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An experiment set-up for analysis of lateralization judgments of binaural stimuli

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Abstract ***Introduction:*** *The aim of this work is to present a physical implementation of a noninvasive methodology to analyze the directional sensitivity of human auditory system. A computer controlled experiment set-up has been designed and developed to study the behavior of human subjects under the presentation of interaural time delays and interaural amplitude differences for several sensation levels.* ***Methods:*** *The proposed methodology comprises: the application of trains of low-pass filtered narrow pulses as acoustic binaural stimuli; the automatic, simultaneous and random variation of interaural time delays and interaural amplitude differences; the absence of human interference along the experimental sessions, except for the decision of the listener under test; the minimization of adaptation effects.* ***Results:*** *Numerous lateralization judgments have been accomplished in order to investigate the transduction mechanism which allows deciding which side of subjects medial plane the source of binaural acoustic stimuli is located in. The behavior of decision time with the order of judgment, the sensation levels and the interaural differences in time and amplitudes has been analyzed.* ***Conclusion:*** *The noninvasive, reliable and automatic approach here presented allows obtaining psychophysical responses associated to the neuro-physiological phenomena underneath lateralization capability.*

Keywords *Lateralization judgments, Psychoacoustics, Interaural time delay, Interaural amplitude difference, Binaural hearing.*

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Introduction

Human binaural hearing has the property of efficiently distinguishing and selectively responding to individual sound sources even in noisy or reverberant environments. For decades this feature of the human auditory system and its subjacent neuro-physiological mechanisms have been arousing a particular scientific interest, which has recently increased with the development of computational auditory scene analysis (CASA) tools (Stern *et al.*, 2005) and with the advent and improvement of bilateral cochlear implants (Fearn *et al.*, 1999; Laback *et al.*, 2004; Long and Eddington, 2003). Moreover, the proper modeling of such mechanisms should provide a better understanding of auditory system directional sensitivity while under strong reverberation environments (Devore *et al.*, 2009).

Since 1907 it has been known that human listeners can localize or lateralize tones on the basis of interaural phase differences or interaural time differences (Clopton and Spelman, 1995; Strutt, 1907). Indeed, an interaural time delay (ITD) occurs because of the slightly different distances taken by the acoustic signal in the way towards the left and right ears (Stern *et al.*, 2005). Also, chiefly at frequencies above a few thousands of hertz, an interaural amplitude difference (IAD) is observed due to the attenuation produced by the head shadow over the ear that is more distant from the sound source (Stern *et al.*, 2005). It is reasonable to suppose that the perception of ITDs and IADs by the auditory system is related to the brain ability of precisely localizing a sound source.

Therefore, an experimental methodology to investigate the psychoacoustical behavior of human subjects in lateralization judgments of binaural acoustic stimuli consists of presenting to the left and right ears pairs of signals with amplitude differences and time delays between each other. These IADs and ITDs should be similar to the ones commonly produced by natural acoustic stimuli. The way subjects recognize that a sound source is either in the left or in the right side with respect to their medial planes may be thus scrutinized in the light of statistical techniques, providing a better comprehension on the phenomenon and reliable resources for model development.

In order to properly implement such methodology, an experiment set-up should allow the computation of numerous judgments with the adequate expedients to avoid hearing accommodation. The present work describes an experiment set-up designed to investigate how volunteer listeners accomplish binaural stimuli lateralization. The proposed set-up deals with subjects in a noninvasive manner and comprises an electronic interface between the volunteer listeners and a computer in order to synchronize and control the presentation of acoustic stimuli and the encoding and recording of human reactions.

Methods

Experimental technique

In the experimental technique here applied a particular configuration of ITD and IAD is presented until the subject decides whether the virtual acoustic-image is located on the right or on the left side of his (her) medial plane. In order to provide a better understanding on the subject's decision process and on the definitions of ITD and IAD, a configuration of pulses and the respective subject's perception are exemplified in Figure 1.

The experimental technique used here (Nogueira *et al.*, 2013) consists of submitting a *volunteer listener* (to be referred hereafter as a *subject*) to binaural earphone presentations of two trains of low-pass filtered pulses at the rate of 20 pulses-per-second and 100 μs pulse width. The cut-off frequency of the low-pass filter is 1560 Hz, which is near the optimal response bandwidth of the human auditory system. Moreover, it should be noted that natural audio stimuli at frequencies above this value produce undistinguishable Interaural Time Delay (ITD) (Stern *et al.*, 2005).

