UPPER LIMITS OF AUDITORY MOTION PERCEPTION: THE CASE OF ROTATING SOUNDS

François-Xavier Féron, Ilja Frissen, Catherine Guastavino

Centre for Interdisciplinary Research in Music, Media and Technology
McGill University, School of Information Studies
Montreal, QC - Canada
`francois-xavier.feron@mcgill.ca`
`ilja.frissen@mcgill.ca`
`catherine.guastavino@mcgill.ca`

ABSTRACT

We report two experiments investigating rotating sounds presented on a circular array of 12 speakers. Velocity thresholds were measured for three different types of stimuli (broadband noises, white noise, harmonic sounds). In the first experiment, we gradually increased or decreased the velocity and asked participants to indicate the point at which they stopped or started (respectively) perceiving a rotating sound. The thresholds ranged between 1.95-2.80 rot/s for noises and 1.65-2.75 rot/s for harmonic sounds. We observed significant effects of the direction of velocity change (acceleration or deceleration), stimulus type and fundamental frequencies for harmonic sounds, but no effect of centre frequency was observed for broadband noises. In the second experiment, stimuli were presented at constant velocities in a single-interval forced-choice paradigm: listeners were asked to indicate if the sound was rotating or not. The thresholds obtained were within the range of those of the first experiment. The effect of frequency for harmonic sounds was confirmed.

1. INTRODUCTION

Two experiments were conducted to investigate the perception of sounds rotating quickly around the listener. Although circular trajectories have been used for decades in contemporary music [1], they did not receive much attention from the scientific community. We will first discuss the musical endeavors and will report the few previous studies dealing with this topic. Then we will describe two experiments conducted to determine velocity thresholds at which listeners cannot longer perceive sound rotating around them. These results could be of interest to engineers and composers working with multichannel speaker array to (re)create auditory motion in virtual environment.

1.1. Electroacoustic music and sound spatialization

In 1948, Pierre Schaeffer developed the concrete music, a new kind of music presented on loudspeakers rather than played by performers. Two years later, Herbert Eimert, Robert Bayer and Werner Meyer-Eppler founded in Cologne the studio of electronic music [2]. Many electroacoustic studios appeared all around the world shortly after. Thanks to the expansion of this new musical aesthetic, sound spatialization became an important preoccupation for composers. Spatial attributes are now considered an integral feature of a musical piece along with other musical attributes such as melody, rhythm or timbre.

Spatial attributes have also been investigated quite extensively in the field of room acoustics (*e.g.* [3], [4]), and more recently in the context of multichannel audio reproduction for auditory displays (see [5], for a review) and psychoacoustic research (*e.g.* [6], [7]).

Karlheinz Stockhausen (1927-2008) was involved in spatial composition as early as 1955. During his entirely life, he had never stopped developing the concept of spatial music as demonstrated by his writings [8], his instrumental, electronic or mixed music and custom-built devices. For *Kontakte* (1959-1960), a piece which exists in two versions (one for four-channel tape alone, and one for four-channel tape and live piano and percussion), he designed and built a rotating table to present amazing rotating sounds. This table was able to reach six rotations per second (rot/s). A directional loudspeaker was attached to its centre and 4 microphones were located around the table. The electronic music played back, in mono, was re-recorded onto four-channel tapes. When this new tape was played back, using 4 speakers placed in the corners of the listening room, the music seemed to spin around the audience at various changing rates and with very distinctive phase and doppler shifts [9].

> "Many listeners exposed to *Kontakte* in its original four-channel version for the first time reported an analogy with orientation loss in an antigravity room."
>
> Jill Purce, 1973 [10].

More recently at IRCAM (Institut de Recherche et Coordination Acoustique/Musique) in Paris, the Portuguese composer Emmanuel Nunes (born in 1941), working in closed collaboration with music assistant Éric Daubresse, conducted empirical experiments concerning the perception of moving sound sources. These investigations were explored in *Lichtung I* (1988-1991) for ensemble and live electronics. In this piece, complex spatialization figures were elaborated using 8 speakers regularly spaced around the audience. Nunes and Daubresse experimented with different trajectories, velocities and amplitude panning [11]. They observed that when velocity increased above a certain threshold, the rotation was perceived as "frenetic immobility and static spin" (our translation of "immobilité frénétique et statisme tourbillonnant" [12]).

