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Decision making on ambiguous stimuli such as prosody by subjects suffering from paranoid schizophrenia, alcohol dependence, and without psychiatric diagnosis

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The aim of this study is the empirical verification of the Bayesian approach applied to the description of the decision-making process with regard to prosodic stimuli in different psychopathological states. Using the Bayesian formalism, the interpretation of a disturbance in internal representation of the contextual information in schizophrenia was given. The results obtained satisfied the formula derived from Bayes' theorem in all tested except a schizophrenic group. Results were interpreted as reflecting cognitive flexibility, and discussed in the context of social adaptation. Although the investigation was based on psychopathological grounds, the results may be applied to the functioning of working memory in general.

1. Introduction

It is widely accepted that working memory is responsible for information processing, and its dysfunction is related to the manifestation of schizophrenia (Barch, Csernansky, Conturo, & Snyder, 2002; Carter *et al.*, 1988; Goldman-Rakic, 1994; Spitzer, 1993). On psychopathological grounds, it was demonstrated that schizophrenic patients became more symptomatic when processing ambiguous stimuli (Safrati, 2000), and ambiguous social stimuli may elicit delusional content (Phillips, Senior, & David, 2000). On the other hand, it should be noted that 'a disturbance in internal representation of the contextual information' was postulated to have been a core deficit in the schizophrenia pathology (Cohen & Servan-Schreiber, 1992; Hemsley, 1994). Could these observations be explained by a single approach?

Recent findings suggest that population coding is appropriate to describe computations performed in the working memory during stimulus processing (Baeg *et al.*, 2003; Constantinides & Goldman-Rakic, 2002). Among models of population coding,

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a Bayesian approach deserves particular attention, because it has been effective in explaining stimulus processing, where uncertainty is the major feature (Pouget, Dayan, & Zemel, 2003). It should also be noted that, according to some authors, the mind is predisposed against performing Bayesian inference (Gigerenzer & Hoffrage, 1995). This observation suggests that the Bayesian approach is a natural description for mental phenomena embedded in biological context. This idea comes as no surprise if one takes into account that a Bayesian approach interprets probability as 'a measure of a state of knowledge', which means that people possessing the same knowledge about the context will render the same decisions (Jaynes, 2003). Therefore, the description of ambiguous stimulus processing in Bayesian terms may reflect different states of people's knowledge resulting from psychopathological contexts of different aetiology, of which an 'internal representation of the contextual information' may be a particular example.

Typical stimuli in which humans encounter uncertainty are prosodic stimuli important for speech recognition (McQueen, Norris, & Cutler, 1994; Wingfield, Goddglass, & Lindfield, 1997). Taking into consideration the objectives of this study, emotional prosody deserves particular attention provided that emotions are assumed to play an important role in schizophrenia psychopathology (Andorfer, 1984; Ciompi, 1994); it is known that people suffering from schizophrenia have disturbed emotional prosody processing (Leitman *et al.*, 2005; Murphy & Cutting, 1990), and the Bayesian formalism has been used effectively to model the intrinsic prosody processing in a word recognition process (Chen & Hasegawa-Johnson, 2004). These features of emotional prosody processing make prosodic stimuli suitable for an experiment dealing with the decision-making process about ambiguous stimuli in terms of the Bayesian formalism.

2. Rationale

According to the Bayes rule,

$$\Pr(A|B) = \frac{\Pr(B|A)\Pr(A)}{\Pr(B)}, \tag{1}$$

where

- $\Pr(A)$ is called the *a priori* probability, or 'prior' in the sense that it does not take into account any information about B;
- $\Pr(A|B)$ is the conditional probability of A given B, also called the posterior probability because it is derived from or depends upon the specified value of B;
- $\Pr(B|A)$ is the conditional probability of B given A;
- $\Pr(B)$ is the prior probability of B, and acts as a normalizing constant.

If we apply the Bayesian formalism to the decoding of prosodic stimuli, using words and numbers, we can define this process in the following way:

$$p(\mathbf{s}|\mathbf{w}) \times p(\mathbf{w}) - p(\mathbf{w}|\mathbf{s}) \times p(\mathbf{s}) = 0 \tag{2}$$

where $p(\mathbf{s}|\mathbf{w})$ is the posterior probability of decoding a stimuli given a set of words, that is, $p(\mathbf{s}|w_1, w_2, w_3, \ldots, w_n)$; $p(\mathbf{w}|\mathbf{s})$ is the likelihood of a word meaning being understood as a set of words associated with particular stimuli, that is, $p(w_1,w_2,w_3, \ldots ,w_n|\mathbf{s})$; $p(\mathrm{s})$ represents the *a priori* probability of a stimulus; $p(\mathbf{w})$ represents the probability of a *word set*, that is, $p(w_1, w_2, w_3, \ldots , w_n)$.

According to this approach, prosodic stimuli are defined with respect to all words participants in social interaction can use to name them. Obviously, the probability that a particular word will be used to name a prosodic signal is varied among words. Moreover, we can think not only of words to be used in particular situation, but sets of words as well (i.e. certain sets of words are more likely to be associated with particular prosody than others). In our experiment, the experimental paradigm used a set of 10 words.

