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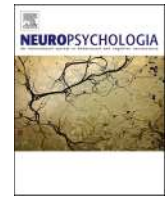

Emotional salience enhances intelligibility in adverse acoustic conditions

María A. Olano [a], Bautista Elizalde Acevedo [a,b,c], Nahuel Chambeaud [c,d], Andrés Acuña [e], Mariano Marcó [c], Silvia Kochen [c], Lucía Alba-Ferrara [a,c,*]

[a] *Departamento de Psicología, Facultad de Ciencias Biomédicas, Universidad Austral, Pilar, Buenos Aires, Argentina*
[b] *Instituto de Investigaciones en Medicina Traslacional (IIMT), CONICET-Universidad Austral, Derqui-Pilar, Buenos Aires, Argentina*
[c] *Unidad Ejecutora para el Estudio de las Neurociencias y Sistemas Complejos (ENyS), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina*
[d] *Facultad de Psicología, Universidad de Buenos Aires, Argentina*
[e] *Instituto de Biología Celular y Neurociencia de Robertis (IBCN), Facultad de Medicina, Universidad de Buenos Aires, Argentina*

A R T I C L E I N F O

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Emotional salience
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Auditory verbal hallucination
Schizotypy

A B S T R A C T

Introduction: Emotion facilitates word recognition under adverse acoustic conditions. We use an auditory emotional paradigm to evaluate the ability to distinguish words from irrelevant random stimuli, elucidating its neural correlates. Secondarily, we evaluate the impact of schizotypy traits on this capacity.
Methods: 25 participants, undertook an fMRI task, indicating whether they recognized words, through a response box. 20 audio files of emotionally negative words and 20 neutral words were presented. Word intelligibility was manipulated merging the audio files with white noise at varying signal-to-noise ratios (SNR), resulting in 3 levels (high, medium, and low). We measured schizotypy with the O-LIFE scale.
Results: A 2x3 factorial ANOVA was performed with emotion (neutral or negative) and intelligibility (high, medium, and low) as factors. There was an interaction between emotion and intelligibility [$F(2,44) = 23.89$, $p<0.001$]. Post hoc *t*-test demonstrated that, in medium and low intelligibility, negative words were more recognized than neutral ones. Negative words minus neutral, activated the right anterior cingulate cortex (rACC), right dorsolateral prefrontal cortex (rDLPFC), and right orbitofrontal cortex (rOFC). Low compared to high intelligibility, activated the left medial temporal gyrus (lMTG), left supramarginal gyrus (lSMG), and left angular gyrus (lAG). Medium compared with high intelligibility, activated the left temporal pole (lTP) and the lMTG. There were correlations between schizotypy and rACC, lMTG, and rOFC activations.
Discussion: Negative emotional salience improves intelligibility, possibly by recruiting selective attention. Less intelligible stimuli activated temporo-parietal regions related to speech processing in adverse acoustic conditions, while emotionally negative stimuli activated areas associated with emotional processing (rACC and rOFC) and selective attention (rDLPFC). High schizotypy correlated with greater responses in rACC, lMTG, and rOFC, during low intelligibility. Irrelevant emotionally salient stimuli would capture automatic attention activating rACC and rOFC, enhancing speech comprehension through additional recruitment of lMTG, which could derive in false word recognition.

1. Introduction

Speech perception is mainly integrated by the decomposition of the acoustic signal and semantic context (Obleser et al., 2007). In adverse acoustic conditions, generally caused by noisy environments or signal distortions, people use semantic context to successfully understand speech (Obleser et al., 2007). Different methods allow to manipulate the difficulty of speech recognition to study, among other properties, the interaction between decomposition of the acoustic signal and semantic context (Alain et al., 2018). Some researches (Obleser et al., 2007; Obleser and Kotz, 2010), studied this interaction applying different levels of acoustic signal degradation by using noise vocoding to manipulate intelligibility. Intelligibility refers to how comprehensible a speech signal is, which besides the quality of the acoustic signal, is influenced by several other language properties, such as the recognition of the word forms and the syntaxes (Scott et al., 2000). The authors

* Corresponding author. ENyS-CONICET, Av. Calchaquí 5402, Florencio Varela, Buenos Aires, Argentina.
E-mail address: lalba@austral.edu.ar (L. Alba-Ferrara).

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proposed that in acoustically adverse conditions, the intelligibility of the words would change depending on its semantic predictability (Obleser et al., 2007). Results demonstrated that this happened specially when the degradation level of the acoustic signal was intermediate and the semantic predictability was high (Obleser et al., 2007). This finding was associated to an increased functional integration among the left angular gyrus, the left medial prefrontal cortex, the left lateral prefrontal cortex, and the posterior cingulate cortex (Obleser et al., 2007). Moreover, the amount of spectral detail of the acoustic signal correlated with activations in left and right superior temporal sulci and the left inferior frontal gyrus, independently of predictability (Obleser et al., 2007). A subsequent study (Obleser and Kotz, 2010) on intelligibility and semantic context, sought to constrain the sentence context to a stable minimum by using a task based on “cloze probability” (see Taylor, 1953), which is a valid measure of lexical expectancy of a word in a given context. It consisted of incomplete sentences with different “cloze probability” or semantic predictability, combined with different levels of acoustic signal degradation (Obleser and Kotz, 2010). This study found greater activation in the superior temporal cortex (superior temporal gyrus and superior temporal sulcus) related to greater intelligibility (Obleser and Kotz, 2010). Another important finding showed a role of the left inferior frontal gyrus on lower semantic predictability sentences processing (Obleser and Kotz, 2010). This interaction is interpreted as an additional effort that only occurred as the sentences became more intelligible due to the lower degradation of the signal (Obleser and Kotz, 2010). Therefore, the left inferior frontal gyrus could participate in the integration of the sentence if the signal is sufficiently intelligible (Obleser and Kotz, 2010). Moreover, both studies found a significant activation in the left inferior parietal cortex (angular gyrus and supramarginal gyrus) when the acoustic signal was compromised and the semantic predictability was higher (Obleser et al., 2007; Obleser and Kotz, 2010). Hence, the left inferior parietal cortex could serve as a mediating structure that facilitates speech comprehension when the intelligibility of the signal is compromised (Obleser and Kotz, 2010).

