TITLE of the PROJECT: Binaural cues and spatial hearing in ecological environments

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ABSTRACT

Spatial hearing underlies our ability to localize sound sources in our environment, and to listen in noisy conditions (the "cocktail party effect"), which are both degraded by hearing loss. This project addresses fundamental aspects of our understanding of spatial hearing in humans, by focusing on the analysis of ecological situations. Indeed, for methodological reasons, research on spatial hearing has focused largely on simplified experimental configurations, for example by considering point sources and by suppressing reflections on the ground. Contextual elements such as source width and ground reflections strongly affect the performance of leading models of sound localization, but the significance of this fact is difficult to assess because relatively little is known on human performance in ecological situations. This project aims at filling this gap by empirically measuring the distribution of binaural cues and human sound localization performance in ecological situations, in particular by including aspects that have been little explored, such as physical sound sources (vibrating objects as opposed to sounds played on speakers) and reflective grounds (grass, pavement). Thus, we propose to analyze the acoustical properties of natural hearing environments, and the influence of these properties on spatial hearing. This analysis will allow us to interpret the large body of experimental results in binaural psychophysics in an ecological context. The specific aims are:

a) to measure binaural cues with physical sources (objects, as opposed to point sources) in ecological conditions (free field with natural surfaces, e.g. grass), and in particular to empirically estimate the distribution of binaural cues for a given source location;

b) to measure human localization performance in ecological situations, and in particular to measure the sensitivity to various aspects of the ecological context (e.g. nature of the ground).

c) to understand how much of human binaural psychophysics can be explained by natural statistics of binaural sounds (using Bayesian models), as opposed to specific physiological mechanisms and constraints (e.g. limits of phase locking of the auditory nerve).

By investigating the aspects of binaural hearing that are critical in ecologically relevant situations, the project is expected to provide crucial information for the design of auditory prostheses and implants.

RESEARCH PLAN

A. Specific aims

The goal of this project is to investigate spatial hearing in ecological situations, using acoustical recordings, human psychophysics and theoretical analysis. The specific aims are:
a) to measure binaural cues with physical sources (objects, as opposed to point sources) in ecological conditions (free field with natural surfaces, e.g. grass), and in particular to empirically estimate the distribution of binaural cues for a given source location;
b) to measure human localization performance in ecological situations, and in particular to measure the sensitivity to various aspects of the ecological context (e.g. nature of the ground).
c) to understand how much of human binaural psychophysics can be explained by natural statistics of binaural sounds, as opposed to specific physiological mechanisms and constraints (e.g. limits of phase locking of the auditory nerve).

B. Background and Significance

Spatial hearing relies on a variety of acoustical cues, in particular binaural cues: interaural differences in intensity and time (IID and ITD, respectively). These are influenced by source location, but also by contextual elements, such as sound spectrum, early reflections on the ground, background noise, source width and directionality, posture. Specifically, our recent work indicates that:
1) There are substantial frequency-dependent variations in ITD in human and animal HRTF at a fine scale, which imply large variations of ITD with sound spectrum and differences between phase and envelope ITD [1]. These variations are not noise but rather reflect the individual geometry of the listener's head and body.
2) The presence and properties of the ground produce early reflections that impact binaural cues in a systematic way [2] (Fig. 1A). These reflections are too early to be suppressed by the precedence effect and instead result in interferences. This comes in addition to the effect of walls in rooms [3].
3) Body posture can impact binaural cues, as assessed from HRTF computed from 3D models [4,5] (Fig. 1B).