Since the pulse width is only 0.2% of its period, its spectral response approaches that of a uniform train of impulses inside the filter bandwidth. Therefore, for each stimuli presentation, 78 harmonics uniformly

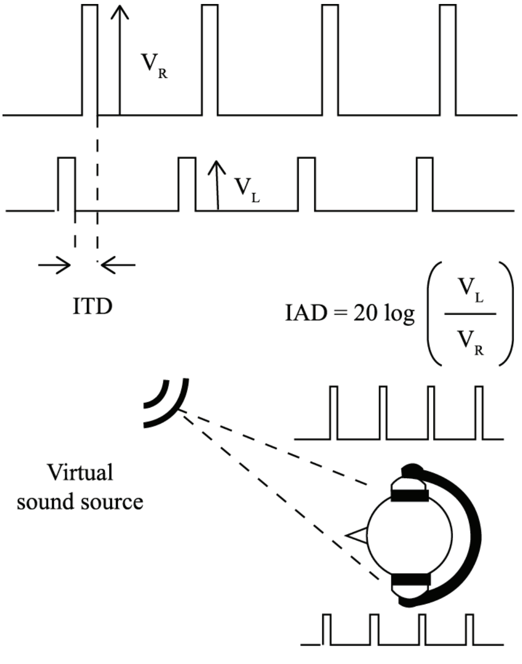


Figure 1. An example of binaural pulses pattern and the respective virtual perception in subject's brain. $V_{R(L)}$ is the amplitude of pulses applied to the right (left) ear.

spaced between 20 and 1560 Hz are available. The magnitude variation of such harmonic components is less than 4%, allowing homogeneous excitation of the hair cells along the basilar membrane following the cochlea spiral. According to the place theory of pitch perception (Fastl and Zwiger, 2007; Fearn *et al.*, 1999), the *pitch* (psychological variable correlated to physical variable *frequency*) is determined by where excitation takes place along this membrane, so that as higher the frequency is, stronger is the vibration next to the cochlea entrance.

The kind of stimulus used in this work distinguishes our methodology from most usual experimental techniques (Chait *et al.*, 2006; Chase and Young, 2008; Delgutte *et al.*, 1999; Riedel and Kollmeier, 2002a, 2002b; Zhang and Hartmann, 2006), which in general adopt either single sinusoidal signals or unfiltered clicks or tone bursts comprising harmonic components above the auditory system bandwidth.

In the experiment set-up here described, ITD ranges from –350 to +350 μs in steps of 100 μs and IAD ranges from –4 to +4 dB in steps of 1 dB. According to diffraction theory the maximum possible ITD for typical sizes of human head is about 660 μs, while the maximum possible IAD is not well predicted and depends upon the source distance, frequency and arrival angle of the sound (Stern *et al.*, 2005). On the other hand, the just-noticeable difference (JND) is in the order of 10 μs for ITDs and in the order of 1 dB for IADs, with low-frequency pure tones (Stern *et al.*, 2005). According to (Fastl and Zwiger, 2007) JND for ITD varies from subject to subject, and is generally about 50 μs for frequencies below 1.5 kHz, corresponding to 5 degrees for frontal incidence.

In the physical set-up designed and implemented in this work for the purpose of applying this technique, the subject's judgments are expressed by pressing a switch either in the right or in the left side with respect to his (her) medial plane, according to his (her) perception of the virtual acoustic-image location. Each judgment is codified by an electronic interface as a pulse with two possible voltage levels. The time elapsed between the beginning of the pulses presentation and the subject's decision is measured and recorded. After a 5 seconds rest period, new trains of pulses are presented to the subject with another configuration, or another set of random values of ITD and IAD. This procedure is repeated 128 times in each session of the experiment, taking approximately 30 minutes.

The threshold level is determined - in each subject - before starting the experiment, and the sensation level (SL) set at 10, 20, 30 and 40 dBA in different sessions, at random.

The present technique has been developed from the classical set-up widely used by psychoacoustic researchers, and the application of this technique is referred to as "judgment of sidedness experiment" (Békésy, 1960). The experiment set-up has been built and measurements have been accomplished in the Department of Bioengineering of Imperial College, London.

Data acquisition system

Figure 2 illustrates the block diagram of the binaural experiment set-up implemented in this work in order to provide an automatic data acquisition system using the technique described in the previous subsection. In this diagram, the computer provides two audio signals which are processed by analog equipment (mixer, attenuator, low-pass filter and amplifier) towards two headphones which excite the subject's left and right ears.