Other way to manipulate the signal to study the interaction between semantic context and intelligibility, can be achieved by using signal-to-noise ratios. This method allows to manipulate speech intelligibility without changing the type of stimulus, by varying the intensity level of speech presented in noise (Zekveld et al., 2006). For instance, Davis et al. (2011) used an fMRI speech in noise task to study whether speech processing in adverse acoustic conditions is strictly bottom-up, or if high-level structures processing semantics interact with perceptual areas to guide low-level perception (Davis et al., 2011). The study applied semantically coherent or semantically anomalous sentences that were degraded by adding signal-correlated noise (SCN) across six different signal-to-noise ratios (SNRs). The results showed that both type of sentences generated similar activity in the left anterior superior temporal gyrus (STG) and inferior frontal regions at low SNRs (Davis et al., 2011). On the contrary, when the two types of sentences were intelligible (high SNRs), activity for coherent sentences decreased in these regions, whilst it increased for anomalous sentences (Davis et al., 2011). The authors argued that coherent sentences would show an effortful processing only when the intelligibility level is intermediate, but not when it is high (Davis et al., 2011). For anomalous sentences, when speech is highly intelligible, the activations would continue to increase in inferior frontal and superior temporal regions in order to obtain a coherent meaning (Davis et al., 2011). Moreover, coherent and anomalous sentences at intermediate SNRs exhibited activations in the posterior STG, the medial temporal gyrus (MTG), and in the right anterior STG (Davis et al., 2011). Since there was not distinction between the two types of sentences, authors claimed for a role of posterior STG and MTG in lower level perceptual processes, and a minor role of this nodes in semantic integration (Davis et al., 2011). Additionally, when evaluating responses time course, temporal lobe preceded the inferior frontal response, suggesting that functional organization of speech processing is more consistent with a hierarchically organized bottom–up stream of information, rather than top-down (Davis et al., 2011).

A research by Zekveld et al. (2006), took a similar approach, by masking spoken sentences with speech spectrum noise at different SNRs, although without manipulating predictability. They also found activations in the left inferior frontal gyrus when listening to unintelligible speech at low SNRs (Zekveld et al., 2006). Moreover, they found frontal responses lower peak amplitudes compared to temporal responses, specially at higher SNRs, when understanding speech in noise. They interpreted this as diminishing need for top-down processing when speech is more intelligible (Zekveld et al., 2006).

In unfavourable acoustic conditions, besides semantic context, other factors such as the speaker familiarity with his local jargon, pragmatic knowledge, prosody, and emotional meaning could facilitate speech comprehension (Obleser and Kotz, 2010). Several behavioural observations, especially in the visual field, showed that individuals tend to detect more easily emotional than neutral stimuli, suggesting that the emotional property of stimuli can modulate sensory processing and attention (Vuilleumier, 2005). In fact, Dupuis and Pichora-Fuller (2008) found that more emotionally arousing visual words can be reliably identified at lower SNR than less emotionally arousing words.

Regarding auditory verbal stimuli, people use two different channels to manifest emotions by talking: the verbal channel and the vocal channel (Berckmoes and Vingerhoets, 2004). The first channel refers to the semantic content, while the second one refers to the prosody (Berckmoes and Vingerhoets, 2004). Semantic content refers to the way in which words (abstract symbols) derive in meaning, which could be emotional (Castelluccio et al., 2015). Prosody consists of tone, duration, and intensity of speech, through which different emotional states can be expressed (Castelluccio et al., 2015). Dupuis and Pichora-Fuller (2014) explored the impact of prosody on word recognition in adverse acoustic conditions, in younger and older adults. To achieve that goal, they used sentences with different emotional prosody (disgust, anger, sadness, fear, happiness, pleasant surprise, and neutral) in background noise (Dupuis and Pichora-Fuller, 2014). Participants were instructed to listen and repeat the last word of the sentence, while the experimenter wrote if the participant responded correctly or not (Dupuis and Pichora-Fuller, 2014). Results showed that emotional prosody influenced word recognition accuracy, especially in sentences that expressed fear, which was the most recognized emotional valence in background noise (Dupuis and Pichora-Fuller, 2014).

Regarding the neural underpinnings of prosody, a study (Ethofer et al., 2012) found bilateral superior temporal gyrus activation posterolateral to the primary auditory cortex in response to emotional voices. Other research (Alba-Ferrara et al., 2011) studied the neural correlates of emotional prosody. Results showed that emotional prosody, simple and complex, depends on a temporo-frontal network that encompasses the middle and superior temporal gyri, left temporal pole, right insula, Broca's area and its homologue in the right hemisphere, and the left motor cortex (Alba-Ferrara et al., 2011). For prosody decoding, the right lateral temporal lobe and its right superior temporal gyrus was crucial (Alba-Ferrara et al., 2011).

In the literature, affective semantics received less attention than prosody (Castelluccio et al., 2015). In general, studies found activations in a left-lateralized lexical-semantic network, rather than in regions related to emotional processing (Binder et al., 2009). Even more, the role of affective semantics in disambiguating speech comprehension in adverse acoustic conditions needs further research. From a theoretical point of view, this research expects to shed light to the importance of affective semantics as a factor that could facilitate intelligibility of speech in noise. Furthermore, we are interested not only in exploring the normal aspects of such phenomenon, but also its possible abnormal manifestation.

It has been reported that in adverse acoustic conditions, a stimulus misinterpreted as emotionally salient, could derive in unusual perceptions (speech illusions, auditory verbal hallucinations) in people within the schizophrenia-spectrum (Galdos et al., 2011). Schizotypy is a useful and unifying construct to better understand the underlying vulnerability for schizophrenia-spectrum (Kwapil and Barrantes-Vidal, 2015). It encompasses a range of subclinical and clinical psychosis phenomenology, such as abnormal auditory perceptions (Kwapil and Barrantes-Vidal, 2015). Following this framework, two studies (Catalan et al., 2018; Galdos et al., 2011) created acoustically degraded stimuli by merging neutral words with different amounts of noise. Participants had to respond if they heard a positive voice (positive speech illusion), a negative voice (negative speech illusion), neutral speech, no speech, or uncertain. Galdos et al. (2011) studied patients with schizophrenia or schizophreniform disorder, affective psychosis, and their healthy siblings. Instead, Catalan et al. (2018) studied patients with first episode psychosis (FEP) and borderline personality disorder (BPD). Galdos et al. (2011) found that patients showed more affectively salient speech illusions than controls. Also, in controls speech illusions were associated with positive schizotypy (magical ideation, illusions, psychotic symptoms, and suspiciousness). Moreover, as the familial risk for psychotic disorder increased, there was also an increase in the rate of speech illusions. Catalan et al. (2018) found that FEP patients experienced more affectively salient speech illusions than BPD patients and controls. Also, BPD patients showed more affectively salient speech illusions than controls, but the difference was not significant. To sum up, as psychosis predisposition increases, people tend to detect more emotional words in noise.

