

A Brain Imaging Study of Procedural Choice *

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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 the choice behavior, the response time, and the brain activations of the subjects. Choices were simple enough to insure consistent behavior with small amount of noise.

The behavioral evidence supports the idea that subjects face the choice task as an estimation of the value of the two lotteries and that some measure of the difficulty of the choice provides an important explanatory variable (together with risk and ambiguity aversion) for the observed behavior. The Neuro-imaging data suggest that the estimation is of approximate nature, and involves mental faculties that are independent of language and shared by all mammals. The regions in the brain that are activated are not located in frontal structures, which are known to be involved in planning, but in parietal regions typically involved in approximate calculations.

The time to decide is shorter for seemingly harder choices, a finding that suggests the need for new models of the allocation of effort in the choice process. Emotional factors seem to play a minor role in the choice.

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

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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 very discipline of Decision Theory is in the light of this method. Decision Theory typically derives, from a set of axioms restricting admissible choices, a representation of the assumed preference order in terms of some utility function. Any such representation can be interpreted as an “as if” construction: subjects may be very unaware of the functional itself as well as of any auxiliary concept which is used in the representation (utility function over consequences, beliefs, and so on). Still his 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. This is also the case if the predictive power of the model is weakened, by introducing 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, the wide applicability of the expected utility model has been called into question. A remedy that has been adopted has produced a proliferation of several “as if” models, or the 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 very use of the term procedural choice suggests a similarity with the method suggested by over the years 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 in the assumption that we adopt is that the 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, new answers to old questions may be found. More importantly, new questions altogether may arise. For example: how much of the decision is a conscious and how much unconscious process? How much of it is automatic and how much reflexive? 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 should add a new method, based on the interaction with Neuroscience, and a new tool which has an important place in the present study: brain imaging.

The Principles of Functional Segregation and Integration

The technical details of the neuro-imaging 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 mental processes: in particular, in our case, decision processes.

It may not be clear why economists should be interested in the location in the brain of the activity that corresponds to a task of economic significance, so we discuss here briefly the theoretical premises behind this.

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. This is the second Principle, the *Principle of functional integration*. The difficulty and the challenge in this research are precisely a consequence 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 others¹. On the basis of this evidence in the past twenty years neuro-scientists have constructed a first rough model of the functional structure of the brain. An example of such reconstruction is the (recent but now classic) book by Shallice ([19]) 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 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. Imaging techniques overcome both limits, allowing the researcher an overall view of the activity of the brain associated with different experimental treatments.

1.2 Specific aims of the study

Main hypothesis

As we have already mentioned, the aim is to identify and test a theory of the procedure that subjects follow in reaching their decision. We think it is advisable, in this first phase of the research, to focus on analysis of one of the least complex decisions, making a forced choice between pairs of economic stimuli.

¹The first to use this type of information to make inferences on the structure and functioning of the brain is Broca ([1])

Consequently, we chose a simple decision problem, in line with the original Ellsberg’s thought experiment ([8]). 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 did 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 the ambiguous lottery he has no information on this probability. In a partially ambiguous he has *some* information. So the partially ambiguous lottery seems located, from a choice theoretic point of view, in an intermediate position between risky and ambiguous lottery. We are going to see, however, that from a procedural point of view it has a very specific nature. If the procedure is important, 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.

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. In subsection 3.2 we focus on an important source of evidence: 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 derive our conclusions, and outline what we think should be done next.

2 Experiment Design

Subjects were instructed to make a sequence of choices between pairs of lotteries.

Lotteries

In the entire experiment, four different types of lotteries were used: certain (C), risky (R), partially ambiguous (PA) and ambiguous (A). Lotteries were described on a screen. The 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. 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 would then check which of the two lotteries in these choices the subject had selected. Then we would fill a real urn with balls in the proportions stated in those lotteries, and ask 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. The urn for the risky lottery had an equal number (90) of balls of each color; that for the ambiguous lottery had no information on the number of balls of either color (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. So the condition *PAC* is given by a partially ambiguous lottery (*PA*) and the certain lottery (*C*), the *AR* by 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*).²

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.