The mixers and the buffer amplifiers were built specifically for impedance matching in the actual

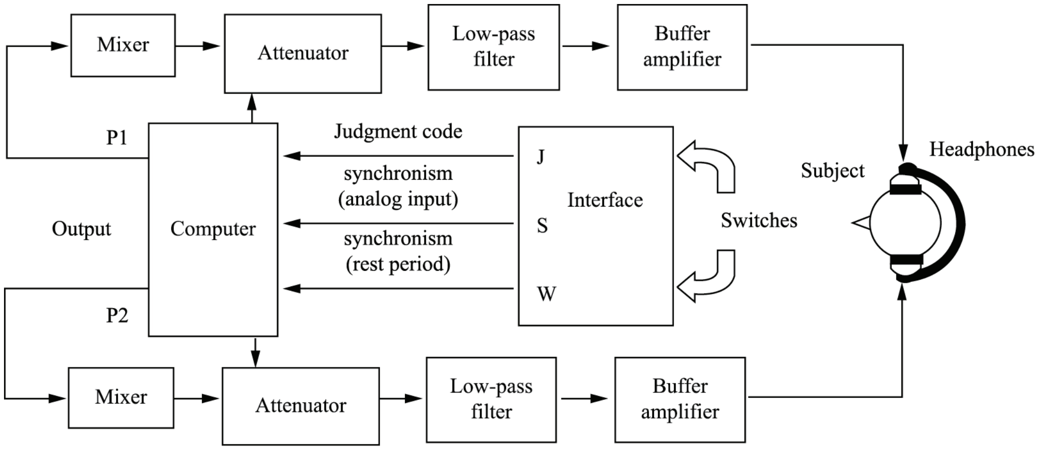


Figure 2. Experiment set-up for lateralization judgments of binaural acoustic stimuli.

binaural experimentations. The output impedance of the mixers, which are not used for frequency modulation in this context, permits a direct connection to the attenuators, and the buffer amplifiers were built to achieve an impedance conversion from the low-pass filters to the headphones.

Time delays and amplitude differences between the trains of pulses presented to the left and right ears are randomized by computer programming. A routine has been developed to generate a random sequence of numbers, each of which is associated to a particular configuration of ITD and IAD. Every time a new train of pulses must be presented to the listener, the current number in the random sequence is verified and the associated pair ITD-IAD is established. The train of pulses is thus provided by the computer output with the current ITD. A digital code corresponding to the current IAD is applied to the proper input of each attenuator, by means of which the amplitude of each train of pulses is automatically adjusted.

Sensation level (SL) is manually adjusted through the attenuator intensity control before each measurement session, for each subject. Before engaging the measurement experiment the volunteer listeners have been submitted to audiometric tests for a complete characterization of their hearing threshold level versus frequency.

The headphones used in this experiment are the KOSS ESP-9 electrostatic stereophones, with the following performance features: frequency response range from 15 Hz to 15,000 Hz, ± 2dB; sensitivity of ± 1dB for 90 dB SPL (sound pressure level) at 1 kHz; 40 dB isolation from external noise; THD (total harmonic distortion) less than 2% at 110 dB SPL.

The subject's responses, in the form of switching voltage pulses, are conveyed to a digital interface circuit which generates the synchronization signals for the proper computer operation. The logic schematic of the digital interface is shown in Figure 3 (inside the dashed rectangle) and the circuit architecture here adopted for its implementation is detailed in Figure 4. In this architecture, integrated circuits from the TTL family have been applied: 7402 for the NOR gates, 7420 for the 4-input NAND gates, 7404 for the NOT gates and 74121N for the monostable multivibrators. Another implementation technique may be chosen