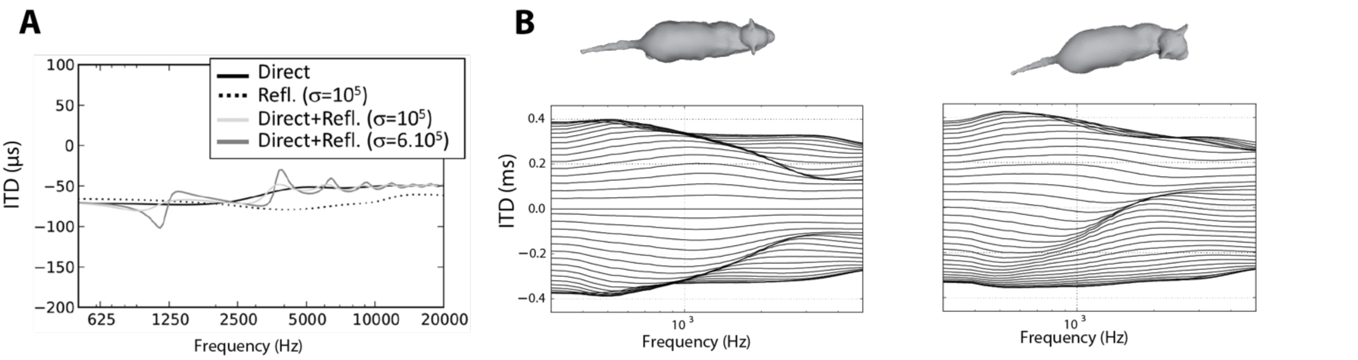

Figure 1. A, ITD v. frequency for one particular source direction in a spherical head model, with grounds of different absorption properties, showing interference patterns [2]. *B, ITD v. frequency for all source directions from the back in a 3D model of a cat with the head straight (left) or turned (right) [4].*

Work by other investigators has shown that properties of the sound source can also affect binaural cues. In particular, real sounding objects, in contrast to omnidirectional point sources typically used in laboratory experiments, have a width (for example a car) and a directivity. Both can have an impact on binaural cues [6].

These contextual elements make the computational task of sound localization challenging, and this is indeed one of the main difficulties that sound localization algorithms in the engineering field aim at solving. Consistently, we have shown that these contextual elements also strongly affect the performance of leading models of sound localization [7,8]. It seems plausible that biological sound localization systems, in animals and humans, are adapted to the complexity of ecological environments and thus are robust to contextual elements. Some indications of this robustness can be found in psychophysical studies showing that lateral localization is not very sensitive to level [9], sound duration [10] or spectro-temporal envelope

[11–13]. Robustness could then provide an important constraint on models of spatial hearing. However, there is currently little empirical data available regarding both the binaural cues produced by sound sources in ecological situations and the performance of humans in localizing sounds in such situations. Indeed, for methodological reasons, most experiments have been designed to minimize these contextual elements, in particular by 1) minimizing reflections, on walls but also on the floor (but see [3]), 2) playing artificial sounds (in particular clicks and noise bursts) on speakers.

This project aims at filling this gap by empirically measuring the distribution of binaural cues and human sound localization performance in ecological situations, in particular by including aspects that have been little explored, such as physical sound sources (vibrating objects as opposed to sounds played on speakers) and reflective grounds (grass, pavement). It will thus produce a database of binaural recordings, labelled with source location and measured human performance, which will be made available to the community.

Secondly, since the mapping from binaural cues to location is uncertain due to contextual elements, the task of sound localization implies some degree of statistical inference. This aspect is typically not included in leading biological models of sound localization, but research in other sensory modalities has shown that Bayesian inference can explain and unify many psychophysical results [14]. In this context, Bayesian inference consists in estimating the most likely source location, given the binaural cues presented and the natural distribution of binaural cues. The estimation of natural distributions of binaural cues might allow us to unify a large body of binaural psychophysical results under a general theory.

C. Preliminary studies

We have gathered and analyzed preliminary binaural recordings with physical sources in a quiet park. The subject wore binaural microphones, while the experimenter, placed at predefined positions, produced sounds with a woodblock, a rain stick, and speech. This preliminary analysis has shown a few interesting aspects, many of which were expected but motivate further analysis of such data sets:

- Even in quiet environments, there is large variability in binaural cues across time in a given recorded sound, which is presumably due to background noise.
- As expected, average ITD varies with frequency.
- ITD tends to be unreliable in high frequency, while ILD is unreliable in low frequency. This supports duplex theory, and might lead to specific predictions regarding the trade-off between ITD and ILD, based on cue reliability.
- Generally, estimating source direction from a single binaural recording is difficult, while it is trivial in quiet artificial conditions.

