DOES REVERBERATION AFFECT UPPER LIMITS FOR AUDITORY MOTION PERCEPTION?

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ABSTRACT

We report three experiments measuring the upper limits, defined as auditory velocity thresholds beyond which listeners are no longer able to perceptually resolve a smooth circular trajectory in various reverberate conditions. These thresholds were measured for white noise, band-limited white noise and band-limited white noise mixed with a pure tone, in different reverberation conditions: acoustically dry room, two simulated source-image-based reverberations and natural reverberation with different configurations of loudspeaker arrays. Experiment 1 took place in a dry room and thresholds were measured with and without a reverberation simulation of an actual reverberant room. In Experiment 2, various simulated reverberation parameters were tested in the same dry room, and two different loudspeaker configurations were tested in a reverberant room. Experiment 3 investigated the effect of audio source type in simulated reverberation condition and for high velocities. No significant effects were observed among reverberation conditions, suggesting that the upper limit is robust against reverberation.

1. INTRODUCTION

One of the major challenges to the auditory system in everyday listening is to track moving sound sources. However, our understanding of dynamic sound localization lags behind that compared for static sound localization. Furthermore, most researches on sound localization has been conducted in anechoic (or dry) environments. However, in almost all natural environments spatial hearing is challenged by the presence of reverberation, which leads to fluctuations in interaural time differences [1]. While reverberation has been shown to have a detrimental effect on static sound localization [2, 3, 4], its effect on auditory motion has received scant attention. To our knowledge, there are only two studies on the topic both using sounds rotating in the horizontal plane around the listener at high velocities. The first exploration [5] conducted by Aschoff in 1962 reported the listeners' impression when presented with white noise revolving on a 18-speaker circular array inside an anechoic room. Above a certain velocity, listeners no longer perceive a rotation but rather a left-right alternation. The second study by Féron et al. [6] in 2010 replicated and extended this same experiment by measuring the upper limit for circular auditory motion, defined as the velocity threshold above which the auditory system is no longer able to resolve circular motion. The upper limit was measured in a reverberant concert hall and an acoustically treated room. Féron et al. [6] observed higher upper limits in the reverberant room than in the dry room suggesting that reverberation could have a beneficial effect on auditory motion perception as reflections could reinforce the impression of circular motion, thus enabling listeners to track sounds moving at higher velocities. However they also note that in the reverberant room, participants were seated slightly off-center which could have provided additional cues for velocity discrimination.

We report a series of experiments further investigating the effect of reverberation on the upper limit. In Experiment 1, we compare the thresholds obtained in an acoustically treated lab in a dry condition and with simulated reverberation (primary early reflections). In Experiment 2, we extend the reverberation simulation to include secondary reflections and we contrast the wall frequency-dependent reflection coefficients to maximize differences between source images. In addition, in Experiment 2, we also measure the upper limit in the same large reverberant room as Féron et al. [6] but with participants seating in the center of the array (as opposed to off-center), thus providing a direct comparison. Experiment 1-2 used white noise stimuli. Experiment 3 extends the investigation by comparing upper limits obtained with white noise and white noise with a pure tone in the dry and simulated reverberation conditions at a wider range of velocities.

2. EXPERIMENT 1 - COMPARISON OF DRY AND SIMULATED REVERBERATION CONDITIONS

The aim of Exp. 1 is to compare upper limits in two different reverberation conditions, namely dry and simulated reverberation. Féron et al. [6] presented sounds rotating around the listening position at different pre-defined velocities and asked participants to judge if the sounds were rotating (i.e., the apparent trajectory of

Figure 1: Experimental set-up in the dry room (Spatial Audio Lab) at CIRMMT used for Experiments 1, 2 and 3.

the sound was a continuous circle), or not (i.e., any other apparent trajectory or lack of motion). Responses to this task may be based not only on sensitivity to motion, but also on participant's criteria for what constitutes motion. We thus decided to use a criterion-free measure by varying the direction of motion randomly across trials and having participants respond whether the sound was moving clockwise (CW) or counterclockwise (CCW). In addition we used an adaptive procedure to allow for a more precise estimation of the threshold instead of relying on a pre-defined range of velocities.

2.1. Apparatus

The experiment was divided into two sessions of 15 minutes each corresponding to two reverberation conditions (dry simulated reverberation) presented in counterbalanced order across participants. On each trial, a moving sound source was presented over the circular array of speakers surrounding the participant. The direction of motion (CW or CCW) and the number of rotations (2-6) was randomized across trials. The task was a 2-alternative forced-choice; participants used a remote control to indicate whether the sound was moving clockwise (CW) or counterclockwise (CWW). Each session uses a 4 intertwined 1-up, 2-down staircases (2 CW, 2 CCW) with an initial velocity of 1.3 rot.s^{-1} and an initial step size of 0.1 rot.s^{-1}, halved after the first and second reversals. We stopped after 12 reversals or 60 trials and averaged over the last 5 reversals to determine the threshold per staircase, then averaged over all 4 staircases to determine the threshold per participant in a given condition.

Participants were tested individually in the hemi-anechoic Spatial Audio Lab (referred to as *dry room* throughout the paper) of the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT) in Montreal (Canada). The dry room is 5.40 m (W) $\times$ 6.40 m (L) $\times$ 3.60 m (H) with a measured Reverberation Time (RT60) and Early Decay Time of 0.09 s and 0.28 s respectively. The circular array consisted of 16 Genelec 8040A (Genelec, Iisalmi, Finland, frequency range 48 - 20,000 Hz) regularly spaced in the horizontal plane spaced along a circle with a diameter of 3.7 m. The experimental set-up is pictured in Fig. 1.