The task in the *C* condition is relatively simple: 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 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 clearly inferior to a subject who is risk and ambiguity averse. As we are going to

²The names main and reference lottery are only used here for expository purposes: they were never used in the experiment, and neither were the labels certain, risky, partially ambiguous and ambiguous.

see, this simple prediction holds.

Time sequence

Each subject faced the six conditions we have just described, plus two Eyes Closed Rest (*ECR*) conditions. The conditions, and the set of choices in each condition were the same for each subject. The order in which conditions were presented was determined randomly and independently for each subject. In each condition, the order of different choices was selected randomly and independently for each subject.

Imaging technique

The study was conducted with *PET* (Positron Emission Tomography). Details on the technique are presented in the appendix (section 8)

Implementation

Subjects were 12 young healthy right-handed individuals. They were chosen among those answering a public announcement posted on campus.

Subjects came in separately, and in most cases on different days. We first paid them 50 dollars in cash. This show-up award was never at risk during the experiment. We then presented the instructions: copy is reported as an attached document. The instructions were very detailed. We also asked the subjects to answer short quiz questions during the presentation to check their level of understanding. The purpose of the detailed and careful instructions was 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 make them familiar with the physical setup: the choice was made by a click on the left or right button of a mouse.

After the instructions we transferred the subjects to the scanner, where the 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. 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 follows 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 then switches to the *C* lottery when the threshold is passed.

We provide an estimate of the cutoff point in the table 1 below. The cutoff is chosen for each subject to minimize the number of deviations, for that subject, of the observed choices from the estimated cut-off policy ³.

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

Variable	Obs	Mean	Std. Err.	95% conf. int.
AC cutoff	187	21.54	.480	20.59, 22.49
PAC cutoff	187	20.63	.422	19.80, 21.46
RC cutoff	170	26.3	.46	25.38, 27.21

Table 2 shows that subjects are consistent in their choices, and the instances of 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. It also seems to suggest that the two conditions *PAC* and *AC* are similar.

A * denotes missing data.

³More precisely, the cutoff has been determined according to the following rules:

1. The last value (in ascending order) at which the choice of the *R*, *PA* and *A* respectively was made;
2. The choice among possible cutoffs is made to minimize the number of deviations from the policy;
3. If the estimated cutoff is among the values at which the subject expressed indifference, then choose the middle if the number of such values is odd, and the next one in ascending order if the number is even.

Table 2: Choices in the C -condition

Subject	27	29	39	40	44	52	53	55	59	68	71	average
Cutoff in RC	25	25	10	25	33	31	30	28	28	28	*	26.3
Deviations from cutoff	0	0	0	0	2	3	3	3	0	1	*	1.09
Cutoff in PAC	20	25	10	15	32	20	30	20	20	15	25	20.63
Deviations from cutoff	0	0	0	0	1	2	0	2	1	0	0	0.5
Cutoff in AC	20	20	10	15	31	30	28	20	28	15	20	21.54
Deviations from cutoff	0	0	0	0	2	0	0	0	0	0	1	.25
PAC-AC	0	5	0	0	1	-10	-3	0	-8	0	5	-0.9

The R -condition

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

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

Subject	27	29	39	40	44	52	53	55	59	68	71	total	percent
RR	0	4	0	0	3	0	6	1	6	2	*	22	14.7
PAR	1	0	0	0	4	0	1	1	4	1	0	12	7.3
AR	1	2	0	0	2	2	3	1	3	0	0	14	8.5

Subjects chose the more risky lottery (the lottery with the greater spread) only 14.7 per cent of the times in RR , 7.3 per cent in PAR , and 8.5 per cent in AR .

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 on average six dollars higher when the main lottery is R than it is when the main lottery is A or PA (see table 1).

The nature of the choice

The choice in the R -condition seems simpler. It involves a qualitative comparison, or at least a decision can be reached on the basis of simply qualitative arguments. As we noted, the two lotteries have the same expected value, but the main lottery has the compound negative effect of the higher risk and the higher ambiguity.