Similarly, if we assume that the meaning of a word is defined by the prosodic stimuli with which the word may be associated with a given probability, this meaning can be defined as

$$p(\mathrm{w}|\mathbf{s}) \times p(\mathbf{s}) - p(\mathbf{s}|\mathrm{w}) \times p(\mathrm{w}) = 0, \tag{3}$$

where $p(\mathrm{w}|\mathbf{s})$ is the posterior probability of ascribing set of stimuli to the particular word, that is, $p(\mathrm{w}|s_1,s_2,s_3, \ldots ,s_n)$; $p(\mathbf{s}|\mathrm{w})$ is the likelihood of decoding a stimulus given the set of words, that is, $p(s_1,s_2,s_3, \ldots ,s_n|\mathbf{w})$; $p(\mathrm{w})$ represents the *a priori* probability of a word; and $p(\mathbf{s})$ represents the probability of a *stimulus set*, that is, $p(s_1, s_2, s_3, \ldots , s_n)$.

Hence

$$p(\mathrm{s}|\mathbf{w}) \times p(\mathbf{w}) - p(\mathbf{w}|\mathrm{s}) \times p(\mathrm{s}) = p(\mathrm{w}|\mathbf{s}) \times p(\mathbf{s}) - p(\mathbf{s}|\mathrm{w}) \times p(\mathrm{w}). \tag{4}$$

Note that if word and stimulus sets *are given*, for example they are supplied by the experimenter,[1] their probability will be 1, that is, $p(\mathbf{w})$ and $p(\mathbf{s})$ will be equal to 1. Similarly, if $p(\mathbf{w}|\mathbf{s})$ and $p(\mathbf{s}|\mathbf{w})$ represent the probability of word sets and stimuli that may be *activated as mental representations*, by definition their probability must also be equal to 1. $p(\mathbf{w}|\mathbf{s})$ cannot be equal to 1, because the strength of relationship between *particular stimuli* and a set of possible words is a question of chance. A similar situation occurs if we again assume that the strength of associations between a *particular word* and a set of possible stimuli is a question of chance.

Hence

$$p(\mathbf{s}|\mathrm{w}) \times p(\mathrm{w}) - p(\mathbf{w}|\mathrm{s}) \times p(\mathrm{s}) = 0. \tag{5}$$

Therefore, if it is assumed that confidence about a particular word, given the set of stimuli, is a sum

$$p(\mathbf{s}|\mathrm{w}) = p(s_1|\mathrm{w}) + p(s_2|\mathrm{w}) + \cdots + p(s_n|\mathrm{w}) = \sum_{k=1}^{n} p(s_n|\mathrm{w}) \tag{6}$$

and confidence about particular stimuli given *set of words* is a sum

$$p(\mathbf{w}|\mathrm{s}) = \sum_{k=1}^{n} p(w_n|\mathrm{s}), \tag{7}$$

[1]I mean not some abstract example, but this particular experiment.

then it can be assumed that

$$p(\mathrm{w}) \times \sum_{k=1}^{n} p(s_n|\mathrm{w}) = p(\mathrm{s}) \times \sum_{k=1}^{n} p(w_n|\mathbf{s}) \tag{8}$$

or

$$p(\mathrm{w}) \times \sum_{k=1}^{n} p(s_n|\mathrm{w}) - p(\mathrm{s}) \times \sum_{k=1}^{n} p(w_n|\mathrm{s}) = 0. \tag{9}$$

Confidence about particular word given the stimuli is related to the number words in the words set multiplied by number of stimuli in the stimuli set. For the sake of simplicity it is assumed that it is evenly spread between words. The same applies to the stimuli. If a person is asked to assess the strength of relationship between words and stimuli that reflects the appropriateness of a word with respect to the stimuli, and of the stimuli to the words, certainty of his/her judgements can be defined as the ratio of the greatest value ascribed to a given word regarding the stimuli and the sum of all values ascribed to these stimuli by a person. If unity is added to the sum in the denominator of the fraction displaying a 'peak', division by 0 is avoided. By symmetry, unity is added to the greatest ascribed value in the numerator of the fraction.

Thus, the confidence about particular variable may be defined as

$$p(v) = \frac{\text{max} + 1}{\text{sum} + 1}, \tag{10}$$

where max is the maximal numeric value from a given scale ascribed by a person to an overheard stimulus with respect to a word from a set of given words; sum is the sum of all numeric values, given in response to a stimulus by a person with respect to subsequent words from a set of words; and v represents a variable.

Thus $p(v_{\mathrm{w}})$ represents the confidence that the word matches the stimuli after taking into consideration other words from the set, and $p(v_{\mathrm{s}})$ represents confidence about stimuli given a word with respect to the rest of the stimuli from the set. Formula (10) resembles the classic definition of probability, differing in that the maximal person's confidence replaces the frequency of an event in the numerator, and the sum representing a person's experience replaces in the denominator the set of all possible events that may happen. The confidence as a measure of uncertainty is introduced the same way as the concept of probability pertains to the realm of possibility. It should be noted that according to the definition given above (10), a person's confidence about stimuli is 0, only if *there is no value in the column or row, depending on which measure is taken into consideration*. On these grounds, it is assumed that $p(\mathbf{w}) \equiv p(v_{\mathrm{w}})$, $p(\mathbf{s}) \equiv p(v_{\mathrm{s}})$, and

$$\sum_{k=1}^{n} p(s_n|\mathrm{w}) = p(v_{\mathrm{s}1}) + p(v_{\mathrm{s}2}) + \cdots + p(v_{\mathrm{s}n}) \tag{11}$$

for a given word and every stimulus from the set of stimuli, and

$$\sum_{k=1}^{n} p(w_n|\mathrm{s}) = p(v_{\mathrm{w}1}) + p(v_{\mathrm{w}2}) + \cdots + p(v_{\mathrm{w}n}) \tag{12}$$

for a given stimulus and every word from the set of words.