Although Stockhausen and Nunes were always interested in psychoacoustical research, they certainly did not base their own composition on scientific studies. Indeed, there is a lack of scientific reports on the perception of fast rotating sounds. A review of the scientific literature on this phenomenon is reported below.

1.2. Scientific literature concerning perception of rotating sound sources

Early studies on auditory localization typically used static sounds. In the 1970s, these investigations were extended to moving sound sources. Many studies dealing with circular motion used velocity discrimination tasks (see [13] for a recent review), investigated minimum audible movement angle (*e.g.* [14]) and the auditory motion after-effect (report to [15], for review). However, these studies only investigated relatively slow velocities (below 360°/s *i.e.* 1 rot/s), with an interesting exception by Aschoff in 1962 [16].

Aschoff investigated the velocity at which participants could no longer perceive a rotation. In an anechoic room, participants listened to rotating sounds presented on a circular array of 18 loudspeakers. A noise signal was shifted from one loudspeaker to another around the circle by using a bank of electrical switches. Velocity was controlled by the experimenter and ranged between 0 and 20 rot/s. At low switching speeds (*i.e.* slow velocities), participants reported that the noise was moving in a circle around them. As the switching speed increased from 3.5 to 6 rot/s, the noise was perceived to oscillate between the left and right sides. This left-right sensation was even more salient between 6 and 14 rot/s. Finally, above 14 rot/s, the sound became diffuse and could no longer be localized. Unfortunately the author provides only a brief sketch of the data and methods used: specifically, the number of participants and data analyses techniques are not reported.

1.3. Persistence effect

In a related set of studies, Blauert investigated the upper limit at which the auditory system can update the spatial location of a sound [17], [18], [19]. He employed the terms “persistence” or “inertia” to refer to the fact that the perceived location of an auditory event can only change with limited rapidity.

In the first study [17], he used a set of stimuli: tones (250, 1,000 and 4,000 Hz), a 15 ms pink noise pulse, and a 0.5 ms pressure impulse. Four loudspeakers were positioned at 0°, 90°, 180° and 270° azimuth. Stimuli were switched at different rates along either the left-right or front-back axis. In case of left-right alternation, thresholds at which observer could not hear individual sounds were around 6.7 Hz (free-field presentation). In case of front-back alternation, the threshold decreased and was around 4.3 Hz. The thresholds were essentially the same across the different stimuli.

In his second study [18], sounds were presented over headphones in order to isolate the main binaural localization mechanisms of interaural time (ITD) and level (ILD) differences. On average, the threshold was around 172.5 ms (± 52 ms), that is, $\sim$5.8 Hz. However, the ILD mechanism was more “sluggish” than the ITD. This is consistent with the idea that in binaural processing ILDs are first converted to ITDs (*e.g.* [20]).

1.4. Goals of the present study

The present study was designed to find the threshold at which the auditory system is no longer able to resolve rotational motion. In the first experiment, we used a procedure similar to Aschoff [16] and Blauert [17] by gradually increasing or decreasing velocity. Listeners were asked to indicate the moment at which they stopped or began hearing the sound rotating around them. In the second experiment we employed a method of constant stimuli with a 2-alternative forced choice: participants were presented with 3 s long stimuli at a constant velocity, and asked to indicate whether the sounds were rotating or not.

In both experiment we used a range of different stimuli in order to quantify the effect of the spectral content on thresholds of the moving sound source. Thus, stimuli consisted of harmonic sounds, broadband noises at different centre frequencies and white noise.

2. APPARATUS

2.1. Audiometric test chamber

Testing took place in the Immersive Presence Lab of the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT) in Montreal. In an acoustically isolated room (floated construction) with internal dimensions [6 x 7.8 x 3.2 m] and a reverberation time of 0.16 s, 12 speakers were mounted on a semi spherical structure with a radius of 2.5 m and arranged in a circle at the level of the listeners’ ears [Figure 1].