The choice in the C conditions, on the other hand, involves a quantitative comparison, since some estimate of the value of the main lottery has to be compared with a certain, but varying amount of the C lottery.

3.2 Response Times

The *response time* (RT) is the length of the time interval between the moment when the stimulus (the two lotteries) appears on the screen and the moment when the subject clicks on the mouse making the choice. Table 4 presents the first surprise. The table shows the average response time, taken over subjects and over the different choices in the same condition, together with some summary statistics ⁴.

Table 4: Average response times (RT) in the different conditions

Variable	Obs	Mean	Std. Err.	95% conf. interval
RT in AC	187	1958.20	62.29	1835.30, 2081.10
RT in PAC	182	2166.37	71.74	2024.81, 2307.94
RT in RC	170	2488.88	77.30	2336.27, 2641.48
RT in AR	162	2911.03	88.01	2737.22, 3084.83
RT in PAR	165	2816.20	90.24	2638.01, 2994.39
RT in RR	148	2723.27	92.00	2541.45, 2905.10

The response time is approximately 0.5 s (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).

Among the C -conditions, the fastest decisions are made in the AC and PAC conditions. The slowest decision are made in the parallel R -conditions, namely AR and PAR . This disparity in response time suggests that subjects approached the two conditions with markedly 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 . Let us examine first the C -conditions. We consider 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 almost indifferent is the outcome of a real life decision process, rather than the premise. To reach this outcome, the subject might need less time when the value of the certain lottery is

⁴The 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

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 response times seem in agreement with the predictions of the procedural model. 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 an approximate 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 [16]).

The different conditions exhibit some interesting differences. 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 seems to indicate a regular, progressive learning, rather than an initial stage where subjects decide a policy in the form of a cutoff and later simply implement the policy. The *discut* variable has a significant coefficient in the *AC* and *RC* conditions as well; but the coefficient in *AC* seems significantly smaller than in the *PAC* condition. The *order* variable seems less significant, or insignificant, in the *RC* and *AC* cases respectively.

Learning in *R*. The reader may find useful to check at this point the description of the lotteries in section 7. Here the reference lottery is *R*. 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* seems to be significant, at least in the *PAR* and in the *RR* condition. The lack of learning seems 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 [21], the authors conduct a careful study of the response time for addition of

two digit integer numbers ⁵. 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 ⁶.

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 [16]. 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 ⁷, 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 ⁸

4 Imaging results and analysis

4.1 Premise

A more detailed explanation of the *PET* technique and of the statistical analysis underlying the study is given in the appendix. Here we present the basic concepts needed to understand the evidence we present.

A point in the brain is defined by a triple of (x, y, z) coordinates. A positive x value denotes a position on the right; a positive y a position in the rostral (anterior) part; finally a positive z denotes a position in the top (dorsal) part of the cerebrum. 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 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. Of course we cannot test the

⁵For 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.

⁶While not explicitly stated, it seems that subjects had no time constraint.

⁷This is defined and discussed in detail in [6]. A second effect, the number size effect, was also documented in [6]: for equal numerical distance, the discrimination of two numbers worsens as their numerical size increases.

⁸Numbers 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.

probability that the $rCBF$ in a condition is different from zero, but only whether the level in one condition is significantly different from another. It is perfectly 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. 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 [22] atlas.

4.2 The evidence

C condition versus *R* condition

The most active contrasts are in the *C* condition. The *R* condition is comparatively weaker. This is particularly true if one considers the difference between the various treatments and the ECR condition⁹. For the *C* condition, the most active is condition with *PA* as main lottery; similarly, in the *R* condition the most active is the condition with *PA* as main lottery.

A large active region common to many of the differences between the *C* condition 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 amounts of visual scanning the main lottery for the purpose of defining the cutoff that is subsequently compared to the (degenerate) constant lottery. Eye-tracking data would provide a strong test of this interpretation.