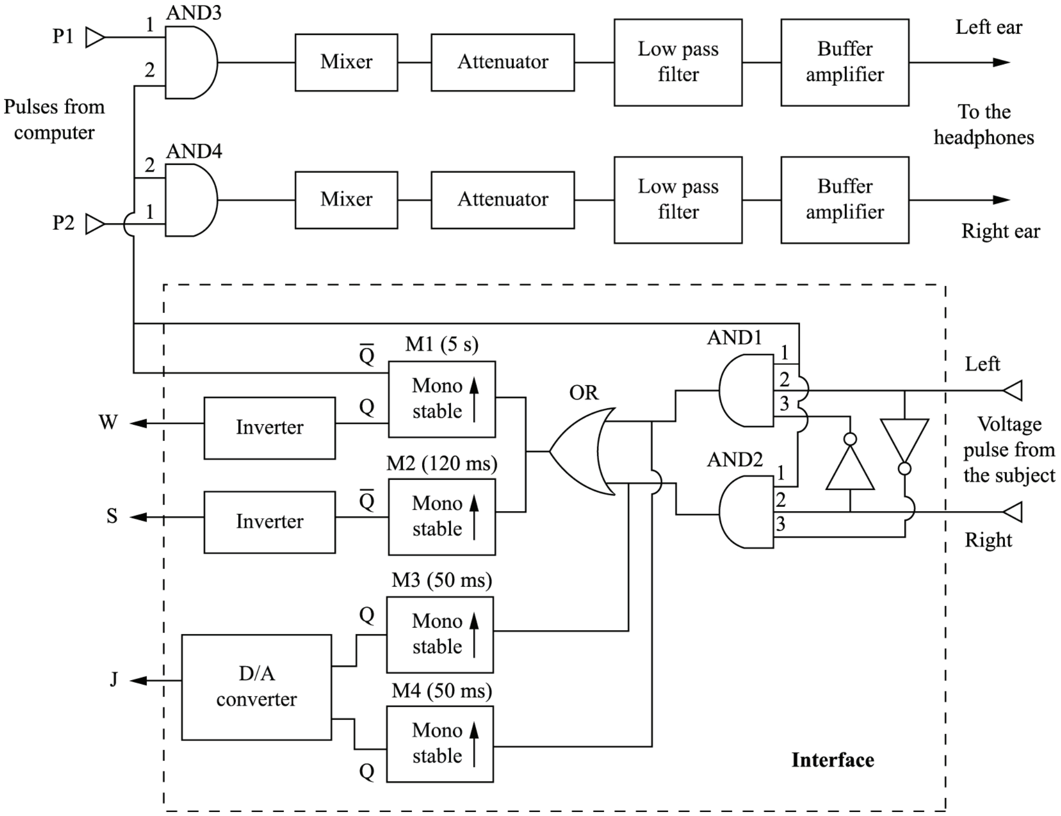


Figure 3. Logic diagram of the electronic interface circuit (inside dashed rectangle) for the automatic control of binaural experiment. LEFT and RIGHT are the decision switch positions to which are assigned complementary logic values only. J is the judgment code and S and W are synchronization signals for computer operation.

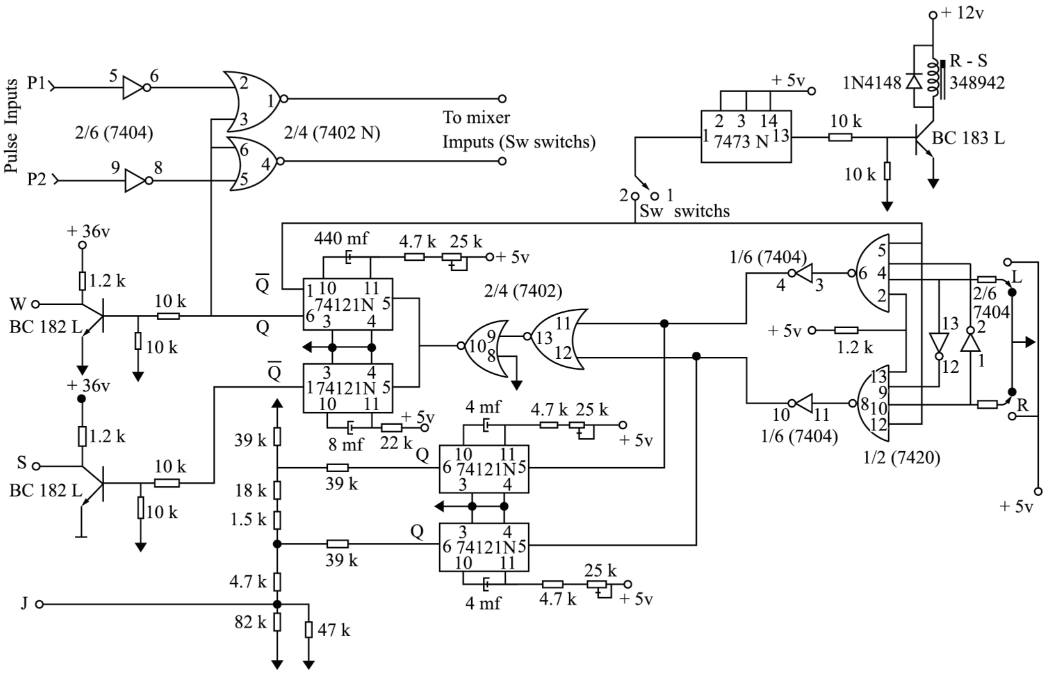


Figure 4. Detailed architecture for the implementation of the electronic interface circuit.

among many possibilities, by taking into account power consumption, area and other performing features, as well as cost.

The controlling computer program has been developed according to the flow graph in Figure 5. This algorithm is better understood by explaining the operation of the digital interface. Let us consider three situations: no judgment, left side decision and right side decision.

In the *no judgment* situation, we assume that trains of pulses are generated at random by the computer and appear at the inputs P1 and P2 of the analog equipment leading to the headphones. However, since the subject has not made a decision yet, the inputs 2 of conjunction gates AND1 and AND2 are both at low logic value and so the output of the OR gate. The output $\overline{Q}$ of the monostable M1 is at a high logic value allowing the audio pulses to be conveyed to the mixers inputs through conjunction gates AND3 and AND4 (not shown in Figure 2) without changing ITD and IAD. The output S of the interface (complementary to the monostable M2 output $\overline{Q}$) is at a low logic value enabling the judgment time counting as seen in Figure 3 (first lozenge from top to bottom). Since the algorithm vertical flow is paused as long as S remains low, the interfaces outputs W and J do not affect the computer operation.