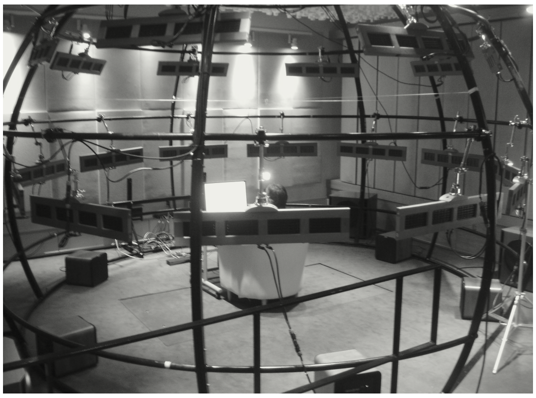

Figure 1: *Immersive Presence Lab - Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT). The participant was placed such as his/her head was in the centre of the sphere. The 12 speakers were positioned at the ear level.*

2.2. Spatialization method

A MAX/MSP patch was developed with Max 5 software to control the starting point and direction (clockwise or counter clockwise) of the motion as well as the velocity and duration of the stimuli. We used Vector Base Amplitude Panning (`http://www.acoustics.hut.fi/software/vbap/MAX_MSP/`) developed by Pulkki to position virtual sound sources between individual speakers [21].

2.3. Audio equipment

Stimuli were played on a Macintosh Mac Pro using an RME HDSPe MADI audio interface connected to a Trinov Optimizer, compensating for loudness and frequency responses of the speakers. A Sony SIU-100 with DMBK-R102 analog out cards fed Flying Mole Cascade power amplifiers (PM162d). Speakers used were Level 9 Sound Designs planar magnetic transducers (PFT 150-50-3-AA) with a frequency response between 200 Hz and 20 kHz (± 3 dB) after compensation.

2.4. General procedure

Participants received a standard hearing test administered using an Apogee Duet FireWire interface connected to Sennheiser HD 280 headphones, calibrated with a analyzer (Bruel & Kjaer Type 2250) and a 0.5 inch prepolarized microphone [6 Hz to 20 kHz] (Bruel & Kjaer Type 4192).

During the experimental session, participants were comfortably seated in the centre of the sphere with dimmed lights. They were instructed not to move during the experiment. Answers were collected with a MAX/MSP graphical interface.

3. EXPERIMENT 1

3.1. Methods

3.1.1. Subjects

Twelve subjects ranging in age from 22-39, participated in this experiment. Eleven of them had normal hearing. One had a partial deficiency at high frequencies (*i.e.* above 8 kHz) and was excluded from the analysis. Participants were music students or researchers in spatial audio.

3.1.2. Stimuli

A total of 12 stimuli was created using noise, broadband noise, and harmonic sounds at a sampling frequency of 44,100 Hz. Pure tones were not used since a pilot study revealed that participants could hardly localize them and were unable to perceive a rotation. Two types of white noise stimuli were used: one using VBAP (denoted “continuous” noise) and one without panning (denoted “stepped” noise) for comparison with Aschoff’s experiment. There were 5 broadband noise stimuli with centre frequencies, 330 Hz (which corresponds to the musical note E3), 440 Hz (A3), 880 Hz (A4), 1,318 Hz (E5), and 1,760 Hz (A6). Five harmonic sounds were generated with the real time additive synthesizer Ssynth, using time-streched clarinet sounds played fortissimo [22]: fundamental frequencies were identical to the center frequencies of the broadband noises.

Stimuli were subjectively matched in loudness by the first author by adjusting the level of each stimulus with respect to the white noise (67.4 dB SPL). The sound level of each signal was measured with the hand-held analyzer (Bruel & Kjaer Type 2250) used with a 0.5 inch prepolarized free-field microphone [6 Hz to 20 kHz] (Bruel & Kjaer Type 4189). The analyzer was positioned at the center of the circle and at the level of loudspeakers. Intensities were measured with stimuli rotating for 5 s at a velocity of 5 revolutions per second. Intensities ranged between 60.3 and 66.5 dB SPL (mean 63.66), and between 63.2 and 68.4 dB SPL (mean 66.26), for broadband noises and harmonics, respectively.