People with a tendency to experience unusual perception phenomena such as speech illusions and auditory verbal hallucinations (AVH), would misattribute relevance to random auditory stimuli (especially if they are emotionally negative), which would lead to a failure in selective attention (Alba-Ferrara et al., 2013). Selective attention (commanded by the dorsolateral prefrontal cortex) would be overtaken by irrelevant information, deriving in abnormal auditory perceptions or AVH (Alba-Ferrara et al., 2012).

Since emotional auditory verbal stimuli enhancing word recognition under adverse acoustic conditions has been studied mostly in psychiatric patients, we propose to study such phenomena in non-clinical participants. First, because AVH are phenomena that can occur in the general (non-clinical) population (Johns et al., 2014; Sommer et al., 2010), being possible to classify non-clinical participants according to their degree of schizotypy and hallucination proneness. Additionally, it allows to sort out the confounding effects of medication.

Our principal aim is to study the influence of emotional salience (given by semantic content) in speech intelligibility under adverse acoustic conditions. Also, we expect to study the role of language processing areas as well as top-down and bottom-up attentional neural networks implicated in the processing of emotionally salient auditory verbal stimuli. Additionally, we expect to find differences in such behavioural and neural processes, related to degree of schizotypy and hallucination proneness.

The present study applies a novel paradigm to evaluate how a subject perceives a signal in adverse acoustic conditions that derives from signal detection theory (SDT) (Dolgov and McBeath, 2005; Vercammen et al., 2008). It consists in auditory verbal stimuli (words) that have different emotional salience (some are negative and some neutral) and three different levels of intelligibility, depending on the ratio of white noise-speech. These three levels are: high, medium, and low intelligibility.

At a behavioural level, we expect an interaction between intelligibility and emotional salience. Participants will spontaneously orient their attention to emotionally salient stimuli, with better recognition of emotional words compared to neutral. We presume that this effect will be greater in participants with high schizotypy and hallucination proneness. At a neuronal level, we predict activations in areas associated to speech perception, such as superior and medial temporal gyri, and areas linked to selective attention toward salient stimuli such as the DLPFC.

2. Materials and methods

2.1. Participants and instruments

A group of 25 (9 males) healthy participants were recruited. Most of them were students (12 graduate and 10 undergraduate) and 3 of them were university technicians from the School of Medicine at University of Buenos Aires and Austral University. The study was approved by the ethics committees of Austral University, Fundación FLENI, and Instituto de Oncología Ángel H. Roffo. Every subject gave written informed consent to participate in the research (for more information, see Table 1).

Participants did not report any hearing problems. Also, they underwent a neuropsychological and a psychiatric evaluation to rule out cognitive deficits and the presence of psychiatric disorders (for more information, see Table 1). The following neuropsychological instruments were applied: Digit Span (Wechsler, 2002), Word Accentuation Test or WAT (Schrauf et al., 2006), and Edinburgh Handedness Inventory (Oldfield, 1971). Additionally, the psychiatric instruments administered were: Beck Depression Inventory (BDI) II Argentine adaptation (Beck et al., 2006; Brenlla and Rodriguez, 2006), State-Trait Anxiety Inventory or STAI Spanish version (Spielberger et al., 1971), the Structured Clinical Interview for the Diagnostic and Statistical Manual of Mental Disorders-IV or SCID-I Spanish version (First et al., 1999), and the Oxford-Liverpool Inventory of Feelings and Experiences or O-LIFE, short version in Spanish (Fonseca-Pedrero et al., 2015; Mason et al., 2005). The latter is a self-administered inventory, developed to measure schizotypal personality traits (Fonseca-Pedrero et al., 2015; Mason et al., 2005). The short version in Spanish includes four sub-scales that assess different aspects of schizotypy (Fonseca-Pedrero et al., 2015; Mason et al., 2005). We used the total O-LIFE to classify participants according to their degree of schizotypy, and the 'Unusual Experiences' sub-scale to assess hallucination proneness.

2.2. Design of the experimental task

Stimuli design: forty (40) words were recorded. Twenty (20) of them had a negative emotional meaning (for example, useless. In Spanish: *inútil*), and the remaining twenty (20) a neutral emotional meaning (for example, red. In Spanish: *colorado*) (For more information, see APPENDIX, Table 3). Both lists (negative and neutral) were matched in use frequency and extension. The negative words were extracted from schizophrenia patient's clinical reports and related to the content of their auditory verbal hallucinations, as this study works as an induction for a further study assessing emotional salience and intelligibility on patients with AVH. Moreover, words were recorded by a female voice in a neutral tone.

Also, word intelligibility was manipulated using Goldwave software

Table 1
Demographic data. Neuropsychological and psychiatric results.

	N = 25 (9 males)	Min.	Max.	Mean	S.D.
Age		18	54	30.56	10.25
Years of education		12	22	17.24	3.28
Manual dominance (R.)	24				
O-LIFE total	15	5	21	10.93	4.96
O-LIFE Unusual Exp.	15	0	5	1.07	1.49
Digit Span		5	14	10.48	2.60
WAT (number of errors)		0	10	4.76	2.72
BDI		0	13	3.74	3.95
STAI-S		1	30	12.15	6.84
STAI-T		3	38	18.24	8.78

Min., minimum; Max., maximum; S.D., standard deviation; R., right; O-LIFE, Oxford-Liverpool Inventory of Feelings and Experiences; Unusual Exp., Unusual Experiences; WAT, Word Accentuation Test; BDI, Beck Depression Inventory; STAI-S, State-Trait Anxiety Inventory-State; STAI-T, State-Trait Anxiety Inventory-Trait.

(https://www.goldwave.com), which allowed to alter the speech signal by adding signal-correlated noise. This technique keeps the duration, amplitude, and spectral characteristics of the original utterance creating different levels of signal-to-noise ratios (SNR). The auditory signal was degraded, obtaining three qualities or conditions, depending on its signal-to-noise ratios SNR. Three levels of intelligibility were acquired: 1) high condition (clear speech), 2) medium condition (SNR = -2 dB), 3) low condition (SNR = -5 dB).

Both variables (intelligibility and emotional salience) combined, resulted in six conditions: high-neutral stimuli, high-negative stimuli, medium-neutral stimuli, medium-negative stimuli, low-neutral stimuli, and low-negative stimuli.