In the *left side decision* situation, by pressing the switch the subject assigns a high logic value to the LEFT input of the interface and a low logic value to the RIGHT input. Thus, the outputs of AND1 and AND2 are temporarily high and low respectively, sending through monostables M3 and M4 a two-bits entry equal to "10" for 50 ms to the D/A converter (a simple ladder network, synthesized only by resistances and shown in the left bottom of Figure 4). This entry is converted to a judgment code J equal to 1.5 volts. As seen in the algorithm flow graph of Figure 3, with the output of the OR gate temporarily set to a high logic value, since S changes to a high logic value for 120 ms, the time counting stops and the value of J, as well as the values of ITD, IAD and of the judgment time are recorded. Also the outputs Q and $\overline{Q}$ of monostable M1 are set to a high and a low logic value respectively for 5 s, so that pulses are no longer presented to mixers during this rest period, after which another configuration of ITD and IAD is randomly assigned and a new test is applied, unless n = 128.

In the *right side decision* situation, the operation is similar to the *left side decision* situation, except for the logic values of AND1, AND2, M3 and M4 outputs, which are complementary to the former situation, and for the analog value of J which is equal to 0.75 volts.

Results

Using the computer-based method described in the previous section, the time each subject has taken to make a decision has been measured for each judgment and the judgment code has been recorded. Sessions

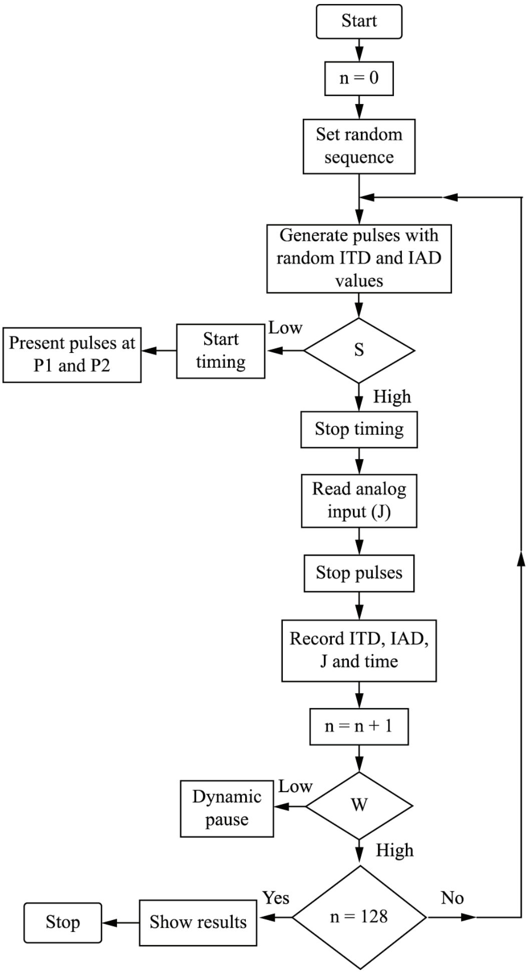


Figure 5. Algorithm flow graph of the computer program for the acoustic-image lateralization experiment.

Table 1. Example of recorded data, subject JN, SL = 40 dBA.

ITD (μs)	IAD (dB)	Total number of presentations	Number of judgments in the right side
–150	–4	20	9
–50	–4	25	22
–150	–3	22	4
–50	–3	24	20
–150	–2	21	3
–50	–2	20	13
–50	–1	21	11
50	–1	23	22
–150	0	22	1
–50	0	24	8
50	0	20	18
–50	1	26	4
–50	2	22	1
50	2	20	11
150	2	30	27
50	3	21	5
150	3	27	21
–50	4	20	1
50	4	28	3
150	4	24	12
250	4	23	21
350	4	23	22

of 128 judgments have been repeated through several days performing a total of about 13 sessions and 1664 judgments per sensation level per subject. The number of 128 judgments per session has proved to be optimal for avoiding fatigue.

Since the aim of the measurement procedure is to provide a great set of data for ulterior statistical analysis, as performed in (Nogueira and Cunha, 2012), the combinations of ITD and IAD are purposely set at random. An example of the registered data for one of the subjects (JN) and for sensation level equal to 40 dBA is presented in Table 1. According to Figure 1, the virtual perception of the sound source in the right side is associated to positive values of ITD and negative values of IAD. Nevertheless, even combinations of ITD and IAD with the same signal (both positives or both negatives) are presented in order to investigate whereas a cue predominates over the other. In Table 1, the third column corresponds to the total number of presentations of the pair ITD-IAD discriminated in the first and second columns. The fourth column corresponds to the number of right side decisions made by this subject.

Each subject's decision time has been averaged along the 13 sessions for each order of judgment (from 1 to 128) for each sensation level. The results have been plotted against judgment number, as illustrated in Figures 6 and 7 for two subjects from a total of six, and for sensations levels of 10, 20, 30 and 40 dBA.