3.1.3. Procedure

The experiment was divided into two sessions, with a short break in between. In the first session, the rotation velocity increased gradually from 0.5 to 5 rot/s in a 20 s interval. Velocity changes occurred after each complete circle. Participants were asked to indicate when the stimulus ceased to be perceived as rotating along a circular trajectory around them. The second session was similar except that the rotation velocity gradually decreased from 5 and 0.5 rot/s in a 20 s interval. The task now was to indicate the point at which the sound started to be perceived as rotating along a circular trajectory.

Each session consisted of two experimental series, one for the noises and one for the harmonic sounds. The order of the series was counterbalanced across participants. Thus half the participants did the noises series first and the other half did the harmonic sounds series first.

Each stimulus was presented 8 times: 4 times rotating clockwise and 4 times counter clockwise, for total of 96 trials per session. For each series, the order of presentation and the starting point (azimuth) were randomized across trials. Participants were not allowed to replay the stimulus. The entire experiment lasted about 1 hour.

3.2. Results

For each stimulus, we averaged the thresholds across the participants, the four replications and the two directions of rotation. The pooling across direction was justified because a preliminary ANOVA showed no significant effect ($F < 1$). The mean results (plus the standard error of the mean [SEM]) shown in Figure 2 allow for several observations.

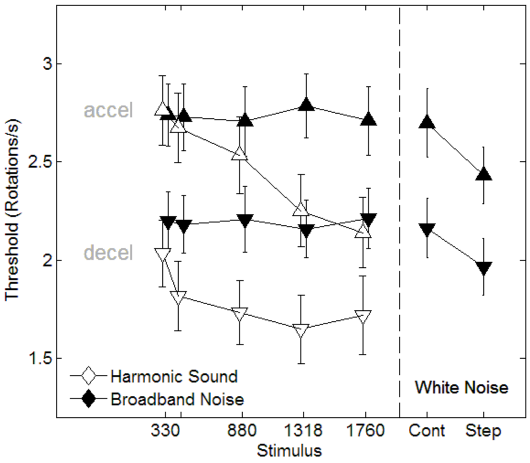

Figure 2: *Mean thresholds, in rot/s, from Experiment 1. On the left hand part of the figure the thresholds are plotted as a function of the center or fundamental frequency (in Hz) of the stimulus: series with open markers are for the harmonic sounds and the filled ones for the broadband noises. On the right hand side are the thresholds for the continuous and stepped white noises. Marker shape indicates whether the series belongs to accelerating (△) or decelerating (▽) stimuli. Error bars represent the standard error of the mean.*

First, the curves for the broadband noise stimuli are virtually flat, meaning that the thresholds are not dependent on the centre frequency. Moreover, the thresholds are virtually identical to those of the (continuous) broadband noise stimulus. In contrast, the thresholds for the harmonic stimuli show a near monotonic decrease as the centre frequency increases. Second, the thresholds for the harmonic and broadband noise stimuli start off at the same value for the very lowest centre frequency (330 Hz). Third, the thresholds for the stepped noise are lower than those for continuous noise. Finally, there is a marked, uniform, shift of approximately 0.6 rot/s in threshold between accelerating and decelerating stimuli.

For the statistical analysis, the thresholds for harmonics and broadband noises were submitted to a 2 (Stimulus type: harmonic *vs.* broadband) × 2 (Velocity change: accelerating *vs.* decelerating) × 5 (Centre frequency), completely within subjects, repeated measures RM-ANOVA. Except for the interaction between Velocity change and Stimulus type all effects were significant (all p-values $< .017$), including the 2nd order interaction between all three factors. Given this highest order interaction, we simplified the analysis by running separate ANOVAs for the two stimulus types to address the effects that speak to the observations above.

For harmonic sounds, the 2 (Velocity change) × 5 (Centre frequency) RM-ANOVA showed significance for all three effects; namely Velocity change (F(1,11) = 6.85, p = .026), Centre frequency (F(4,40) = 10.65, p = .001), and their interaction (F(4,40) = 6.38, p = .004). The effect of Velocity change reflects the observation that decelerating sounds produced lower thresholds than accelerating ones. The interaction between Velocity change and Centre frequency suggests that the drop-off in threshold is larger for the accelerating stimuli than for the decelerating ones.