Thus equation (9) can be rewritten as

$$p(v_s) \times \sum_{k=1}^{n} p(v_{wn}) - p(v_w) \times \sum_{k=1}^{n} p(v_{sn}) = 0, \tag{13}$$

where '**w**' and '**s**' stand for word and stimulus, respectively, and subscript n stands for the number of words/stimuli appearing in the experiment.

Equation (13) was subsequently empirically verified in groups of participants with supposed deficits in their working memory during decision making about ambiguous stimuli. The value on the right-hand side of equations (9) and (13) will later be called the 'difference value'.

Formula (10) defines a person's assessment confidence. However, particular assessments may be varied according to the person's personal experience, thus representing variants of possible meaning. That is why another measure was introduced to deepen the analysis of the relationship between values given by people participating in the experiment.

The square root of the sum of squares of differences defined as below represents the dispersion between values given by participants – their judgements in fact. This latter measure is similar to the statistical standard deviation, but with the greatest ascribed value put in place of the mean:

$$r(v) = \sqrt{[((\max - o_1)/n)^2 + ((\max - o_2)/n)^2 + \cdots + ((\max - o_n)/n)^2]/n}. \tag{14}$$

Here max has the same meaning as earlier; o_n is the nth assessment of a stimulus/word made by a person with respect to the subsequent stimulus/word from the set; v represents a variable, that is, v_s or v_w; n is the number of words/stimuli.

In the proposed experiment, a person was supposed to assess 10 stimuli with respect to 10 words. Thus every stimulus had 10 assessments, and every word was assessed with respect to the 10 stimuli.

3. Participants

Individuals prone to the development of organic psychoses, on the one hand, and functional psychoses, on the other, were considered appropriate as experimental participants. Taking into consideration what is known about working memory deficits in schizophrenia, and observations that long-term alcohol abuse might lead to the development of schizophreniform symptomatology (Soyka, Dresel, Horak, Ruther, & Tatsch, 2000), working memory and cognition impairment (Fein, Bachman, & Fisher, 1990; Pitel *et al.*, 2007), individuals suffering from paranoid schizophrenia, alcohol dependence, and without psychiatric diagnosis were included in the experimental paradigm.

One hundred randomly selected participants were tested, from whom three groups of 18 people were formed so that maximum homogeneity was achieved with respect to age and educational level. Because participants should not understand the semantic meaning of the soundtracks, the inclusion criteria were a self-reported inability to speak English (the presented material was in this language), lack of hearing disturbance, and psychiatric diagnosis. Verbal declaration was regarded as satisfactory. Even assuming that participants were dishonest about their language ability, there was no reason to believe that participants from one group were more dishonest than the others. Alcohol-dependent and control groups did not have any lifetime psychiatric history.

Demographic data are given in Table 1. Test groups were formed in such a way that they did not significantly differ in respect of age and education. Every participant was diagnosed by an independent psychiatrist according to the DSM-IV criteria. Every schizophrenic patient was under pharmacological treatment. The symptom severity was assessed by means of the Brief Psychiatric Rating Scale (BPRS), items of which were later used to compose five dimensions (Ruggeri *et al.*, 2005). The first dimension was labelled 'manic excitement/disorganization', and consisted of the following items: elevated mood, bizarre behaviour, self-neglect, excitement, distractibility, motor hyperactivity, and mannerisms. The second dimension was labelled 'positive symptoms', and was composed of grandiosity, suspiciousness, hallucinations, unusual thought content, and conceptual disorganization. The third one was 'negative symptoms', and included disorientation, blunted affect, emotional withdrawal, motor retardation, mannerisms, and posturing. The fourth, called 'depression/anxiety', comprised of anxiety, depression, suicidality, and tension. Alcoholics were undergoing addiction therapy, did not take any medication, and were abstinent for at least 2 months. The study design was reviewed by an appropriate ethical committee and informed consent of the participants was obtained after the nature of the procedures had been fully explained. The study conforms with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Table 1. Socio-demographic data of the participants

Participants	Paranoid schizophrenics	Alcohol dependents	Control group
Age in years	39.8 ± 2	37.1 ± 1.6	38.7 ± 1.4
Females	9	9	12
High education	4	4	4
Secondary education	9	9	8
Elementary education	5	5	6
Mean duration of the disorder in years	6.9 ± 3.6	1 ± 0.6	–
Mean BPRS score	1.25 ± 0.87	–	–
Manic excitement/disorganization	1.11 ± 0.86		
Positive symptoms	1.82 ± 1.00		
Negative symptoms	1.42 ± 0.45		
Depression/anxiety	0.43 ± 0.39		

4. Method

4.1. Stimuli

The prosodic stimuli were fragments of English film soundtracks with emotional content described by their titles. Participants were supposed not to understand the verbal meaning of the fragments. Three of the fragments were non-articulated exclamations, and seven were fragments of articulated utterances of a single person. The duration time of a particular stimulus was 2 s, and the duration of the whole series was 90 s, during which participants were supposed to assess the appropriateness of a particular word with respect to the overheard fragment of the film. They made their assessments in numbers, which they subsequently wrote in the cells of a specially prepared table. Every participant was tested individually and listened to the tape twice. All listened to the tape in the same place and at the same distance from the tape-recorder. The playback volume of the apparatus was the same in all experiments.