The plots in Figure 6 correspond to the results obtained from a normal hearing subject whereas Figure 7 refers to one subject suffering from a partial unilateral hearing loss of 20 dB in the left ear. The dots, in the figures, represent the averaged time, and the continuous line represents a low-pass-filtered version of the resultant signal to show the overall trend.

In Table 2, which summarizes the numerical results, MEAN is the average decision time along all judgment orders per session and along all sessions, SD is the standard deviation, RANGE consists of the minimum and maximum values of the measured decision time.

The time distribution has been plotted as a function of ITD and IAD for each sensation level employed and for all subjects. These plots are presented in Figure 8 for subject AN.

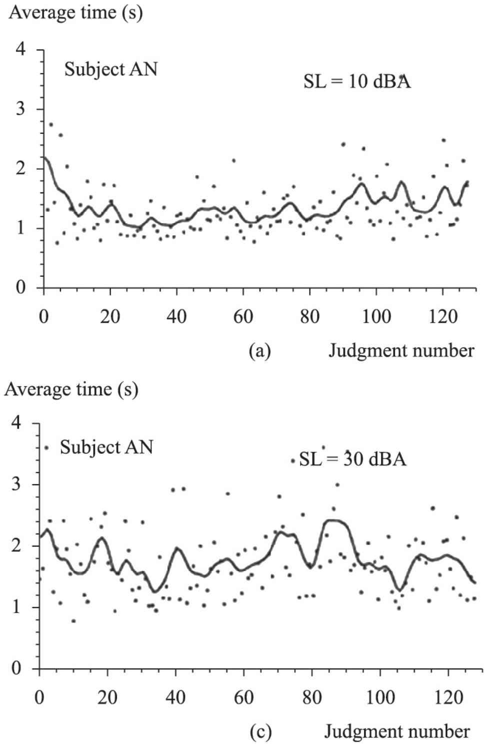


Figure 6. Average time to perform a judgment versus judgment number for subject AN, with Sensation Level (SL) equal to 10 dBA (a), 20 dBA (b), 30 dBA (c) and 40 dBA (d). Dots: measured time averaged along 13 sessions; continuous line: overall trend obtained by low-pass-filtering the averaged time variation.

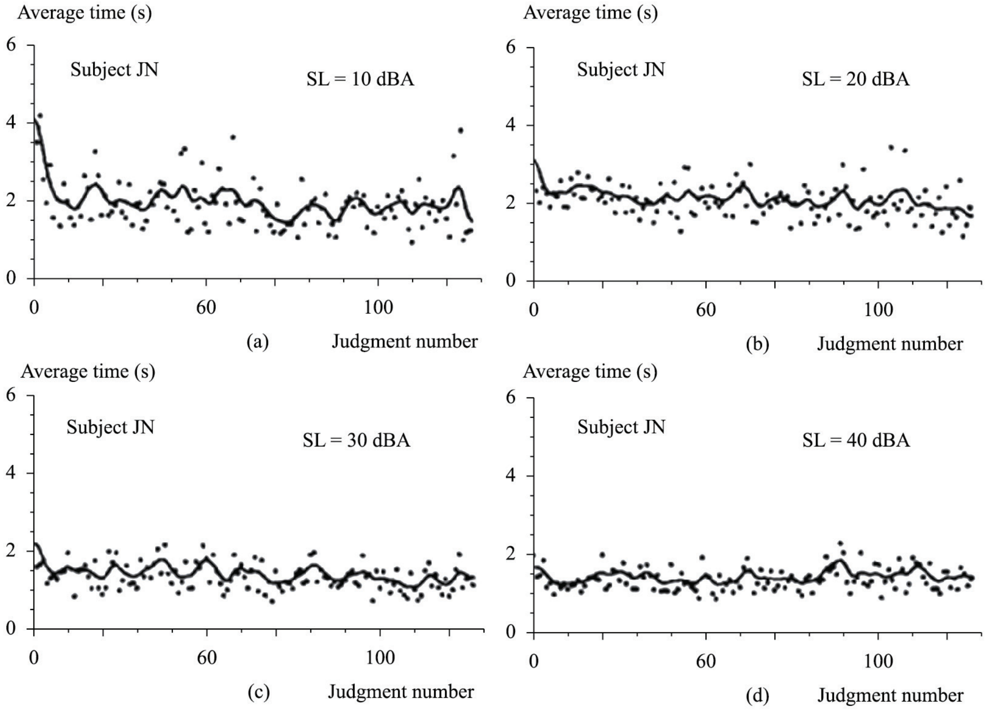


Figure 7. Average time to perform a judgment versus judgment number for subject JN (suffering from a partial unilateral hearing loss of 20 dB in the left ear), with Sensation Level (SL) equal to 10 dBA (a), 20 dBA (b), 30 dBA (c) and 40 dBA (d). Dots: measured time averaged along 13 sessions; continuous line: overall trend obtained by low-pass-filtering the averaged time variation.