The *PAC* condition

The two differences $PAC - AC$ and $PAC - RC$ have similar patterns. 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

⁹See [10] for a recent illuminating discussion of the role and interpretation of the “baseline” conditions in Brain Imaging

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.

The main areas of activation in the two differences *PAC* – *AC* are:

1. a right frontal lobe, middle frontal gyrus, with peak at $(42, 50, -2)$, with a *Z* score 4.59;
2. a parietal lobe, subgyrus, with a peak at $(25, -55, 42)$, with a *Z* score 4.42;
3. a parietal lobe, subgyrus, with peak at $(34, -55, 33)$, with a *Z* score 4.11;
4. an occipital lobe, lingual gyrus, with peak at $(-15, -91, -14)$, with a *Z* score 4.1.
5. a parietal lobe, precuneus, with peak at $(1, -37, 42)$, with a *Z* score 3.89;

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 $(46, 39, -9)$, 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 an utterly novel experience for our subjects.

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 even 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, with peak at $(-15, -13, 63)$ with a Z score = 4.1. 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.

OK, I am confused now. Why are the areas discussed in the previous paragraph NOT included in the enumeration above? Also, there are two different uses of the letter z in this paragraph. One for z -score and one of the vertical coordinate. I think we should use the phrase z -score whenever that is what we are referring to.

Particularly the Pre-frontal cortex (PFC) does appear prominently among the regions that are activated. The PFC ¹⁰ is associated with planning, namely the ability to organize cognitive behavior in time and space¹¹.

Ventromedial

There seems to be no strong activation of the ventromedial regions, that is, in areas known to mediate the processing of visceral and emotional information.

A partial exception is the an area that appears in some of the differences. The most noticeable instance is in 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.

5 Conclusions

It is time to collect the different observations that are particularly significant (in section 5.1), and try to provide a tentative interpretation of the results (in the section 5.2.)

5.1 Summary

1. The observed choice behavior is not noisy: subjects behave as expected by model 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;

¹⁰The PFC is the area of the cortex comprising the pole of the frontal lobe. It corresponds to the Brodmann areas 9, 10, 11.

¹¹This is by now a classic finding. It has first been suggested by lesion studies (see for example the early studies of Shallice ([20]). These early results have been confirmed by brain-imaging studies. For this, see for example [23], [12], [13]. But the literature on this is very large: a useful review is in Cabeza *et alii*, [3]. Owen (1997) ([14]) offers a detailed review of definition and properties of planning ability in human subjects.

3. learning seems to be effective in the *PAC* condition, less so in the other two *C* conditions, and almost absent in the *R* type 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. there is a larger activation in the parietal regions

5.2 Interpretations

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, by those on response times, and by the imaging data. The various *C* conditions are not uniformly harder. However, the *procedural* difficulty of the choice seem 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. The worse 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.

Conscious and unconscious estimates

There is no reason to think that the procedure we have outlined is 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 does not involve substantial calculation and may even 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 need in this arena.

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 [4], [7]; also see [17], [11]).

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 [5] for a review of these findings¹². Subsequent work by the same team (see [6]) 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 [7] 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 both behavioral and brain-imaging studies, exact calculations are shown to be language dependent, while approximations rely on a visuo-spatial cerebral network (see [21] and [7]¹³).

¹²For instance, in [7] 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”.

¹³In the [21] 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 representations that humans share with other mammals. Language appears to play a role in learning about exact numbers in a variety of contexts..

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 than 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 [2], 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.

Emotions

The lack of strong activations in emotional regions suggests that in a standardized task of choice between lotteries subjects may follow a procedure that relies, perhaps in some automatic way, on quantitative estimates¹⁴. I don't think we can say that just because the process does not involve emotions that it is necessarily quantitative. I am under the impression that we have worked hard to establish that it is qualitative and approximate. I suggest: relies less on what is familiarly called "intuition" (whatever that may be) and more on approximation or qualitative estimation.

5.3 Procedural choice

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 test ?? for accuracy ?; 'accurate' here may anticipate among the possible tests some criteria other than the observed choice behavior.