Once the direction-dependent distribution of binaural cues is known, it is possible to derive a Bayesian model based on maximum likelihood estimation. The model outputs the most likely source direction that has produced a given set of binaural cues. For example, a classical psychophysical experiment to study how ITD and ILD are perceptually combined into sound lateralization is the measurement of the "binaural trading ratio" [15]: a tone (or band-passed click) is presented with a given ITD and the subject changes the ILD so that the sound is perceived in the center; the binaural trading ratio is the quantitative relation between the two cues. The trading ratio in µs/dB is higher in low frequency than in high frequency. The Bayesian model provides an interpretation and a prediction for this trading ratio, by proposing that each pair of ITD and ILD values produces a lateralization that corresponds to the source direction that is most likely to have produced these values, given the natural variability of these cues. We have used a synthetic data set produced with simulation of rooms and Kemar HRTFs by T. May [16] to make predictions on an binaural trading experiment. Fig. 2 shows the most likely azimuth of the source for any given pair of ITD and ILD, at two different frequencies. We can see that the pairs of values that are mapped to azimuth 0° (green) fall on a line with two different slopes. Expressed in µs/dB, the slope is higher at the lower frequency than at the higher one, consistent with experiments. Thus, the binaural trading ratio observed in psychophysical experiments may reflect optimal inference of sound direction from uncertain binaural cues.

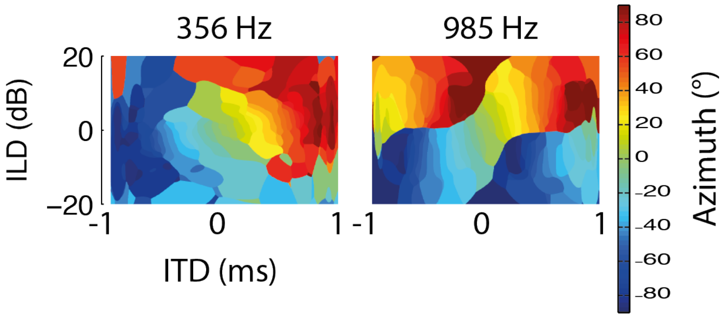

Figure 2. Most likely source azimuth (color-coded) for a given pair of ITD and ILD values, at two different frequencies. Predictions produced using a synthetic data set of binaural recordings [16] *(T. May, personal communication).*

D. Research Design & Methods

The project consists of three parts: 1) producing a data set of binaural recordings in a variety of ecological situations; 2) measuring sound localization accuracy in human subjects in ecological situations; 3) making a Bayesian model of sound localization and comparing it with psychophysical data.

1) Binaural recordings in ecological situations

The goal of this part is to gather a database of binaural recordings with sources at specified locations, in different contexts. Part of the initial work in this project is to refine the methodology so as to maximize the throughput and quality of the procedure. We will start from the following design.

Subjects
We will select 10 normal hearing subjects (young adults, <30 years), with <10 dB hearing loss between 250 and 8000 Hz. This selection will be important for the psychophysical study (part 2). We will take morphometric measurements of each subject: head width and height.

Recording conditions
The subject will wear binaural microphones. She will be sitting on a stool with a seatback and adjustable height; we will consider two vertical positions. To maintain the head at fixed position during the session, a visual target will be placed in front of the subject, at eye level. To have recordings with different postures, two other conditions will be considered, with the visual target at ±30° relative to the subject's body.

Environments
The recordings will take place in several environments. In this project, we do not address the problem of separating distinct sound sources, but rather that of natural background noise. For this reason, we will select quiet environments. The initial selection is: a park; a forest; a quiet urban environment. These environments have in common to have a reflective ground, with different acoustical properties, in contrast with typical laboratory recordings.