2.3. The experimental task before and during the fMRI

Participants were trained off-line before the scanning session. They sat in front of a PC with headphones and were instructed to listen to the stimuli and answer by pressing 1 if they recognized the word, and 2 if they did not recognize the word. After a series of trials on the computer, once the participants learned how to perform the task, they were sent to the scanner.

The participants were scanned using a 3 Tesla Siemens Trio. They were comfortably positioned in dorsal decubitus, with MRI compatible pneumatic headphones. During the acquisition of volumetric T1 images, we communicated with the participants via intercom to check the audio system and to assure they could hear properly. Participants were given a response box and were asked to answer as they were trained. Before the start of the run, participants were reminded of the instructions through the intercom.

In the scanner, one hundred and twenty (120) trials were presented and twenty (20) silent events used for jittering. The trials corresponded to the twenty (20) negative words and the twenty (20) neutral words, in the three levels of degradation (high, medium, and low) in an event-related design manner. Stimuli were pseudo-randomly presented with E-Prime software (Psychology Software Tools, Pittsburgh, Pennsylvania), with an inter-trial interval of 3.85 s. The task consisted in one run of 8 min and 59 s (excluding the instruction time of 16 s).

2.4. MRI images

2.4.1. MRI acquisition

2.4.1.1. Structural images (MPrage). The structural images were acquired using a repetition time (RT) of 2000 ms, in 28 sagittal slices of the whole brain with a slice thickness of 0.98 mm. The acquisition time (TA) was 4 min and 38 s, the echo time (TE) was 2.27 s, and the field of view = 250 x 250.

2.4.1.2. T2 images.* The T2* images were acquired in 1 run of 222 vol, with an RT of 2070 ms, in 28 sagittal slices of the whole brain with a slice thickness of 3 mm, and a flip angle of 77°. The TE was 21 s and the field of view = 1344 x 1344.

2.4.2. MRI analysis

The T2* images were pre-processed and analysed using Statistical Parametric Mapping (SPM12; https://www.fil.ion.ucl.ac.uk/). The first five volumes were discarded to avoid inhomogeneities in the magnetic field. The functional images were realigned, to be later co-registered with the anatomical image, and normalized stereotaxically in the MNI space (https://www.mcgill.ca/neuro/), based on the weighted structural 3D volume in T1. Finally, the images were smoothed using an isotropic 8-mm^3 kernel.

The data analysis was based on the General Linear Model (GLM; Friston et al., 1995), using SPM12. Responses to events of interest were modelled using a canonical hemodynamic response function (Friston et al., 1998). In the first level analysis, images of each subject were analysed to observe activations in each condition. The following contrasts of interest were generated: a) negative – neutral, b) medium – high intelligibility, and c) low – high intelligibility. The contrast a) was selected to determine the brain areas that were activated by emotionally negative stimuli. The contrasts b) and c) were used to observe the brain activity when the intelligibility of the stimuli was compromised, either from an intermediate degradation of the acoustic signal (b) or from a deep degradation (c). The images of the individual contrasts of the first level were subjected to a whole-brain second level model, deriving in a group analysis that allowed to compare conditions. The resulting contrast images were subjected to one sample t-tests subsequently explored at a threshold of $p<0.005$. Correction for multiple comparisons to $p<0.05$ was achieved using a cluster extent threshold procedure first described by (Slotnick et al., 2003). As reported in a previous study (Slotnick and Schacter, 2004), the cluster extent threshold procedure relies on the fact that given spurious activity or noise (voxel-wise type-I error), the probability of observing increasingly large (spatially contiguous) clusters of activity systematically decreases. Therefore, the cluster extent threshold can be enforced to ensure an acceptable level of corrected clusterwise Type I error. For an individual voxel Type I error of $p<0.005$, this procedure identified a cluster extent of 20 contiguous resampled voxels as necessary to correct for multiple voxel comparisons across the whole brain at $p<0.05$.

Further, a secondary analysis was performed to evaluate associations between brain activations and hallucinatory traits. Regions of interest (ROIs) were defined based on previously reported contrasts, by picking the main voxel activation and making 10 mm spheres, using MarsBaR for SPM. The spheres were located within the right anterior cingulate cortex (rACC), the right dorsolateral prefrontal cortex (rDLPFC), the left medial temporal gyrus (lMTG), the right orbitofrontal cortex (rOFC), the left temporal pole (lTP), the left supramarginal gyrus (lSMG), and the left angular gyrus (lAG). Then, data extracted from ROIs were correlated (Pearson coefficient) with O-LIFE schizotypy scale and its 'Unusual Experiences' subscale, to reveal variations at the brain level in the different conditions, related to the greater or lesser degree of schizotypy and tendency to experience unusual perceptions.

3. Results

3.1. Behavioural results

3.1.1. Main analysis

To measure the percentage of word recognition in terms of intelligibility and emotional salience, we applied a repeated-measures ANOVA with emotion (neutral or negative) and intelligibility (high, medium, and low) as factors. Behavioural data from two participants were not recorded due to technical problems with the response box.

A main effect of intelligibility was found, meaning that words from high intelligibility condition were more often recognized [$F(2,44) = 303.86, MSE=0.03, p<0.001$] (M = 97%,SD = 0.006) than those from medium (M = 54%,SD = 0.04), and low intelligibility condition (M = 13%,SD = 0.03). Also, words from medium intelligibility condition were more recognized than those from low intelligibility condition. In addition, a main emotion effect was observed [$F(1,22) = 59.81, MSE=0.02, p<0.001$], through which negative words (M = 63%,SD = 0.027) where more often recognized than the neutral ones (M = 46%,SD = 0.023).

Moreover, a significant interaction between intelligibility and emotional salience was found [$F(2,44) = 23.89, MSE=0.01, p<0.001$]. This interaction was investigated exhaustively through a post hoc analysis, using t-tests. Findings showed that in high intelligibility condition, there was no significant difference in the recognition of words based on their emotional salience. Instead, under medium and low intelligibility conditions, significant differences were observed in the percentage of word recognition in terms of their emotional salience. In medium intelligibility condition ($t(22) = -7.8, p<0.001$), 70% of the negative words were recognized, compared to 38% of the neutral words. In low intelligibility condition ($t(22) = -4.08, p<0.001$), 20% of the negative words/noise were recognized, and only 5% of the neutral ones (see, Graph 1).