4.2. Procedure

Participants were asked to ascribe numbers reflecting the strength of the relationship between the words and audible stimuli. Every participant was given a table consisting of 12 columns and 11 rows. There were 10 nouns put in the first column of the table, and there were 12 strings of letters of different length in the 13th column. This last column was devoted to the control of disturbance variables. Each participant listened to the 10 film soundtracks, and was instructed to assess the correspondence between words from the 1st column of the table, and recorded fragments of film soundtracks solely on the basis of their prosodic content. Participants were told to make assessments on a '0–9' scale, on which the number of the scale reflected the appropriateness of a word as a description of overheard fragment. Thus '0' meant that a given word definitely did not reflect the meaning of a stimulus, '1' meant very low correspondence, and so on up to '9', which meant a perfect match. After listening to the 10th fragment there should have been 100 assessments in the table, creating a matrix on which measurements could be made with respect to the vertical, and horizontal dimension of the table. Participants were allowed to change their assessments when listening and make corrections to the table (Table 2).

Participants were requested to assess the appropriateness of a word from a given set of words with respect to the particular stimulus from a given set of stimuli in a given numerical scale. The choice of a number was the participant's decision. Thus, a particular stimulus from a given set of stimuli had as many assessments as there were words in a set, and every word would be defined by its relationship to the set of stimuli.

After the first part of the experiment all cells of the table were supposed to be filled and 100 assessments made, but it was not an obligatory condition for a table to have been analysed, i.e. empty cells did not exclude a table from the analysis.

Participants were instructed not to deliberate on their choices, and act spontaneously in spite of the fact they were allowed to make changes. There was no evidence that participants, including schizophrenic patients, would have liked more time to fill the table.

After completion of the table, $p(v)$ and $p(h)$ estimators with respect to the vertical or horizontal dimension of the table, and values of the difference according to equation (13), were calculated for each participant. Results of these calculations were pooled together for every test group, and subjected to analysis of variance (ANOVA) with a repeated measures design.

4.3. The problem of disturbing variables: Artefact score

To exclude the influence of psychomotor retardation, poor motivation, and drug effects on the performance of participants, global control of artefacts was applied at the end of the experiment. The idea was to apply a test similar to the prosodic one, which would address the factors cited above, but which would operate on a different principle.

For this reason, in the last part of the experiment, participants were asked to listen to the recorded series of phonemes, and find series of letters corresponding to them in the last column of the table. After that, participants were to assess the degree of

Table 2. The finished task by the patient C. S. aged 39 suffering from paranoid schizophrenia

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	flya		$r(v_w)$	$p(v_w)$
Anger	0	0	1	0	0	0	0	0	0	0	alfy	10	0.03	1.00
Joy	0	0	0	0	0	1	0	4	0	0	rtwdef	10	0.12	0.69
Sadness	0	0	0	0	0	0	0	0	0	0	wdeftr		0.00	1.00
Request	0	2	0	3	3	0	0	0	0	0	zyeghbn	10	0.08	0.65
Fear	0	0	0	0	0	0	0	0	0	1	btwfac		0.3	1.00
Pain	0	0	0	0	0	0	0	0	2	0	bwtfac		0.06	1.00
Despair	0	0	0	0	0	0	0	0	0	1	zyhnbe		0.03	1.00
Satisfaction	0	0	0	0	0	0	0	0	0	0	ttwdef		0.00	1.00
Threat	0	0	0	0	0	0	0	0	0	0	alfy	10	0.00	1.00
Order	0	0	0	0	0	0	4	0	0	0	zyehgbn		0.12	1.00
											btfac	10		
$r(v_s)$	0.00	0.19	0.09	0.28	0.28	0.09	0.38	0.38	0.19	0.09				
$p(v_s)$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.67	**Artefact score**	1		

Note. Bold boundaries constrain a table given to a person. Numbers in bold from the first row indicate subsequent film soundtracks that were prosodic stimuli. Calculated values of $p(v_w)$, $p(v_s)$, and artefact score are enclosed.

correspondence between them, that is, to assess their own level of certainty that a given string of letters matched the series of phonemes that they had just heard. Participants were told to express their certainty on an 11-point scale. Only strings of letters matching the recorded strings of phonemes were to be found. The scale began with '0' and ended with '10'. In this case, '0' meant absolute conviction that an overheard series was not the one from the strings of letters put in the 13th column, and '10' meant that an overheard string was the one from the set of strings. The scale contained '0' because participants could use it in the previous part of the experiment. However, the use of '0' by participants demonstrated, how they understood the instruction of filling the 13th column of a table, because use of the '0' made no sense in this part of the experiment.

There were five phoneme series recorded and 11 letter strings put in the 13th column of the table. All material was listened to once. Errors of omission and commission were included in the proposed index simultaneously. This was because of the global character of the artefact score. The level of disturbance variables was assessed according to the formula

$$M = \frac{-A + B + 50}{100}, \tag{15}$$

where, M is the artefacts index; A the sum of values ascribed to wrong answers; B the sum of values ascribed to correct answers; and 100 is twice the maximal value that can be obtained after completing the task.

Therefore, M must take values between 0 (all answers wrong) and 1 (all answers correct). The assessment is on the basis of the assumption that participants who were poorly motivated to participate in the experiment (tired, unable to follow instructions, etc.) would give accidental answers that would be reflected in low values of M.

5. Results

The effect of gender was tested statistically because it was impossible to establish similar gender ratios across experimental groups. This assessment was done using Student's t test by comparing $p(v_{\mathrm{w}})$ and $p(v_{\mathrm{s}})$ estimators in two groups consisting of 19 participants homogeneous with respect to age, education, and mental status. Gender did not differentiate participants with respect to $p(v)$, $t(36) = 0.21, p(|t| \leq |t_{0.05}|) = .84$, or $p(b)$, $t(36) = .44, p(|t| \leq |t_{0.05}|) = .66$.