Sound sources
Sound sources will be placed at predetermined positions. Markers will be put on the ground, arranged in two circles around the subject, at 2 and 5 meters, at 15° increments (or 5°, see below). We will consider a variety of sound sources producing sounds at marked positions:

- A speaker (on a stand mounted on wheels) playing clicks, facing the subject's position. This will be used for control and comparison.
- Footsteps: the experimenter stamps at a fixed position. The interest is that the resonating object is the ground, which should be acoustically very different from a point source.
- Speech: the experimenter reads a sentence written in advance. Here the body of the experimenter resonates.
- Rain stick: this object produces sustained sounds with large acoustical width.
- Movie clapper: this produces a strong transient sound.
- Paper rustling: this produces a type of broadband noise but with a physical source.

The experimenter will move to a position, produce the sound repetitively for about 10 s, then move to the next position. This should take no more than 15 seconds per condition. Independently of the recording session, the manipulation of each source will be recorded on video camera, and the vertical position of the source will be measured.

The total number of conditions listed above is large: 6 postures (3 head angles times 2 vertical positions), 3 environments, 48 positions, 6 sources, totaling 5184 conditions. This corresponds to about 22 hours of recording, not including breaks. To reduce this duration, we will not include all possible combinations. Instead, we will produce the following sets, for each of the 3 environments:

- A high spatial resolution set with 5° increments at two distances (144 positions), a single posture, a single type of sound (claps). Total: 144 conditions or 36 min.
- A set with diverse sources: 15° increments at fixed distance on a half-circle (13 positions), single posture, 5 sources (all sources excluding the one used in the first set). Total: 65 conditions or 16 min.
- A set with diverse postures: 15° increments at fixed distance on a half-circle (13 positions), 1 source, 5 postures (excluding the posture already measured in other sets). Total: 65 conditions or 16 min.

In total, we obtain 274 distinct conditions, corresponding to just over 1h. Allowing for regular breaks, we obtain three sessions of about 1h30 (one per environment) for each subject. We plan to include 10 subjects. This will produce in total 8220 binaural recordings.

Analysis

The set of all recordings with associated data (positions, environments, morphometric measurements, etc) will be uploaded to a public repository. This requires segmenting the audio recording of each session into waveforms corresponding to each condition. We will simply use the power in the recording to delimit the conditions automatically. We will verify that no segmentation error has occurred by:

- counting the number of delimited segments and comparing it with the number of conditions;
- identifying segments of abnormal durations and manually checking them.

Each recording is about 10 s long and therefore contains a large amount of binaural information. Indeed, at 1000 Hz, 10 s corresponds to 10 000 cycles and therefore potentially 10 000 data points for IPD and ILD at each frequency. In practice, this number will be smaller depending on the sounds, because some are transient (eg repeated claps), and some have power in restricted regions of the spectrum (eg speech). Nonetheless, it will be possible to obtain a distribution of IPD and ILD for each condition and frequency.

Further analysis is described in part 3.

2) Psychophysics of sound localization in ecological situations

We will then measure sound localization performance (both accuracy and precision) in 10 human subjects, in the same contexts as used for the binaural recordings. Half of the subjects will be the same as those for binaural recordings.

The design of these experiments must be quite different from that of the recordings for methodological reasons. First, the subjects do not wear binaural microphones. Second, presentation of the sounds must be randomized. The methodology will be adapted from published experimental protocols [17]:

- Head position is continuously tracked with an electromagnetic head tracker.
- The subject is blindfolded. At the beginning of the trial, the subject’s head is at 0°.
- The sound is played by the experimenter, as in part 1. The subject is instructed to remain still until the sound has finished playing, then turn her head towards the sound source.
- While the experimenter moves to the next position, predetermined with a random order, the subject wears a noise-cancelling headphone and listens to a masking noise, so as to cover the sounds produced by the experimenter while moving.