3.1.2. Secondary analysis

Additionally, in order to reveal differences in word recognition related to hallucination proneness (according to ‘Unusual Experiences’ O-LIFE subscale), we divided the sample in two groups. An artificial cut off was established, utilizing the mean of ‘Unusual Experiences’ O-LIFE subscale as a reference (M = 1.07). Group 1 (M=0.4) was composed by participants with marks for ‘Unusual Experiences’ subscale below the mean (M<1.07), indicating low tendency to experience unusual perceptions. Group 2 (M=3.7) was formed by participants with results above the mean (M>1.07), reflecting a high tendency to experience unusual perceptions. Then, we applied a factorial repeated measures ANOVA. The intra-subject variables were intelligibility (three levels) and emotional salience (two levels), while the inter-subject variable was Group (Group 1 and Group 2). Results showed a lineal interaction between intelligibility and the tendency to have unusual perceptions [$F(2,22) = 4.19, p<0.05$]. Post hoc t-tests revealed that the significant difference occurred in low intelligibility condition, where a high tendency to experience unusual perceptions (Group 2) was associated to increased intelligibility (greater word recognition) ($t(13) = 3.4, p<0.05$).

3.2. Neuroimaging results

3.2.1. Main analysis

The following contrasts of interest were tested: a) negative – neutral, b) medium – high intelligibility, and c) low – high intelligibility (see, Table 2).

The contrast negative – neutral implied a subtraction between trials with negative stimuli, in the three conditions of intelligibility (high, medium, and low), and the trials with neutral stimuli in the three conditions of intelligibility. This contrast activated the right anterior cingulate cortex (rACC), the right dorsolateral prefrontal cortex (rDLPFC), and the right orbitofrontal cortex (rOFC) (see, Table 2, Fig. 1).

The contrast medium – high intelligibility, implied a subtraction between trials from -2 dB SNR condition and clear speech trials. This subtraction elicited activations in the left temporal pole (lTP) and the left medial temporal gyrus (lMTG) (see, Table 2, Fig. 2).

Finally, the contrast low – high intelligibility, implied a subtraction between trials from -5 dB SNR condition and clear speech trials. Results showed activations in the left medial temporal gyrus (lMTG), the left supramarginal gyrus (lSMG), and the left angular gyrus (lAG) (see, Table 2, Fig. 3).

Table 2
Overview of results obtained in every neuroimaging contrast (p<0.005).

Site		Z	k	MNI Coordinates
Negative > Neutral				
ACC	R	3.40	27	14, 28, 34
DLPFC	R	3.07	220	34, 52, 16
OFC	R	2.49	339	26, 24, 10
Medium > High				
TP	L	3.60	441	−28, 8, −22
MTG	L	3.44	207	−50, −10,-16
Low > High				
MTG	L	4.03	28	−50, −10, −16
SG y AG	L	3.29	177	−62, −32, 46

R, right; L, left; MNI, Montreal Neurological Institute; k, cluster size in number of voxels, ACC, anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; OFC, orbitofrontal cortex; TP, temporal pole; MTG, medial temporal gyrus; SG, supramarginal gyrus; AG, angular gyrus.

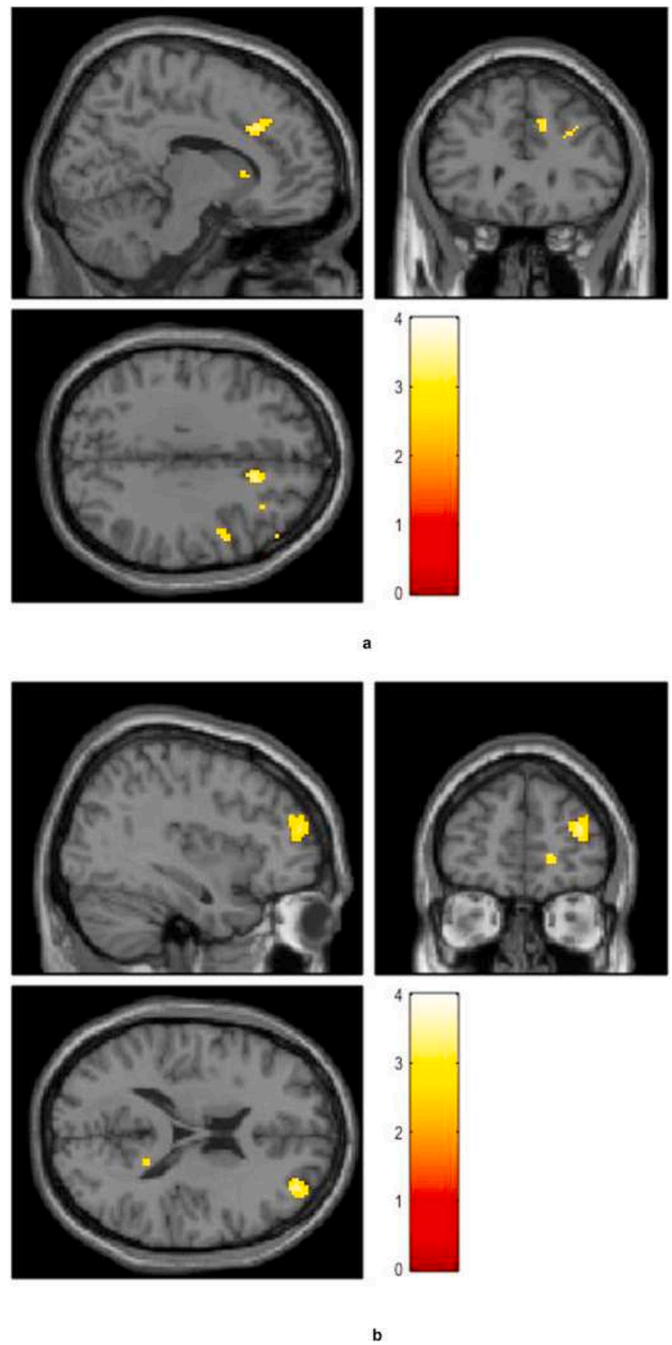


Fig. 1. Overview of results obtained during negative – neutral contrast. Left image shows activations in the right ACC. Right image shows activations in the right DLPFC ($p<0.005$).

3.2.2. Secondary analysis

We applied correlations between O-LIFE scale scores and neuroimaging results. A first correlation (Pearson coefficient) between total O-LIFE score and regions of interest (rACC, rDLPFC, rOFC, lMTG, lTP, lSMG, and lAG), showed a significant association between total O-LIFE score and activations in the rACC ($r = 0.67, p<0.05$), the rOFC ($r = 0.62, p<0.05$), and the lMTG ($r = 0.61, p<0.05$), during low intelligibility condition.