For broadband noises, there was no effect of Centre frequency and only Velocity change (F(1,11) = 10.52, p = .008), was significant, again confirming that decelerating sounds produced lower thresholds than accelerating ones.

As for the broadband noises, a separate 2 (Noise: continuous vs stepped) × 2 (Velocity change) RM-ANOVA confirmed that the thresholds for the stepped noise were significantly lower than for continuous noise (F(1,11) = 12.86, p = .004). Also the main effect for Velocity change was significant (F(1,11) = 17.88, p = .001), confirming that the thresholds for decelerating stimuli were lower than for accelerating ones. There was no significant interaction ($p > 0.15$).

4. EXPERIMENT 2

One striking feature in the results of Experiment 1 is the marked differences in threshold between the accelerating and decelerating stimuli. Although we defer the discussion of the possible reasons for this to the general discussion, it does pose the question which one of the two is more representative of the "true" threshold. We therefore ran another experiment using constant velocity stimuli and a 2 interval forced-choice (2IFC) paradigm.

4.1. Methods

4.1.1. Subjects

Fourteen subjects with normal hearing, aged 19-34, participated in this experiment. Ten of them also took part in the first experiment. All were musicians and/or researchers in audio laboratories.

4.1.2. Stimuli

In this experiment only 5 stimuli were used: the continuous and stepped noises, and 3 harmonic sounds with fundamental frequencies, 330 Hz (E3), 880 Hz (A4), and 1,760 Hz (A6) since all broadband noises yielded similar to the continuous white noise. All stimuli were presented for 3 s.

4.1.3. Procedure

The experiment was divided into two sessions with a break in between. One session used the two noise stimuli and the other the three harmonic sounds. The sessions were presented in counterbalanced order across participants. The order of presentation was randomized within each session.

A single interval, two alternative forced-choice task was employed. On each trial, the participant was asked to judge if the sound was rotating around him/her (*i.e.* that the trajectory of the sound was a continuous circle), or not (*i.e.* any other trajectory or lack of motion). Participants could repeat the stimuli as many times as needed. To enter their response, they clicked on the corresponding button of the graphical interface.

Stimulus	Velocities									
HS 330 Hz	1	1.4	1.8	2	2.2	2.4	2.6	2.8	3.2	3.6
HS 880 Hz	0.6	1	1.4	1.6	1.8	2	2.2	2.4	2.8	3.2
HS 1,760 Hz	0.4	0.8	1.2	1.4	1.6	1.8	2	2.2	2.6	3
WN continuous	1	1.4	1.8	2	2.2	2.4	2.6	2.8	3.2	3.6
WN stepped	0.8	1.2	1.6	1.8	2	2.2	2.4	2.6	3	3.4

Table 1: *Constant velocities (in rot/s) used in Experiment 2 in function of each stimulus (HS = harmonic sounds, WN = white noise).*

For each of the 5 stimuli we chose a range of 10, constant, test velocities [Table 1] that were centred on the corresponding thresholds found in Experiment 1. Each stimulus was presented 8 times (4 times rotating clockwise and 4 times rotating counter clockwise) for total of 160 trials (noise series) and 240 trials (harmonic series). For each trial, the starting position of the stimulus was randomized. The entire experiment lasted less than one hour.

4.2. results

Because of a technical problem, the data set from one subject was incomplete, and was therefore not included in the analysis. For each participant, and for each stimulus, we calculated the proportion of times that the stimulus was judged to be rotating. To obtain psychometric functions, these data were fitted with cumulative Gaussians free to vary in position and slope using the software package psignifit (see `http://bootstrap-software.org/psignifit/` [23]). An example from one participant is shown in Figure 3.