The sounds will also be recorded with a microphone placed near the subject so as to check the acoustical properties of the sound offline (in particular duration and level). To aid the experimenter, numbered panels will be placed next to the source positions, the number corresponding to the rank in the randomized sequence of positions. Since the subject indicates the source position by turning the head, only front positions will be considered.

The presented sound will be shorter than in part 1 (just one presentation), so the duration of the trial will be mostly determined by the sequence of actions. We estimate that each condition should take about 20 s. Accuracy and precision can be estimated from slope and standard deviation of the regression line to the data (target angle vs. response angle) [17]. This requires a large enough number of data points; we will aim for about 100 data points (similar to [17]). The set of all front positions spaced by 5° angles produces 37 data points. We will therefore consider sets of 3 random permutations of these positions, so as to produce 111 data points, taking about 37 min to complete. As this is quite long, the set of psychophysical measurements will be smaller than the set of binaural recordings. We will consider a single posture and distance, and two sources used in random order (roving). This produces 222 data points, taking about 1h15 min to complete. With breaks, each session will last about 1h30-1h45. This will be repeated in each of the 3 environments.

The database will also be uploaded to a public repository. The data will be analyzed with standard methods to evaluate precision and accuracy (e.g. [9,17,18]).

3) Bayesian model of sound localization

Model

From our recordings, we will estimate the frequency-dependent distribution of interaural cues, conditioned on source location. An example is shown on Fig. 3, where the joint distribution of ILD and ITD is shown in 4 narrow frequency bands, calculated from simulations of sources in reverberating rooms, placed at azimuth 0° [16]. These distributions show that there is uncertainty in ILD and ITD for a given source location. It also shows that in high frequency, the ITD distribution has several peaks corresponding to identical IPD values. Conversely, several source locations are consistent with a given pair of ITD and ILD values. Thus, statistical inference is required to determine the likely position of the source. This can be done with Bayes' theorem, which, in the context where all source locations are equally likely, stipulates that the probability that the source is at a given location given the cues is proportional to the probability of observing those cues at that location (P(location | cues) $\propto$ P(cues | location)). This has been used in the engineering field to derive an efficient sound localization algorithm, using distributions of cues obtained from simulations [16]. Here we will use our measured distribution of cues to compare the predictions of the Bayesian model to psychophysical data.

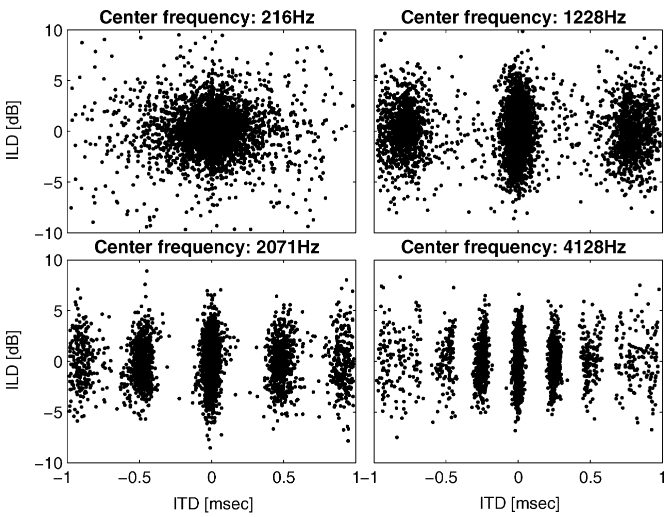

Figure 3. Joint distribution of ITD and ILD in 4 narrow frequency bands, calculated from simulations of sources in reverberating rooms, placed at azimuth 0° [16].

The model will be developed along the following lines:

- For each condition, we analyze ITD and ILD distributions in different frequency bands, as done in [16].
- Since our data are obtained at discrete points (spaced by 5 or 15°), we will need to interpolate between to obtain a spatially continuous parametrization of ITD/ILD distributions. This will be possible once ITD/ILD distributions are fitted to parametrized distributions (e.g. mixture of Gaussians in [16]).