A second correlation included results in ‘Unusual Experiences’ O-LIFE subscale and ROIs. Results showed a significant association between such subscale and activations in rACC ($r = 0.62, p<0.05$) and the lMTG ($r = 0.65, p<0.05$), during low intelligibility condition.

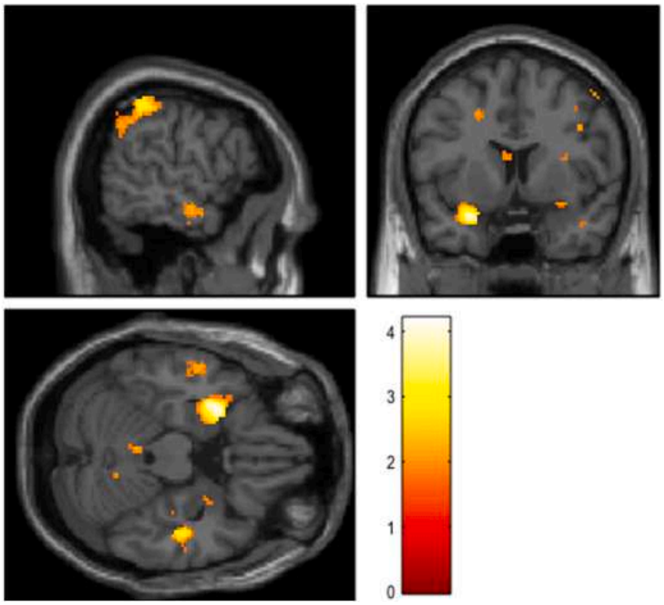


Fig. 2. Overview of results obtained during medium – high intelligibility contrast. Activations in the left TP are observed (p<0.005).

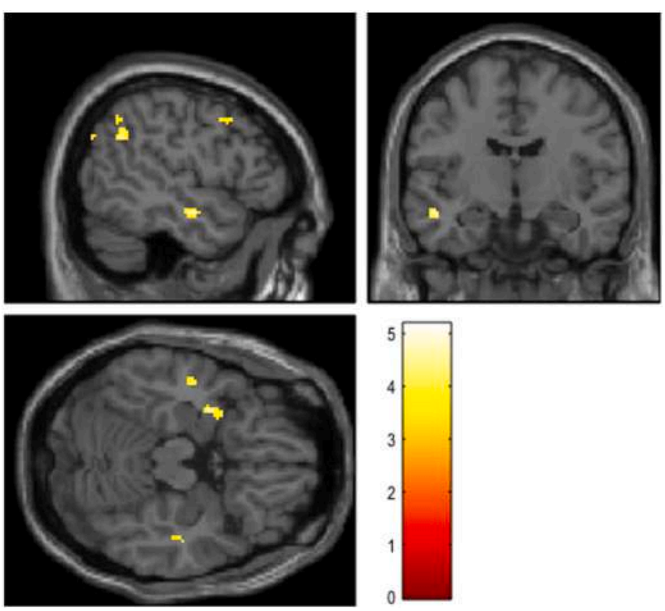


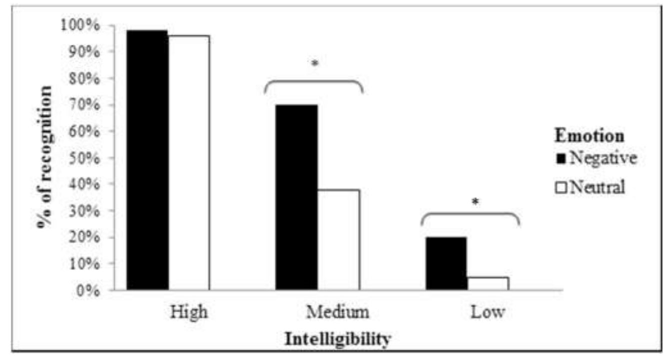
Fig. 3. Overview of results obtained during low – high intelligibility contrast. Activations in the left MTG are observed (p<0.005).

4. Discussion

4.1. Intelligibility and emotional salience

4.1.1. Word recognition and emotional salience

Behavioural results showed an advantage for high intelligibility in word recognition. The stimuli of high intelligibility condition were more recognized than those from medium and low intelligibility condition. Also, medium condition trials were more recognized than low condition trials. These results, in line with the literature, reflect the importance of acoustic signal decomposition as one of the components that supports speech perception (Obleser et al., 2007), meaning that the clearer the speech signal, the greater the intelligibility. Additionally, our results showed that negative emotional stimuli were more recognized than neutral ones, regardless of intelligibility. Such finding is in agreement with the literature, as people tend to direct their attention to emotional stimuli rather than to neutral ones (Vuilleumier, 2005).



Graph 1. Percentage of word recognition in high, medium, and low intelligibility conditions, depending on emotional salience.

Moreover, we found a significant interaction between emotional salience and intelligibility in acoustically degraded speech. Dupuis and Pichora-Fuller (2015) found that emotional words are more recognizable than neutrals. Even more, another study by the same authors on prosody and word recognition in adverse acoustic conditions, revealed that emotional prosody (especially in sentences that expressed fear) enhanced word recognition accuracy in background noise, suggesting that emotion influences intelligibility (Dupuis and Pichora-Fuller, 2014). Hence, in cases of degraded quality of the acoustic signal, emotional cues would be used to increase the understanding of verbal stimuli (Obleser and Kotz, 2010). Emotional stimuli, especially those with negative valence, capture selective attention (top-down) and direct it to them (Alba-Ferrara et al., 2013), increasing their perception or recognition. Instead, when the signal was clear (high intelligibility condition), we did not find a significant difference in the percentage of word recognition in terms of emotional salience. Emotional cues were not required to distinguish words, as they were highly intelligible. Thus, the influence of emotional salience on word intelligibility would be crucial when the signal is compromised.

It is noteworthy that our sample showed a large age range, which may be a limitation. Despite other researches (Dupuis and Pichora-Fuller, 2014, 2015) found that older adults were less accurate than younger adults in identifying some emotional valences on speech, they used a larger age range (comparing young adults against the elderly). Instead, we included participants that were within working age.