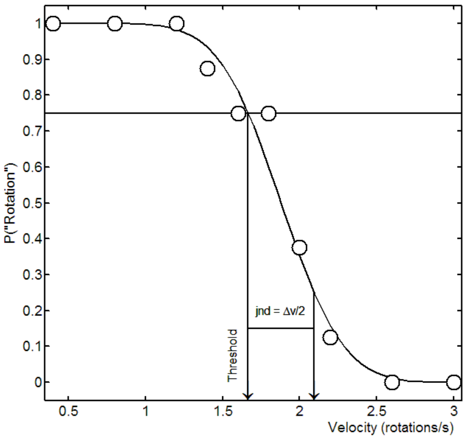

Figure 3: *Example of individual psychometric function from Experiment 2. The ordinate gives the proportion of trials in which the stimulus was perceived to be rotating and the abscissa the stimulus velocity (in rot/s). The markers are the observed proportions and the solid line is the obtained fits (see text). As per convention, thresholds represent the velocity at which people hear a sound as rotating in 75% of the cases (horizontal line). The slope (difference between the velocities at 25 and 75% over 2) of the function was taken as a measure of discrimination sensitivity (i.e., the "Just Noticeable Difference", or JND).*

The mean thresholds and JNDs are plotted in the left and right panels of Figure 4, respectively. The thresholds fall within the range of values obtained in Experiment 1. A repeated measures ANOVA with one factor revealed a significant effect of fundamental frequency for harmonic sounds (F(2,22) = 27.29, $p < .001$). Separate (Bonferroni corrected) t-test showed that all thresholds differed from each other, 330 Hz *vs.* 880 Hz (t(12) = 3.50, p = .012), 88 Hz *vs* 1,760 Hz (t(11) = 4.14, p = .005), and 330 Hz *vs.* 1,760 Hz, (t(11) = 7.40, $p < .0001$). An ANOVA showed a significant difference in thresholds for continuous and stepped noise (F(1,12) = 28.15, $p < .001$), with the latter producing lower thresholds. A single repeated measures ANOVA on the JNDs for all five stimuli did not reveal any significant differences ($F < 1$).

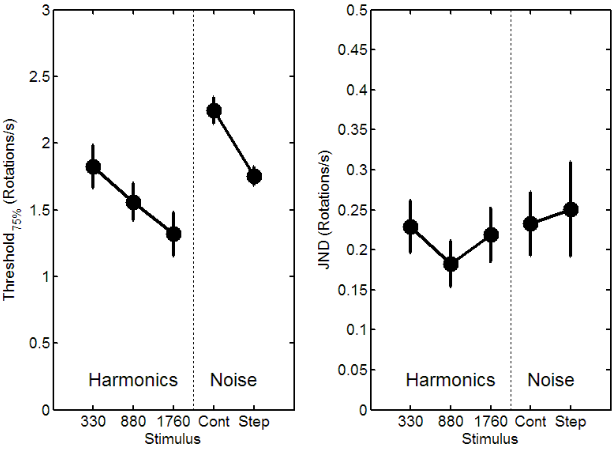

Figure 4: *Main results from Experiment 2. On the left panel are shown the thresholds plotted as a function of fundamental frequency (in Hz) for the three harmonic sound stimuli (left hand part) or type of noise (right hand part). The right panel shows the corresponding JND values. Error bars represent the standard error of the mean.*

5. GENERAL DISCUSSION

We investigated the upper limits of the auditory system for resolving smooth continuous motion. At a certain speed, people are unable to discern a continuously circular motion, and the sound starts to alternate between left and right sides. We determined these velocity thresholds for different kinds of signals (white noise, broadband noises and harmonic sounds).

In the first experiment, velocity was gradually increased or decreased. Participants were asked to indicate the instant they stopped or started to hear the sound as rotating around them, respectively. This experiment helped us to target the velocity range for which we became unable to discern a rotational motion. The thresholds ranged between 1.95-2.80 rot/s for noises and 1.65-2.75 rot/s for harmonic sounds. But this depended on whether the sound was accelerating or decelerating.