Table 2. Results concerning judgment time measurements.

Subject	SL (dBA)	Mean (s)	SD (s)	Range (s)
AN	10	1.35	1.51	25.67-0.44
	20	1.39	1.14	13.20-0.02
	30	1.78	1.84	16.93-0.14
	40	1.15	1.02	18.20-0.39
JM	10	1.62	0.89	10.23-0.25
	20	1.32	0.76	6.99-0.13
	30	1.29	0.74	6.35-0.37
	40	1.35	0.69	6.65-0.24
MF	10	7.61	4.33	29.73-1.07
	20	3.92	3.40	28.93-0.74
	30	3.87	3.80	30.92-0.30
	40	1.91	1.14	12.92-0.64
TA	10	2.33	2.42	24.87-0.16
	20	2.06	1.31	19.50-0.51
	30	1.27	0.66	8.21-0.43
	40	1.12	0.59	5.31-0.34
ZB	10	0.92	0.66	6.45-0.30
	20	1.47	1.72	18.33-0.34
	30	1.03	1.03	11.70-0.27
	40	0.57	0.35	4.18-0.07
JN	10	2.03	1.89	17.55-0.54
	20	2.18	1.72	15.22-0.32
	30	1.47	1.42	14.09-0.49
	40	1.48	1.10	10.34-0.53

Discussion

The frequency of left or right decisions for each combination of ITD and IAD and for each Sensation Level has been recorded and the ensemble of all frequencies for each subject have been submitted to statistical analysis, as reported in (Nogueira and Cunha, 2012), using the Probit Method (Finney, 1977) in order to model binaural lateralization mechanism.

Although the combination of zero ITD and zero IAD has not been considered for the statistical analysis, it should be mentioned that each subject has been submitted to an exhaustive sequence of binaural pulses with such combination. These tests produced 50% of decisions for each side, thus assuring the reliability of the measurement system.

Since in the present study ITD and IAD vary simultaneously in a random fashion, the actual acoustic input, used as stimulus, has been assumed to be balanced. In order to test such an assumption further and study the time-dependence of the actual psychoacoustical binaural judgments, it is interesting to investigate whether the time the subject needs to achieve a psychoacoustic perception and produce a response (pressing the switch, expressing his/her judgment about the position of the binaural image) depends firstly on the particular judgment number which is made in the course of the experimental session, and secondly on the particular combination of ITD and IAD used as stimulus.

If this study shows that the subject-timing is dependent on the judgment number, the previous assumption of balanced acoustic input may be refuted. Rather it would suggest that a fatigue effect could be influencing the subject's performance, and that the judgments which are made at the end of the session would not be as reliable as those at the beginning.

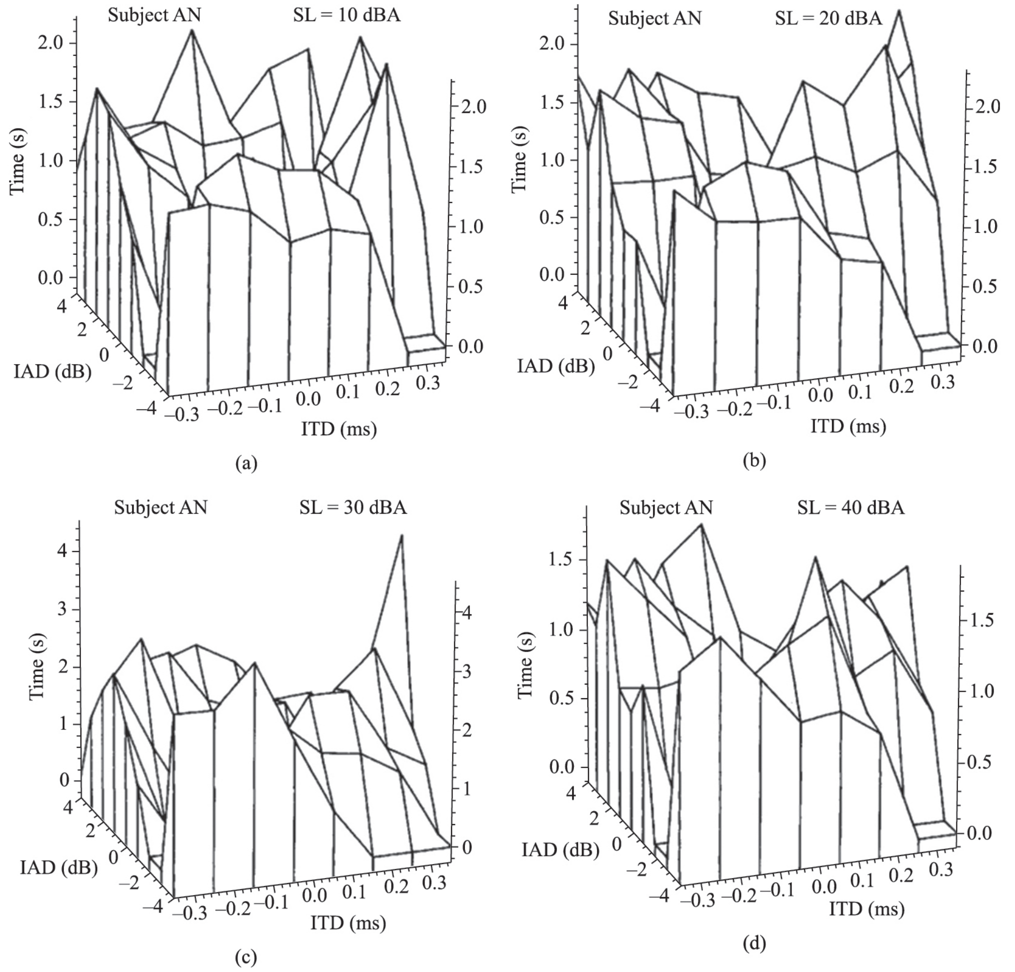
In the second case, if the time taken to make a judgment presents any association with the pair of variables used as stimulus (ITD and IAD), further analysis should be attempted to identify physiological mechanisms to account for such eventual relationships. For instance, a change in the latency of the action potential (Eggermont and Odenthal, 1974; Salomon and Elberling, 1971), related to the Interaural Time Delay, Interaural Amplitude Difference and/or Sensation Level, could have an important influence on the subject's judging-time.