4.1.2. Schizotypy and word recognition

Additionally, when the relation between hallucination proneness ('Unusual Experiences' O-LIFE subscale) and the percentage of word recognition was assessed, results showed that in low intelligibility condition, those who manifested a greater tendency to experience unusual perceptions (Group 2) recognized more words than those who presented a lesser tendency (Group 1). Thus, a greater tendency to experience unusual perceptions would be associated to an increase in word intelligibility in acoustic conditions where irrelevant and random stimuli predominate, i.e., white noise. This finding agrees with a previous study (Galdos et al., 2011) that used a paradigm with white noise to study the tendency to detect emotionally salient speech illusions. In the mentioned research, one of the experimental groups included non-clinical participants, classified according to their degree of schizotypy and the prevalence of positive symptom traits (speech illusions, AVH), or negative symptom traits (difficulties to experience pleasure from social or physical situations, avoidance of intimacy), which were evaluated with the Structured Interview for Schizotypy-Revised (Galdos et al., 2011). Researchers found that the tendency to detect emotionally salient speech illusions in white noise was associated to high levels of positive, but not negative schizotypy in that group of non-clinical controls (Galdos et al., 2011).

Our results regarding the impact of schizotypy on the task are promising but should be taken cautiously. One of the limitations consists in the small sample size undertaking that test. Also, none of our participants scored at the high-level end of schizotypy, but some of them scored at the low end of this scale. Despite these limitations, the results are in line with our initial hypothesis, and we anticipate further research will replicate our findings.

4.2. Effects of emotion at the neural level

Neuroimaging results showed activations in the right anterior cingulate cortex (rACC), the right dorsolateral prefrontal cortex (rDLPFC), and the right orbitofrontal cortex (rOFC), when contrasting trials with negative stimuli against neutral trials in the three intelligibility levels. The bilateral ACC is associated with a series of processes that include attention, cognitive control, and affect (Devinsky et al., 1995). Generally, different functions are assigned to its two main subdivisions: the dorsal region and the rostral-ventral region. The dorsal region is associated with cognitive processing, while the rostral-ventral region is linked to emotional processing (Bush et al., 2000). The cognitive subdivision is part of an attentional network that maintains reciprocal interconnections with regions associated to high-order cognitive functions (Comte et al., 2016), such as lateral prefrontal cortex (Devinsky et al., 1995). Among other functions, some argue that the ACC modulates attention by influencing in the selection or answer to sensory stimuli (Bush et al., 2000). The affective subdivision is connected to the amygdala, the periacueductal grey matter, the accumbens nucleus, the hypothalamus, the anterior insula, the hippocampus, and the orbitofrontal cortex (Devinsky et al., 1995), areas related to the limbic system and to emotional processing. This affective subdivision is primarily involved in the evaluation of the emotional and motivational salience of sensory information, as well as in the regulation of emotional responses (Bush et al., 2000).

The results of negative – neutral contrast suggests that the increased activity of the rACC during exposure to emotionally negative stimuli would be in line with the evaluation of emotional salience and modulation of attention. More specifically, it is considered a putative region for the evaluation of stimuli emotional salience and the automatic response towards them, as well as a region that modulates selective attention, and influences the selection of stimuli to which it is directed. If emotional stimuli capture attention, the rACC would have a key role in recruiting and directing selective attention towards stimuli previously valued as emotionally salient.

Activation of rOFC during the same contrast could be due to its function in processing the emotional value of stimuli, in order to generate appropriate choices and courses of action (O'Doherty et al., 2001). An investigation claims that limbic structures such as the OFC and the amygdala are activated by both novel, and emotionally negative or positive stimuli (Hartikainen et al., 2012). The affective valence and novelty would contribute to the salience and importance given to the stimulus, modulating the distribution of attentional resources (Hartikainen et al., 2012). Emotions in speech are transmitted through two different channels: semantic content and prosody (Berckmoes and Vingerhoets, 2004). Some functional neuroimaging studies that used verbal stimuli with anger prosody, found activations of bilateral OFC, suggesting a role of this structure in the processing of affective characteristics of auditory stimuli (Ethofer et al., 2012). The processing of semantically emotional words is performed by a lexical-semantic processing network, lateralized in the left hemisphere, rather than by regions associated with emotional processing (Binder et al., 2009). On the contrary, our research found activations in rOFC when processing words with emotionally negative meaning. If we consider the aforementioned role of this area in the modulation of attentional resources, the rOFC, same as the rACC, would be activated to evaluate the emotional salience of the stimulus (in this case, given by the semantic content), influencing the allocation of attention towards it.

The third structure activated during this contrast (rDLPFC) integrates a high order network that includes frontal, parietal, and insular cerebral regions (Duncan, 2013), and participates in complex cognitive and attentional operations (MacDonald et al., 2000), including top-down modulation of processes relevant to the task (Duncan, 2013). The DLPFC is connected with the amygdala (in charge of automatic emotional processing or bottom-up processing) through the ACC, whose dorsal (cognitive) region is linked to DLPFC, while its rostral-ventral (affective) subdivision is connected with the amygdala (Comte et al., 2016). It has been demonstrated that this cognitive circuit compounded by the interconnection between the DLPFC and the ACC, only activates during emotional regulation strategies, mediating its regulatory action through ventral circuit ACC-amygdala, involved in the automatic control of emotion (Delgado et al., 2008). Some authors used a visual paradigm with emotional salient stimuli (positive and negative), to explore the role of these areas in the processing and response to emotional stimuli (Comte et al., 2016). Regarding bilateral DLPFC, the authors found activations when stimuli were emotionally negative (Comte et al., 2016). Despite the fact that the cited article uses visual stimuli, it is in partial agreement with our results, since rDLPFC also activated with negative stimuli.

4.3. Effects of degradation of the acoustic signal at the neural level

The intermediate intelligibility condition (medium – high contrast), revealed activations in the lMTG and the lTP. The lTP is an area involved in the processing of auditory stimuli with emotional negative or positive valences (Olson et al., 2007). Moreover, studies that used degraded auditory stimuli along with manipulation of the semantic context, found activation in the lTP in an intermediate level of degradation, when the semantic predictability was high (Obleser et al., 2007), suggesting a role of such area in the semantic processing when the signal is degraded. The current investigation partly uses auditory stimuli with negative emotional content. Therefore, it would combine two aspects (emotion and semantics) that the lTP process. Thus, it could be argued that when the intelligibility of the signal is compromised, the lTP is recruited because it would help in the processing of stimuli with negative emotional content.