Thus thresholds are considerably higher in the case of an accelerating sounds (2.70 and 2.45 rot/s for continuous and stepped noises respectively, a range between 2.15-2.75 rot/s for harmonic sounds) as opposed to the decelerating sounds (2.15 and 1.95 rot/s for continuous and stepped noise, a range between 1.65-2.05 rot/s for harmonic sounds). Part of this shift could be attributed to the procedure used to collect their answers. Since the stimuli are changing in velocity, by the time the threshold is reached and the participants enter their response the logged speed will have changed in the direction observed. Another contributing factor could be that in the case of the decelerating stimulus the listeners were waiting sufficiently to get a clear impression of the sound trajectory. That is, they waited until they could also resolve the direction of the motion, which presumably required some additional time. Conversely, in the case of acceleration, listener continued to perceive the rotation at higher velocities. Finally, there could also be some hysteresis in the perceptual system, with the percept lagging behind the physical stimulus.

Aschoff's results [16] reported a difference in thresholds between accelerating and decelerating noise. This difference was around 0.6 rot/s, similar to the one observed here. However, the difference was in the opposite direction, with namely higher thresholds when velocity was gradually decreasing. We cannot explain this difference. On the other hand, the results reported by Aschoff seem to be based on a single participant.

Broadband noises, irrespective of centre frequency, gave thresholds similar to the one found for the continuous white noise (2.70 and 2.15 rot/s). The use of broadband stimuli might not have given us the sensitivity to observe an effect of center frequency, and further studies using narrow-band noises are warranted to address this question.

Fundamental frequencies did have an impact on the threshold in case of harmonic sounds: threshold decreased when pitch became higher. This could be explained by the fact that spectrum is impoverished in case of high pitches so it became more difficult to correctly perceive the direction of the sound.

The second experiment used stimuli with constant velocities in order to deal with the issues raised by the first experiment. The results are in close agreement with those of Experiment 1. We observed a significant effect of fundamental frequency for the harmonic stimuli, and a significant difference between continuous and stepped noise. In case of harmonic sounds and stepped white noise, thresholds were a little lower to those found in the decelerating session of Experiment 1. But in case of the continuous white noise, threshold is similar (around 2.2 rot/s).

The finding of a significant decrease in threshold as a function of fundamental frequency increases is perhaps puzzling in light of Blauert's finding of a lack of such an effect [17], [18]. However, there are major differences between the studies. Indeed, Blauert used pure tones whereas we used harmonic sounds and noises. Moreover, Blauert was not necessarily interested in the threshold at which people still perceived a rotating stimulus, but more in the point at which people could no longer reliably update the spatial position of a sound per second. To do so, he presented sounds alternating between two positions (left/right or front/rear) but not rotating as in the case of our experiments. It would therefore be interesting to repeat Blauert's experiment with our stimuli. An interesting possible outcome would be to no longer find the dependency on fundamental frequency.

In conclusion, velocity thresholds for resolving a circular motion depend on spectral content. On the basis of our findings, we speculate that velocity thresholds increase as a function of spectral richness and, in the case of harmonic sounds, decrease as a function of fundamental frequency. The observed upper limit, where it becomes difficult to perceive a rotation collapsing for all types of sounds is around 3 rot/s. As Stockhausen conferred to Jonathan Cott in 1961 [24]:

> "If revolutions of sound in space go beyond a certain barrier of revolutions per second, they become something else."

This "something else" should open a vast psychological research area of interest to composers developing sound spatialization figures and more generally for the design of virtual auditory scenes. Further research will investigate whether similar thresholds are found in reverberant concert halls and look into quantifying the relative contribution of spectral cues and frequencies variation on the perceived trajectory of the moving sounds.

Acknowledgement

This research was supported by FQRSC (113581) grant of Pr. Catherine Guastavino. The authors would like to thank Julien Boissinot and Vincent Verfaille for their assistance.

6. REFERENCES

[1] M. Trochimczyk, "From circles to nets: On the signification of spatial sound imagery in new music," *Computer Music Journal*, vol. 25, no. 4, pp. 39–56, Winter 2001.

[2] P. Manning, *Electronic and Computer Music*, Oxford University Press, Oxford (England), New York (USA), 1985, 2004 (fourth edition rev. and expanded).

[3] L.L. Beranek, *Music, Acoustics and Architecture*, Wiley, New-York (USA), 1962.

[4] M.R. Schroeder, D. Gottlob and K.F. Siebrasse, "Comparative study of European concert halls," *J. Acoust. Soc. Am.*, vol. 56, no. 4, pp. 1195–1201, Oct. 1974.