5.1. Evaluation of difference values according to equation (13) in the three groups of participants

According to equation (13) it was supposed that

$$p(v_{\mathrm{w}}) \times \sum_{k=1}^{n} p(v_{\mathrm{s}n}) - p(v_{\mathrm{s}}) \times \sum_{k=1}^{n} p(v_{\mathrm{w}n}) = 0,$$

where n is the number of rows/columns in the table. Thus according to equation (13), every participant has 100 evaluations of the difference values (Table 3).

When all values were pooled together, and analysed with ANOVA with repeated measures, significant differences were revealed between groups with respect to the diagnosis, $F(2,51) = 3.89$, $p = .03$, and columns with difference values obtained from

Table 3. Histogram of values obtained according to formula (13) from all tested participants grouped in bins of 0.1 length

Bin	Control group		Sch group		Alc group	
	Frequency	Per cent	Frequency	Per cent	Frequency	Per cent
−0.50	0	0.00	1	0.56	0	0.00
−0.40	2	1.11	0	0.00	0	0.00
−0.30	1	0.56	1	0.56	4	2.22
−0.20	8	4.44	4	2.22	5	2.78
−0.10	17	9.44	12	6.67	18	10.00
0.00	70	38.89	63	35.00	73	40.56
0.10	51	28.33	79	43.89	56	31.11
0.20	17	9.44	13	7.22	10	5.56
0.30	5	2.78	6	3.33	7	3.89
0.40	8	4.44	1	0.56	4	2.22
More	1	0.56	0	0.00	3	1.76
Total	180	100	180	100	180	100

formula (13), $F(9,459) = 4.01, p < .01$. The interaction was not significant, $F(18,459) = 0.53$ $p = .94$. Zero values constituted 7% of all values in the control group, 7.5% of all values in the Alc group, and 8% in the Sch group (Figure 1).

5.2. The relationship between p(v) and r(v) grouped in bins of length 0.1

The distribution of $p(v)$ and $r(v)$ values in the tested groups was compared pairwise, namely $p(v_w)–r(v_w)$, $p(v_s)–r(v_s)$, using the chi-square test after grouping them into bins of length 0.1. The distributions differed significantly at the .0005 level in all groups of participants with respect to all the dimensions: in the control group for $p(v_s)–r(v_s)$, pair $\chi^2(9) = 285.84$; for $p(v_w)–r(v_w)$, pair $\chi^2(9) = 302.14$; in the alcohol-dependent group for $p(v_s)–r(v_s)$, pair $\chi^2(9) = 247.85$; for $p(v_w)–r(v_w)$, $\chi^2(9) = 302.14$; in the schizophrenic group for $p(v_s)–r(v_s)$, $\chi^2(9) = 1{,}064.24$; for $p(v_w)–r(v_w)$, $\chi^2(9) = 323.88$.

For all combinations, Pearson correlation coefficients were calculated. The results are shown in Table 4.

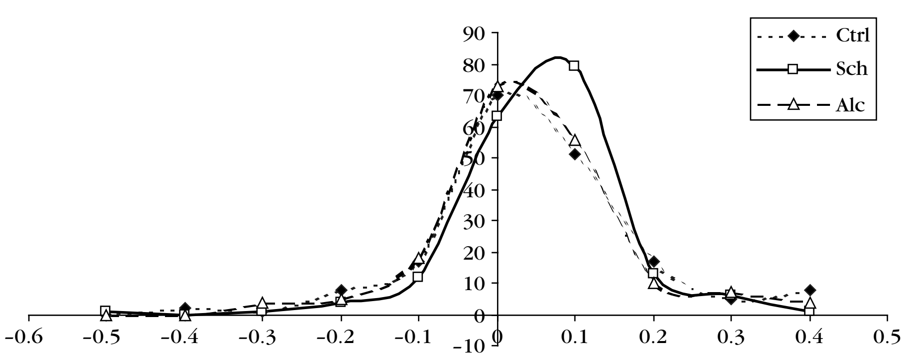

Figure 1. Distributions of difference values according to equation (14) in the three groups of participants.

Table 4. Correlation matrix of $p(v_s)$, $p(v_w)$, $r(v_s)$, and $r(v_w)$ for the three groups of participants at the .05 significance level

	Alc				Control				Sch			
	$p(v_s)$	$r(v_s)$	$p(v_w)$	$r(v_w)$	$p(v_s)$	$r(v_s)$	$p(v_w)$	$r(v_w)$	$p(v_s)$	$r(v_s)$	$p(v_w)$	$r(v_w)$
$p(v_s)$	1.00	.48	.64		1.00	.27	.63		1.00	.51	.85	
$r(v_s)$		1.00	.30	.21		1.00	.15	.22		1.00	.60	.47
$p(v_w)$			1.00				1.00				1.00	
$r(v_w)$				1.00				1.00				1.00

5.3. Artefact score

The assessment was done by means of one-way ANOVA with repeated measures. Total artefact scores did not reveal significant differences between groups: $F(1,12) = 1.92\ p = .69$; artefact level $F(1,24) = 1.28, p = .27$; interaction $F(2,24) = 1.59, p = .22$.

6. Discussion

Bayesian formalism was deemed to be an appropriate tool to describe decision making about ambiguous stimuli, because population coding is embedded in the biological structure of the brain, and its realizations by means of Bayesian formalism are effective in modelling ambiguous stimulus processing.