The lMTG is an area related to the processing of verbal stimuli (Vouloumanos et al., 2001). Some researchers observed that temporal regions, such as the lMTG, would activate when increasing the intelligibility of the acoustic signal in acoustically adverse conditions (Abrams et al., 2013; Alderson-Day et al., 2017; Davis et al., 2011; Obleser et al., 2007). In contrast with previous findings, we found that this zone activated not only in the condition of intermediate intelligibility but also in the condition of greater degradation (low – high intelligibility contrast), implying that it processes verbal stimuli in conditions of reduced intelligibility. Hence, lMTG would be recruited to process verbal stimuli both when increasing and reducing intelligibility of the acoustic signal, which would implicate a general language function of such area, sensitive to changes in the acoustic signal.

The third contrast (low – high intelligibility), revealed recruitment of lSMG and the lAG on top of the lMTG activation. It has been suggested that the inferior parietal cortex, formed by the lSMG and the lAG, is a mediating structure that facilitates speech comprehension when the intelligibility of the signal is compromised (Obleser and Kotz, 2010). Using degraded stimuli and manipulating semantic context, researches showed a role of the lAG in the comprehension of sentences when the semantic predictability was high and the acoustic signal was moderately degraded (Obleser et al., 2007; Obleser and Kotz, 2010). Such structure is associated with various functions, being one of them semantic processing (Abrams et al., 2013). It is also associated with reorientation or attentional switch when stimuli are highly salient, either by their emotional value or meaning, or by their emotional or motivational components (Gottlieb, 2007).

In our research the lAG showed activations in low intelligibility condition, adding evidence to lAG role in the comprehension of verbal stimuli in unfavourable acoustic conditions. lAG would contribute to the processing of degraded stimuli through semantic processing and attentional switch depending on the emotional salience of the stimuli. This is in line with described activations in the lAG with angry verbal auditory stimuli (Castelluccio et al., 2015). Regarding lSMG, it is considered an association structure that integrates a lexical-semantic processing system, as well as the lAG (Ardila et al., 2016). Additionally, some authors proposed that the lAG and the lSMG, would be a part of a bottom-up attentional subsystem that mediates automatic attention to stimuli relevant for the task (Ciaramelli et al., 2008), which could facilitate, in this case, the recognition of emotionally negative words in acoustically adverse conditions.

The current study has a limitation. To reduce the confounding effect of scanning noise, some authors opted to use sparse sampling sequence for imaging acquisition (Alderson-Day et al., 2017; Obleser et al., 2007). Instead, and in line with Abrams et al. (2013), we used a standard acquisition with the shortest TR possible to prioritize amount of data collected. Although we acknowledge scanning noise may impact on intelligibility, our results are similar to those obtained by sparse sampling sequence investigations.

4.4. Association between a higher degree of schizotypy and hallucination proneness, and the recruitment of certain brain regions

The correlation between neuroimaging data and the O-LIFE scale, revealed a significant association between total O-LIFE scores and activations in the rACC, rOFC, and lMTG during low intelligibility condition. Moreover, results showed a significant association between the 'Unusual Experiences' O-LIFE subscale and activations in rACC and lMTG, during the same condition. This could imply that in the most degraded condition, participants with higher schizotypy and tendency to experience unusual perceptions, would show greater brain activity in such brain regions. Previous studies showed activations in ACC (Woodruff, 2004) and MTG (Bushara et al., 1999), during AVH. Additionally, a research that used emotionally negative and neutral words conveyed by semantic content and prosody, revealed that participants with schizophrenia and history of AVH, showed greater activations than controls in the lMTG (main effect), the right cingulate, and the rOFC, when they heard emotionally negative words (Sanjuan et al., 2007). Moreover, the lMTG has been associated with speech processing when acoustic signal is degraded, facilitating the recognition of verbal stimuli in acoustically ambiguous contexts. Our research shows that, in participants with high schizotypy and hallucinatory traits, emotionally salient irrelevant stimuli could capture attention automatically. Activations in the rACC and rOFC correlate with schizotypy and unusual perceptions, when listening to emotionally salient but irrelevant stimuli, as the role of these structures is to evaluate and respond to emotional salience. Therefore, this could derive in exacerbated speech detection through the additional recruitment of lMTG, which could result in false recognition of words even when hearing random and irrelevant stimuli (low intelligibility condition).

5. Conclusion

By using a verbal auditory paradigm with different degrees of intelligibility and emotional salience in a non-clinical population, this study allowed to better understand the neural underpinnings of the perception of emotional auditory stimuli, which could have relevance for the study of AVH. Firstly, at a behavioural level, intelligibility (or word recognition) improved with negative emotional salience, possibly due to the recruitment of selective attention. Secondly, at a neural level, less intelligible stimuli displayed activations in the lMTG, lSMG, and lAG, regions associated to speech processing in adverse acoustic conditions. Moreover, areas related to emotional processing (rACC and rOFC) and selective attention (rDLPFC) activated during emotionally negative stimuli, replicating findings of the literature. These speech, emotion, and attention processing regions, could have a differential role in the experience of auditory unusual perceptions or AVH, derived from the aberrant processing of stimuli evaluated as emotionally salient. People with a greater tendency to experience auditory unusual perceptions would have stronger responses in such brain areas, as well as a greater tendency to recognize words in emotionally salient but irrelevant stimuli when the acoustic context is ambiguous, which could derive in AVH.

The current study anticipates fur ther investigations with this paradigm in psychiatric patients, in order to reveal the behaviour and brain areas associated to the processing of emotionally salient and ambiguous stimuli, which could predispose to AVH in patients and in general population.

Credit author statement

Bautista Elizalde Acevedo: Funding acquisition, Formal analysis, interpretation of the results. **Nahuel Chambeaud:** Formal analysis. **Andrés Acuña:** assisted with participant recruitment, Funding acquisition. **Mariano Marcó:** assisted with participant recruitment, Funding acquisition. **Silvia Kochen:** Writing - review & editing.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2020.107580.

Appendix

Table 3
Negative and neutral words that were modified by the 3 conditions of intelligibility (high, medium, and low). The words are in Spanish.

N.°	Negative	Neutral
1	Atorrante	Cercano
2	Bastardo	Chico
3	Basura	Colorado
4	Degenerado	Emisor
5	Enfermo	Federal
6	Escoria	Graduado
7	Fracasado	Liso
8	Guacho	Mecánico
9	Idiota	Mediano
10	Ignorante	Mellizo
11	Imbécil	Natural
12	Infeliz	Payador
13	Inútil	Principal
14	Lacra	Público
15	Ladrón	Silencioso
16	Maldito	Sujeto
17	Miserable	Sutil
18	Pervertido	Tercero
19	Sucio	Tío
20	Vago	Vasco

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