The results here obtained and sampled in Figures 6 and 7 indicate that the variability in judging time is idiosyncratic, peculiar to each subject, within a relatively wide range for each single record and among subjects. They also suggest that the current assumption of balanced acoustic input is justified and also that there is no evidence of any significant adaptation effects in the experimental psychoacoustical results shown here.

In order to study the possible association between ITD and IAD, presented as stimuli, and the lapse of time needed by the subject to accomplish a judgment, a multiple correlation analysis has been used. The variables ITD and IAD occur as discrete values and their occurrences, in the long term, present a very large number of replications. For this reason the Kendall rank correlation (*tau*) procedure (Siegel, 1956; Zar, 1999) has been used in order to calculate the partial correlation Kendall coefficients between ITD and judging-time for constant IAD and between IAD and judging-time for constant ITD, for all subjects and all sensation levels.

From this analysis, it was observed that the partial correlation Kendall coefficients between ITD and judging-time is limited between –0.2105 and 0.0843 and the partial correlation Kendall coefficients between IAD and judging-time is limited between –0.0623 and 0.0413. Since the absolute values of the partial correlation coefficients resulted very small, no indisputable association between those variables has been verified. Therefore, it was concluded that, at least for the kind of stimuli employed here, no association between judging-time and ITD or IAD could be detected.

To reinforce this view, it is worth mentioning that the peaks in the plots of Figure 8 appear in no



(a) (b) (c) (d)

Figure 8. Judgment time as a function of ITD and IAD for subject AN, with Sensation Level (SL) equal to 10 dBA (a), 20 dBA (b), 30 dBA (c) and 40 dBA (d).

consistent fashion and do not suggest any specific trend of time values related to ITD and IAD, thus further supporting the finding of a lack of association.

Therefore, as assessed from the approach used here, there is no evidence of any systematic true-dependence of judgments, either by adaptation or by interaction of IAD or ITD variables.

This work describes the implementation of an experiment set-up for the analysis of human behavior in lateralization judgments of binaural acoustic stimuli. This experiment set-up employs a classical methodology based on the presentation to both ears of trains of pulses with interaural time delays (ITD) and interaural amplitude differences (IAD).

In our experimental system, the low-frequency pulses applied are rectangular and very narrow, thus providing many harmonic frequency components of significant and similar amplitudes in the range of the human receptive field.

The ITD and IAD values are randomly set by a computer program for each presentation of train of pulses, so that the actual acoustic input can be assumed to be balanced. As soon as the volunteer listener makes his(her) decision (left or right side) and after a 5 s rest period another configuration is automatically established. A proper synchronization between the pulses presentation and the subject's reactions is provided by an electronic interface.

Such features allow the fast computation of a great amount of subject's responses. Moreover, the system operates automatically and, except for the interaction with the listeners under test, there is no need of other human interference. In turn, the listener's interaction with the experimental system is limited to the pressing of a switch followed by the rest period. Hearing adaptation is strongly minimized, which assures the reliability of measured data.

The approach used in this work offers a simple way to obtain psychophysical responses that can be related to neuro-physiological phenomena. Indeed, according to such approach it is possible to access neural information through psychoacoustical experiments, without requiring invasive methods.

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