After applying formula (13), the results of the experiment spread out in the shape of a Gaussian distribution grouped around 0 in the alcohol-dependent and control groups, in contrast to the schizophrenia group, in which the majority of values grouped around 0.1. Statistical validation of formula (13) provided evidence that a Bayesian approach might be applied to the description of decisions made by control and alcohol-dependent participants about prosodic signals. The same statistical procedures applied to formula (13) revealed that the schizophrenia group differed significantly from the other two groups in decoding emotional prosody. This finding means that the majority of assessments made by control and alcohol-dependent, but not schizophrenic participants followed formalism defined by the formula (13) while making decisions. This result comes as no surprise, if we assume that neuronal computations underlying participants' performance and thus rationality testing are made in the working memory postulated to play a key role in schizophrenia pathology (Barch *et al.*, 2002; Goldman-Rakic, 1994).

The results obtained are also consistent with other experiments investigating affective prosody (Bozikas *et al.*, 2006; Leitman *et al.*, 2005), especially those postulating the relationship of impaired prosody processing with positive symptoms (Matsumoto *et al.*, 2006). Therefore, the validity of the equation (9), and its equivalent form (13) gains indirect empirical support from other studies.

However, taking into account the distributions of difference values in the groups of participants, it might be said that in fact

$$p(v_s) \times \sum_{k=1}^{n} p(v_{wn}) - p(v_w) \times \sum_{k=1}^{n} p(v_{sn}) \to 0, \tag{16}$$

because not all values in the experiment were equal to 0. There are two possible explanations of this fact. The first is that it is because of simplifying assumptions regarding *priors*, and possible psychological transfer of meaning during consecutive assessments. It should be stressed that the results represent the *population* of participants, who may have different experiences regarding the emotional stimuli, and thus were in different 'state of personal knowledge', despite the fact that they have the same cultural background.

The second explanation, however, is more interesting. According to this interpretation, the Bayesian formalism may be considered as a kind of state towards which decision-making tends, but not necessarily fulfilling the 'exactly zero' criterion at every moment of the processes described by formula (13). According to this interpretation values other than 0 reflect dynamical characteristics of this process, which might have been revealed because of the experimental paradigm implemented. In other words, zero is the value postulated by the model, but this is the value towards which mental processes described by formula (13) 'tend'. In fact 7% of all values in the control group, 7.5% of all values in the alcohol group, and 8% in the schizophrenia group were exactly 0. This means that mental processes described by the model may never reach zero, but 'they are trying', as evidenced by the population of values 'close to 0'. Participants from the schizophrenia group differ from the other two groups in that they 'get to 0' more quickly, which is further evidenced by the relationship between $p(\cdot)$ and $r(\cdot)$ discussed later, but the majority of their statements are centred round 0.1, which means their statements are directed 'the wrong way', as evidenced by the population of 0.1 values. This observation leads to the conclusion that the processes described by formula (13) that 'are not 0', but 'tend to 0', may be responsible for cognitive flexibility, and when impaired result in psychotic disadaptation.

This interpretation differs from other approaches utilizing Bayesian formalism for the description of decision making, which take this process as stable, even while making errors (Burns, 2000). It should be noted that dynamic interpretations of the kind proposed here may be easily reconciled with evolutionary understanding of scientific reasoning (Jaynes, 2003).

Taking into consideration the fact that a *statistically significant* deviation from zero took place only in the schizophrenic group, it may be concluded that the psychotic state – or at least its acute form – is a state in which 'personal knowledge' is more or less severely damaged. Although the BPRS items comprising the positive symptom dimension scored the highest among the rest of the BPRS items, it raises the question whether violation of the rationality described as above would lead to the specific forms of psychotic experience, or whether it is manifestation of a psychosis 'in general'.

However, one can easily imagine experiments in which prosodic stimuli would be substituted, for example, with visual ones, and relationships established between them on the grounds of appropriate formulas later on. An experiment can be imagined based on a similar paradigm, in which words would be mapped on words, or numerical operations on numerical operations. Therefore, it could be said that formula (16) may be generalized to other aspects of information processing, thus linking modalities by corresponding formulas, or making descriptions of meta-level of cognitive activity in terms of computational procedures.

If

$$p(v_{s1}) \times \sum_{k=1}^{n} p(v_{wn}) - p(v_{wn}) \times \sum_{k=1}^{n} p(v_{s1,n}) \rightarrow 0, \tag{17}$$

$$p(v_{s2}) \times \sum_{k=1}^{n} p(v_{wn}) - p(v_{wn}) \times \sum_{k=1}^{n} p(v_{s2,n}) \rightarrow 0, \tag{18}$$

where v_{s1}, v_{s2} denote different modalities related to stimuli, and v_{wn} refers to a word variable in the sense given above, then

$$p(v_{s2}) \times \sum_{k=1}^{n} p(v_{s1}) - p(v_{s1}) \times \sum_{k=1}^{n} p(v_{s2,n}) \rightarrow 0, \tag{19}$$

or in general

$$p(v_{si}) \times \sum_{k=1}^{n} p(v_{sj,n}) - p(v_{sj}) \times \sum_{k=1}^{n} p(v_{si,n}) \rightarrow 0, \quad (i,j = 1, 2, 3, \ldots). \tag{20}$$

The right-hand side of equations (17)–(20) tends to 0. This implies that not every process would reach stability, i.e. zero, at the same time, thus not every decision would be based on the rationality principle – if we assume that the Bayesian formalism represents rationality. Comparing processes that share the same variables on the left-hand sides of these equations, it can be seen that a fatal error preventing processes represented by these equations from obtaining stability at the same time may lead to 'a disturbance in internal representation of the contextual information' postulated to be a core deficit in the schizophrenia pathology (Cohen & Servan-Schreiber, 1992; Hemsley, 1994).

