcomes. One was always equal to zero, the other ranged from 60 to 80 [22].

In the implementation of the lottery in the final stage of the experiment (when the payment to the subjects was decided) we used a uniform distribution over the number of

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[20] More precisely, the values in the range were: 10, 15, 20, 25, 28, 30, 31, 32, 33, 34, 35, 36, 38, 40, 42, 45, 50.

[21] More precisely, the values in the range were: 30, 32, 35, 38, 40.

[22] The values in this case were 60, 64, 70, 76, 80

blue balls to determine the actual composition of the ambiguous and partially ambiguous lotteries.

8 Appendix: *PET*

PET measures the amount of *regional Cerebral Blood Flow* ($rCBF$) to specific regions of the brain. The procedure begins with the slow injection of a lightly radioactive liquid into an arm vein. Almost immediately after the injection begins, the scanning also begins.

What PET detects

In a PET study, a radioisotope emitting positrons (positively charged electrons) is administered by injection. The isotope then circulates through the bloodstream to reach, among others, the brain tissue. Positrons are positively charged electrons, emitted from the nucleus of radioisotopes that are unstable because they have an excessive number of protons and a positive charge. When a positron comes in contact with an electron, the two particles annihilate turning the mass of the two particles into two gamma-rays that are emitted at 180-degree to each other. These gamma rays easily escape from the human body and can be recorded by external detectors. The tomography detects these coincident rays, which indicates that positron annihilation has occurred somewhere along that coincidence line. The scanner then reports the amount of radiation from all different positions in the brain on average over the period in which the scan is taken. When the gamma rays interact with scintillation crystals, they are converted into light photons in the crystals. The scintillation events can be compared among all opposing detectors along many coincidence lines.

The procedure is reliable, accurate, and gives a complete picture of the brain, with a uniform precision for deep and superficial structures. However, it is necessary to take averages of $rCBF$ over a relatively long period (on the time scale of the experiment) and the technique is therefore not suitable to detect changes that take place in short time intervals. See for example [27] for details.

8.1 Statistical Analysis

An exposition of the conceptual and statistical foundations of the analysis is given in ([16]). For each individual and each treatment, we have a four dimensional vector (x, y, z, CBF) recording the Cerebral Blood Flow (CBF) at the location described by the (x, y, z) coordinates.

Normalization

The data are for each individual subject, with brains of possibly different size and shape. We normalize the data onto a standard brain, so that a point in the brain corresponds to the same point in different brains.

We then analyze each pair of treatments separately, subtracting at each voxel the CBF of the two activations, and then subtracting from this number, one for each subject, the average over subjects. A two-sided test gives the probability that the difference is larger than zero under the null hypothesis that the treatment is not influential.

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