¹⁴We are not going to deny here the role that emotions can have on human decision making.

The nature of the procedure

Here is procedure that subjects might be following in the C condition, and which gives an account of the observed behavior. 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 division by two. In the A case, suppose that 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 easy to estimate, and is a certain amount equal to the prize associated with the only type of ball existing in the urn. 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 $\frac{17}{18}$. How about they just ignore the two known values and treat it exactly like ambiguity? I resist the idea of fractions. And am more inclined to pursue the ”avoid the zero outcome” model for both AC and PAC.

Basic Assumptions

Two basic assumptions make the model of procedural choice a useful and interesting model.

First, 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 (for example, an experimental economics laboratory rather than the stock market).

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.

Second, 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 (that is the choice).

A final methodological observation. 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 which 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

6 Appendix: additional 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.
$discut$	-28.40	6.90	-4.11	0.000	[-42.02, -14.77]
$order$	-5.28	12.15	-0.43	0.664	[-29.27, 18.70]
constant	2381.13	159.80	14.90	0.000	[2065.84, 2696.42]

Table A2: Response time for PAC on $discut$ and $order$					
Variable	Coeff.	Std.Err.	t	$P > t$	95% conf.int.
$discut$	-51.91	7.30	-7.10	0.000	[-66.33, -37.49]
$order$	-26.15	12.59	-2.07	0.039	[-51.00, -1.29]
cons	3104.06	158.79	19.54	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.
$discut$	-44.23	9.29	-4.75	0.000	[-62.58, -25.88]
$order$	-29.40	14.82	-1.98	0.049	[-58.67, -.14]
constant	3213.33	165.95	19.36	0.000	[2885.69, 3540.97]

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	4.56	12.49	0.365	0.715	[-20.13, 29.26]
order	-6.54	21.29	-0.308	0.759	[-48.63, 35.53]
variance	128.32	112.66	1.139	0.257	[-94.38, 351.03]
constant	2570.14	919.77	2.794	0.006	[752.02, 4388.26]

Table A5: Response time for PAR on value, order and variance					
Variable	Coeff.	Std.Err.	t	$P > t$	95% conf.int.
value	23.31	12.26	1.901	0.059	[-.91, 47.54]
order	2.64	20.94	0.126	0.900	[-38.74, 44.03]
variance	253.38	111.48	2.273	0.024	[33.05, 473.72]
constant	1279.31	878.11	1.457	0.147	[-456.14, 3014.77]

Table A6: Response time for RR on value, order and variance					
Variable	Coeff.	Std.Err.	t	$P > t$	95% conf.int.
value	11.65	12.23	0.953	0.342	[-12.51, 35.83]
order	-15.14	20.99	-0.722	0.472	[-56.63, 26.34]
variance	289.636	111.60	2.595	0.010	[69.04, 510.22]
constant	2024.83	887.83	2.281	0.024	[269.96, 3779.71]

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 to 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 ¹⁵.

In the risky lottery R the urn had 90 blue, 90 red balls; the outcomes had expected values ranging from 30 to 40 ¹⁶. 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 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 ¹⁷.

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

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

¹⁶More precisely, the values in the range were: 30, 32, 35, 38, 40.

¹⁷The values in this case were 60, 64, 70, 76, 80

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 [15] for details¹⁸.

8.1 Statistical Analysis

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.

¹⁸A web site on PET which can be useful for introductory information is at <http://www.crump.ucla.edu/software/lpp/>