There is evidence that processing verbal and non-verbal stimuli may be mediated by the right dorsolateral prefrontal cortex, responsible for choosing the appropriate cognitive strategy (Barch *et al.*, 2002). In this way, ascribing numbers to the prosodic stimuli with respect to the given words may be understood as a result of this integrating activity.

As might be presumed, the distributions of $p(\cdot)$ and $r(\cdot)$ values differed significantly. The opposite nature of the processes defined by $p(\cdot)$ and $r(\cdot)$ is rather obvious. The process $p(\cdot)$ 'tends to assign one maximal value', whereas $r(\cdot)$ represents complexity, which may be important for adaptive strategy. From this point of view, it is interesting that there is no significant correlation between processes $p(v_s)$ and $r(v_s)$ in the control, but not in the other two groups with respect to the s dimension despite of the fact that $p(v)$ and $r(v)$ had different distributions in every group, as ascertained by means of chi-square test. In other words, the higher the 'peak' measured by the $p(v)$ value, the more circumscribed is the dispersion of assessments around this 'peak' manifested by lower values of $r(v)$. This result indicates that in the schizophrenia and alcohol group, there was a straightforward relationship between certainty of judgements and dispersion of values used to reflect the relationship between words and prosodic stimuli. On the other hand, there was no linear relationship between these two parameters observed in the control group. This relationship may reflect rigidity of judgements characteristic of the abovementioned disorders, and by contrast flexibility of the cognitive adaptive strategy in controls, therefore enabling an insight into delusion formation as an extreme example of decision making. This conclusion is further supported by the observation that only in the schizophrenic participants were there statistically significant correlations between $p(v_s) - r(v_s)$ and $p(v_w) - r(v_w)$. It should be noted that if we imagine a network that could simultaneously operate an algorithm based on formula (20) and formula (14), it would not require the back-propagation of the error while learning (see Cohen & Servan-Schreiber, 1992, for comparison), that is, it would be of the unsupervised learning type. On the other hand, such a network might require feedback from other network(s). Assuming that a parallel like this is not so far-fetched, such a feature of the network performing operations of decision making could explain the fact that schizophrenic participants become more symptomatic when processing ambiguous stimuli (Safrati, 2000), and that ambiguous social stimuli may elicit delusional content (Phillips *et al.*, 2000).

Every participant from the schizophrenic group was under a pharmacological regime. There are no data available to suggest that the improvement of the mental status is parallel to the dose of a drug or that the duration of the illness leads linearly to deterioration. The global artefact score was intended to comprise drug influence, effects of fatigue, or poor motivation. Since this score was similar in all groups it was not taken into consideration, when interpreting the obtained results. Thus, where statistical significance was obtained, the differences between groups were thought to be reliable.

The '1' value in the confidence measure was introduced to avoid division by 0. Therefore, the estimates of $p(\cdot)$ values were constrained to lie between 0 and .9. This means that according to this measure, classification of objects is disjunctive only with respect to the negation, i.e 'is not' may be categorically classified in opposition to 'is', which may be classified with only .9 certainty. The appropriateness of this approach was later empirically verified with respect to the aim of the study.

It was mentioned previously that results of participants from schizophrenia group deviated from 0 to 0.1 difference according to equation (13). It should be noted that the sign of the deviation is not important. The deviation from 0 implies that there is discrepancy between what is designated by prosodic signals, and what is meant by words used to describe them.

One more thing merits attention. It was demonstrated that processing of verbal stimuli is mediated by the left hemisphere, and emotional stimuli by the right hemisphere (Leitman *et al.*, 2005). These data strongly support the thesis that the experimental paradigm implemented involved integrating activity typical of working memory. However, this is not an iron-clad proof that working memory operates in accordance with the Bayesian formalism, but a strong premise that it may be the case. It should be noted that this kind of indirect reasoning is not uncommon in inferring about cognitive processes (see Gigerenzer & Hoffrage, 1995, for example). It should be stressed that the experimental paradigm presented substantially differed from other experiments in that it did not involve reaction times, or hit rates, but directly referred to the computation procedure. Despite the time given to complete the task, participants were free to change their decisions during the experiment, so that time was used as a motivational factor, not constraint.

The demonstration that the proposed approach is consistent with available knowledge about information processing in schizophrenia, and attentional deficits in particular, will be the aim of the next study.

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References

Andorfer, J. C. (1984). Affective pattern recognition and schizophrenia. *Journal of Clinical Psychology*, *40*(2), 403–409. doi:10.1002/1097-4679(198403)40:2<403::AID-JCLP2270400203>3.0.CO;2-6

Baeg, E. H., Kim, Y. B., Huh, K., Mook Jung, I., Kim, H. T., & Jung, M. W. (2003). Dynamics of population code for working memory in the prefrontal cortex. *Neuron*, *40*(1), 177–188. doi:10.1016/S0896-6273(03)00597-X

Barch, D. M., Csernansky, J. G., Conturo, T., & Snyder, A. Z. (2002). Working and long-term memory deficits in schizophrenia: Is there a common prefrontal mechanism? *Journal of Abnormal Psychology*, *111*, 478–494. doi:10.1037/0021-843X.111.3.478

Bozikas, V. P., Kosmidis, M. H., Anezoulaki, D., Giannakou, M., Andreou, C., & Karavatos, A. (2006). Impaired perception of affective prosody in schizophrenia. *Journal of Neuropsychiatry and Clinical Neuroscience*, *18*(1), 81–85.

Burns, K. (2000). *Mental models and normal errors*. Fifth Conference on Naturalistic Decision Making, Tammesvik, Sweden, 26–28 May.