- Different versions of the model will be produced, depending on what is considered known or unknown. For example, the model may take into account the knowledge of the type of source, or it may consider it as a source of uncertainty.

Prediction of accuracy and precision in ecological situation

The model will then be used to produce artificial behavioral responses to signals presented at different target azimuths. This will be done in two ways (two version of the Bayesian model):

- Maximum likelihood: the response to a signal with a given set of cues it the source location that has maximum probability of generating those cues.
- Sampling: the response to a signal with a given set of cues is a source location drawn at random with probability equal to the probability of the location to generate those cues.

These two versions will likely produce the same accuracy (gain), but not the same precision, the latter being less precise than the former.

We will then compare the outputs of the model with measured psychophysical performance (part 2). We expect that precision is lower near ±90° because ITD and ILD are less sensitive to azimuth near ±90°. We also expect that the gain is lower than 1 (i.e. the behavioral range of responses is compressed relative to the full range of targets), because target responses are distributed within ±90°.

Comparison with previously published psychophysical data

We will then produce predictions of the Bayesian model for different situations investigated in the psychophysical literature, in particular:

- Just-noticeable differences (JND): in the sampling version of the model, sounds produced at two nearby locations, or with two slightly different ITD or ILD, cannot be discriminated not because the inputs are noisy, but because the distributions of inferred of source locations are very similar in the two cases. Thus, predicted JNDs can be calculated from the model for different situations (different frequencies, JND in ITD, ILD, azimuth).
- High-frequency limit of IPD discrimination: in the same way, the model produces a prediction for the frequency above which IPD does not produce significant information about source location. This should be related but not equal to the frequency corresponding to a wavelength equal to head width.
- ITD-ILD trading: as already explained previously, the model produces predictions about the ITD-ILD trading ratio at different frequencies [15].
- Duplex theory [20]: the model predicts the amount of information about sound location provided by ITD and ILD as a function of frequency, which is expected to be in favor of ITD in low frequency, and in favor of ILD in high frequency (see preliminary results). Predictions can be compared quantitatively with published results by replicating the experimental design with the model.

This list is not exhaustive; for example the model could be extended to address frequency integration, with the concepts of centrality and straightness [19].

We anticipate that some predictions of the Bayesian model will match human psychophysics, and some will not. For example, it is possible that the limit of IPD discrimination is determined by the limit of phase locking, and not by acoustical factors. This investigation will allow us to delineate the range of auditory spatial behavior that can be explained by statistical inference in an uncertain auditory world, and which ones require other, possibly physiological, explanations.

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PRINCIPAL INVESTIGATOR’S BIOGRAPHICAL SKETCH

Name & Degree: Romain Brette, PhD **Position: DR2 INSERM, Institut de la Vision**

A. Education, Training, Positions & Honors

Positions

2014-	DR2 INSERM (senior research scientist), Team leader “Computational neuroscience of sensory systems” in the Vision Institute (Paris).
2008-2014	Assistant professor, ENS (Paris), Cognitive Science Department, Audition team.
2005-2008	Assistant professor, ENS (Paris), Computer Science Department, Odyssée team (INRIA).
2004	Postdoc with Alain Destexhe (CNRS Gif-Sur-Yvette) and Wulfram Gerstner (EPFL, Switzerland) in Computational neuroscience

Education and training

2016	Certification for animal experimentation (level I), INSERM.
2009	Habilitation (HdR) in cognitive science (ENS Paris).
2000-2004	PhD in Computational neuroscience (UPMC, Paris).
1999-2000	DEA in Applied mathematics (ENS Cachan, France).
1998-1999	MSc in Neural network theory (King’s College, London).
1997-2000	Magistère in Computer science (ENS Lyon).

Honors

2009 ERC Starting Grant

2009 Institut Universitaire de France (junior member)

B. Peer-Reviewed Publications

Selected list of 10 publications relevant to this project:

1. Zheng Y and Brette R (2017). On the relation between pitch and level. *Hearing Research* doi: 10.1016/j.heares.2017.02.014.
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