References

- [1] Broca, P., (1861), “Remarques sue le siege de la faculte du langage articule, suivies d’une observation d’aphemie”, *Bul. Mem. Soc. Anat.* Paris, 2, 330-357
- [2] Bundesen, C., (1990), “A Theory of Visual Attention”, *Psychological Review*, 97, 523-527
- [3] Cabeza, R. and Nyberg, L., (2000), “Imaging Cognition II: An Empirical Review of 275 PET and fMRI Studies”, *Journal of Cognitive Neuroscience*, 12, 1, 1-47
- [4] Dehaene, S. Tzourio, N, Frak, V. *et alii*, (1996), “Cerebral Activations during number multiplication and comparison: a PET study”, *Neuropsychologia*, 34, 1097-1106
- [5] Dehaene, S., (1992), “Varieties of numerical abilities”, *Cognition*, August, 44, 1-2, 1-42
- [6] Dehaene, S., Dehaene-Lambertz, G. and Cohen, L., (1998), “Abstract representations of numbers in the animal and human brain” *Trends in Neuroscience*, 21, 8, 355-361
- [7] Dehaene, S., Spelke, E., Pinel, P., Stanescu, R. and Tsivkin, S., (1999), “Sources of Mathematical Thinking: Behavioral and Brain-Imaging Evidence”, *Science*, May 7, Vol.284, 970-974
- [8] Ellsberg, D., (1961), “Risk, ambiguity, and the Savage axioms”, *Quarterly Journal of Economics*, 75, 643-669
- [9] Frackowiak, R., Friston, K., Frith, C., Dolan, R. and Mazziotta, J., (1997), *Human Brain Function*, Academic Press.
- [10] Gusnard, D. and Raichle, M., (2001), “Searching for a Baseline: Functional Imaging and the Resting Human Brain” *Nature reviews, Neuroscience*, 2, October, 685-694
- [11] Jonides, J., Schumaker, E., Smith, E. *et alii*, (1999), “The role of parietal cortex in verbal working memory” *Journal of Neuroscience*, 18, 5026-5034
- [12] Koechlin, E., Corrado, G., Pietrini, P., and Grafman, J., (2000), “Dissociating the role of the medial and lateral anterior prefrontal cortex in human planning”, *Proceedings of the National Academy of Sciences*, 97, 7651-7656
- [13] Koechlin, E., Basso, G., Pietrini, P., Panzer, S., and Grafman, J., (1999), “The Role of the Anterior Frontal Cortex in Complex Goal-Directed Behavior”, *Nature*, 399, 148-151
- [14] Owen, A. M., (1997), “Cognitive Planning in humans: neuropsychological, neuroanatomical and neuropharmacological perspectives”, *Progress in Neurobiology*, 53, 431-450

- [15] Phelps, M. E., (1992), “Positron Emission Tomography”, in Mazziotta, J. and Gilman, S., eds., *Clinical Brain Imaging: Principles and Applications*, Davis Co.
- [16] Pinel, P., Dehaene, S., Riviere, D., and LeBihan, D., (2001), “Modulation of parietal activation by semantic distance in a number comparison task”, *Neuroimage*, November, 14(5), 1013-26
- [17] Pugh, K., Shaywitz, S., *et alii*, (1996), “Auditory selective attention: an fMRI study”, *Neuroimage*, 4, 159-173
- [18] Simon, O., Mangin, J-F., Cohen, L., Le Bihan, D. and Dehaene, S., (2002), “Topographical Layout of Hand, Eye, Calculation, and Language-Related Areas in Human Parietal Lobe”, *Neuron*, 33, 475-487
- [19] Shallice, T., (1988), *From Neuro-psychology to mental structure*, Cambridge University Press, Cambridge, UK
- [20] Shallice, T., (1982), “Specific Impairments of planning”, *Philosophical Transactions of the Royal Society of London, B, Biological Sciences*, 298, 199-209
- [21] Spelke, E. and Tsivkin, S., (2001), “Language and Number: a bilingual training study”, *Cognition*, 45-88
- [22] Talairach J. and Tournoux, P. (1988), *Co-planar stereotaxic atlas of the human brain*, Thieme, New York.
- [23] Zalla, T., Koechlin, E., Pietrini, P., Basso, G., Aquino, P., Sirigu, A., and Grafman, J., (2000), “Differential Amygdala Responses to Winning and Losing: a functional Magnetic Resonance Imaging Study in Humans”, *European Journal of Neuroscience*, 12, 1764-1770