Carter, C. S., Peristein, W., Ganguli, R., Brar, J., Mintun, M., & Cohen, J. (1988). Functional hypofrontality and working memory dysfunction in schizophrenia. *American Journal of Psychiatry*, *55*, 1285–1287.

Chen, K., & Hasegawa-Johnson, M. (2004). How prosody improves word cognition. In B. Bel and I. Marlien (Eds.), *Speech Prosody 2004* (pp. 583–586). ISCA Archive. Retrieved from http://www.isca-speech.org/archive/sp2004

Ciompi, L. (1994). Affect logic: An interactive model of the psyche and its relations to schizophrenia. *British Journal of Psychiatry*, *23*, 51–55.

Cohen, J. D., & Servan-Schreiber, D. (1992). Context, cortex and dopamine: A connectionist approach to behavior and biology in schizophrenia. *Psychological Review*, *99*(1), 45–77. doi:10.1037/0033-295X.99.1.45

Constantinidis, C., & Goldman-Rakic, P. (2002). Correlated discharges among putative pyramidal neurons and interneurons in the primate prefrontal cortex. *Journal of Neurophysiology*, *88*, 3487–3497. doi:10.1152/jn.00188.2002

Fein, G., Bachman, L., & Fisher, S. (1990). Cognitive impairments in abstinent alcoholics. *Western Journal of Medicine*, *152*, 531–537.

Gigerenzer, G., & Hoffrage, U. (1995). How to improve Bayesian reasoning without instruction: Frequency formats. *Psychological Review*, *102*(4), 684–704. doi:10.1037/0033-295X.102.4.684

Goldman-Rakic, P. S. (1994). Working memory dysfunction in schizophrenia. *Journal of Neuropsychiatry and Clinical Neuroscience*, *6*, 348–357.

Hemsley, D. R. (1994). A cognitive model for schizophrenia and its possible neural basis. *Acta Psychiatrica Scandinavica*, *90*(Suppl. 384), 80–86. doi:10.1111/j.1600-0447.1994.tb05895.x

Jaynes, E. T. (2003). The quantitative rules. In G. Larry Bretthorst (Ed.), *Probability theory: The logic of science* (pp. 24–49). Cambridge: Cambridge University Press.

Leitman, D. I., Foxe, J. J., Butler, P. D., Saperstein, A., Revheim, N., & Javitt, D. C. (2005). Sensory contributions to impaired prosodic processing in schizophrenia. *Biological Psychiatry*, *58*(1), 56–61. doi:10.1016/j.biopsych.2005.02.034

Matsumoto, K., Samson, G. T., O'Daly, O. D., Tracy, D. K., Patel, A. D., & Shergill, S. S. (2006). Prosodic discrimination in patients with schizophrenia. *British Journal of Psychiatry*, *189*, 180–181. doi:10.1192/bjp.bp.105.009332

McQueen, J. M., Norris, D., & Cutler, A. (1994). Competition in spoken word recognition: Spotting words in other words. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *20*, 621–638. doi:10.1037/0278-7393.20.3.621

Murphy, D., & Cutting, J. (1990). Prosodic comprehension and expression in schizophrenia. *Journal of Neurology, Neurosurgery and Psychiatry*, *53*(9), 727–730. doi:10.1136/jnnp.53.9.727

Phillips, M. L., Senior, C., & David, A. S. (2000). Perception of threat in schizophrenics with persecutory delusions: An investigation using visual scan paths. *Psychological Medicine*, *30*, 157–167. doi:10.1017/S0033291799001397

Pitel, A. L., Witkowski, T., Vabret, F., Guillery-Girard, B., Desgranges, B., Eustache, F., & Beaunieux, H. (2007). Effect of episodic and working memory impairments on semantic and cognitive procedural learning at alcohol treatment entry. *Alcoholism: Clinical and Experimental Research*, *31*(2), 238–248. doi:10.1111/j.1530-0277.2006.00301.x

Pouget, A., Dayan, P., & Zemel, R. (2003). Inference and computation with population codes. *Annual Review of Neuroscience*, *26*, 381–410. doi:10.1146/annurev.neuro.26.041002.131112

Ruggeri, M., Koeter, M., Schene, A., Bonetto, C., Vázquez-Barquero, J. L., Becker, T., … Thornicroft, G. (2005). EPSILON Study Group. Factor solution of the BPRS-expanded version in schizophrenic outpatients living in five European countries. *Schizophrenia Research*, *75*(1), 107–117. doi:10.1016/j.schres.2004.05.017

Safrati, Y. (2000). Deficit of the theory-of-mind in schizophrenia: Clinical concept and review of experimental arguments. *Canadian Journal of Psychiatry*, *45*, 363–368.

Soyka, M., Dresel, S., Horak, M., Ruther, T., & Tatsch, K. (2000). PET and SPECT findings in alcohol hallucinosis: Case report and super-brief review of the pathophysiology of this syndrome. *World Journal of Biological Psychiatry*, *1*(4), 215–218. doi:10.3109/15622970009150594

Spitzer, M. (1993). The psychopathology, neuropsychology, and neurobiology of associative and working memory in schizophrenia. *European Archives of Psychiatry and Clinical Neuroscience*, *243*, 57–70. doi:10.1007/BF02191566

Wingfield, A., Goddglass, H., & Lindfield, K. C. (1997). Word recognition from acoustic onsets and acoustic offsets: Effects of cohort size and syllabic stress. *Applied Psycholinguistics*, *18*, 85–100. doi:10.1017/S0142716400009887

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