[5] C. Guastavino and B. Katz, "Perceptual evaluation of multi-dimensional spatial audio reproduction," *J. Acoust. Soc. Am.*, vol. 116, no. 2, pp. 1105–1115, Aug. 2004.

[6] C. Guastavino, B. Katz, J.D. Polack, D. Levitin and D. Dubois, "Ecological validity of soundscape reproduction," *Acta Acustica united with Acustica*, vol. 91, no. 2, pp. 333-341, March-April 2005.

[7] C. Guastavino, V. Larcher, G. Catusseau and P. Boussard, "Spatial audio quality evaluation: Comparing transaural, ambisonics and stereo," Invited paper at the *13 th Int. Conf. on Auditory Display*, Montreal (Canada), June 2007.

[8] K. Stockhausen, "Musik im Räum," *Die Reihe*, no. 5, pp. 67-82, 1959.

[9] R. Maconie, *Other Planets: the Music of Karlheinz Stockhausen*, Scarecrow Press, Lanham (USA), 2005.

[10] J. Purce, "The Spiral in the Music of Karlheinz Stockhausen," *Main Currents in modern thought - The Journal of the Center for Integrative Education*, vol. 30, no. 1, pp. 18-27, Sep.-Oct. 1973.

[11] É. Daubresse, "Le projet informatique, de l'élaboration à la collaboration," in P. Szendy ed., *Emmanuel Nunes*, L'Harmattan / Ircam Centre Georges Pompidou, Paris (France), pp. 125–149, 1998.

[12] E. Nunes, "Lemmes," in P. Szendy ed., *Emmanuel Nunes*, L'Harmattan / Ircam Centre Georges Pompidou, Paris (France), pp. 153–180, 1998.

[13] S. Carlile and V. Best, "Discrimination of sound source velocity in human listeners," *J. Acoust. Soc. Am.*, vol. 111, no. 2, pp. 1026–1035, Feb. 2002.

[14] D.R. Perrott and J. Tucker, "Minimum Audible Movement Angle as a function of signal frequency and the velocity of the source," *J. Acoust. Soc. Am.*, vol. 83, no. 4, pp. 1522–1527, Apr. 1988.

[15] M.F. Neelon and R.L. Jenison, "The effect of trajectory on the auditory motion aftereffect," Hearing Research, vol. 180, no. 1-2, pp. 57-66, Jun. 2003.

[16] V. Aschoff, "Über das räumliche Hören," Arbeitsgemeinshaft für Forschung des Landes Nordrhein-Westfalen, Heft 138, pp. 07–38, 1962.

[17] J. Blauert, "Ein Beitrag zur Trägheit des Richtungshörens in de Horizontalebene," *Acustica*, vol. 20, pp. 200–206, 1968.

[18] J. Blauert, "Zur Trägheit des Richtungshörens bei Laufzeit und Intensitätsstereophonie," *Acustica*, vol. 23, pp. 287-293, 1970.

[19] J. Blauert, *Spatial hearing: the psychophysics of human sound localization*, Cambridge (USA), London (England), MIT Press, 1974, 1997 (rev. edition).

[20] E.R. Hafter, "Quantitative evaluation of a lateralization model of masking-level differences," J. Acoust. Soc. Am, vol. 50, no. 4, pp. 1116-1122, Oct. 1971.

[21] V. Pulkki, "Virtual sound source positioning using vector base amplitude panning," *J. Audio Eng. Soc.*, vol. 45, no. 6, pp. 456-466, June 1997.

[22] V. Verfaille, J. Boissinot, P. Depalle and M.M. Wanderley, "Ssynth: a Real Time Additive Synthesizer With Flexible," in *Proc. of the Int. Computer Music Conf.*, New Orleans (USA), Nov. 2006.

[23] F.A. Wichmann and N.J. Hill, "The psychometric function: I. Fitting, sampling, and goodness of fit," *Percept. Psychophys.*, vol. 63, no. 8, pp. 1293-1313, Nov. 2001.

[24] J. Cott, *Stockhausen: Conversations with the Composer*, London (England), Robson Books, 1961.