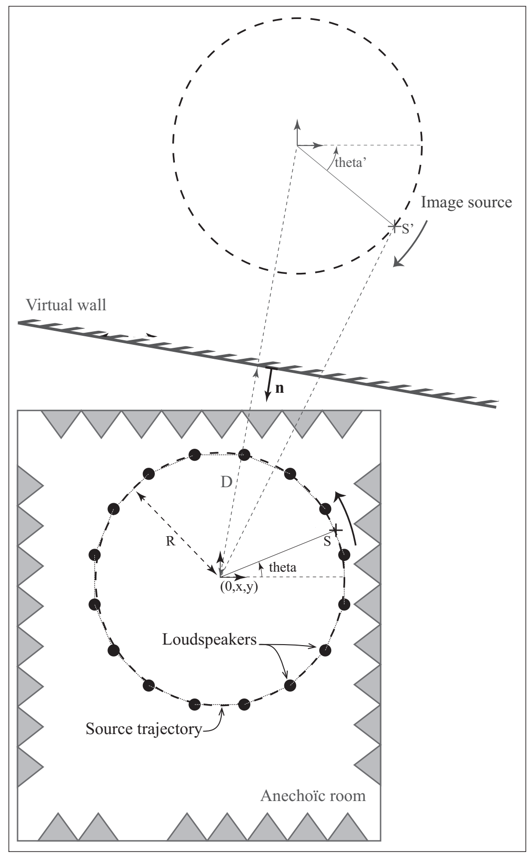

Figure 2: Experimental set-up, sound source trajectory and a virtual source resulting from the reflection of a virtual wall

WALL A (x,y) [m]	$(2.63, 0)$
WALL B (x,y) [m]	$(0, 3.66)$
WALL C (x,y) [m]	$(-2.63, 0)$
WALL D (x,y) [m]	$(0, -3.66)$
SABINE COEFFICIENT	0.272

Table 1: Geometrical and material parameters for the reverberation simulation in Experiment 1.

For comparison purposes , the sound used to generate the stimuli was a full-range white noise (WN) as in previous studies ([5, 6]). On each trial, the white noise was generated in real-time by the Max/MSP function NOISE.

2.2. Participants

Twelve subjects, aged 28 to 36 years, participated to the experiment. They were musicians and/or researchers from audio laboratories with self-reported normal hearing.

2.3. Simulation

Static soundfield synthesis has been extensively studied over the last decades and allows for accurate and robust simulation results [7]. However, dynamic spatial rendering has received scant attention in the literature. Franck [8] and Ahrens and Spors [9] have studied the dynamic artefacts for the case of Wave Field Synthesis whereas Pulkki [10]'s Vector-Based Amplitude Panning (VPAB) allows for the rendering of virtual auditory scenes in real-time

An original virtual source spatial rendering Max/MSP object using VBAP was implemented for audio rate computation in order to guarantee smooth angle variations at very high velocities. The object was programmed in JAVA (with the MXJ˜ functionality) by the authors to sample the angle parameter at the audio sample rate. In order to test the hypothesis that reflections reinforce auditory motion perception [6], we only model the primary reflections upon four virtual walls and omit specular reflections. The experimental set-up, the sound source trajectory and a exemplified mirrored image are schematized in Fig. 2. The configuration of the virtual walls has been set to match the acoustics and the geometric ratios of the reverberant environment used by Féron et al. [6] in the Multi-Media Room (called *reverberant room* throughout this paper). It is a large empty room with a wooden floor and curtains covering the walls. They used a circular array with a radius of 6 m and the room was 17.07 m $\times$ 23.77 m $\times$ 16.50 m with a reverberation time of 1.82 s. To keep the same geometrical ratio (radius of array to distance to the walls), we modeled the virtual dimensions shown in Table 1. Moreover, a uniform frequency band reflection coefficient has been selected to match the RT60 of the reverberant room, on the basis of the Sabine Formula. A global Sabine absorption coefficient equal to 0.272 was deduced from the RT and from the room dimensions. Virtual source gains resulting from the four primary reflections to the virtual walls were uniformly set to respect the absorption coefficient. Also, the stimuli were presented in all conditions to fit a Leq Level at 67 dB, measured with a B& K sound level meter at the listening position.

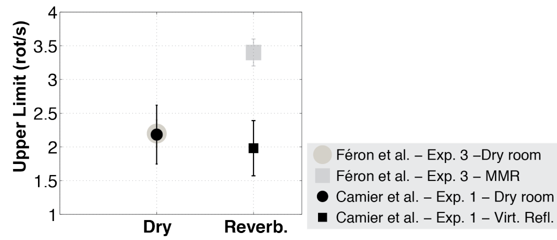

Figure 3: Thresholds for Experiment 1 in dry and virtual reflections (primary reflections only, referred as VIRT. REFL.) conditions. Previous results established by Féron et al. [6] are reported in gray, measured in dry and natural reverberation conditions.

2.4. Results

The upper limits averaged over all participants are presented in Fig. 3 along with upper limits reported in [Féron et al., Exp. 3] using the same stimulus signals (white noise). In Exp. 1, we observed an upper limit of 2.18 rot.s^{-1} in the dry condition and 1.98 rot.s^{-1} with the simulated reverberation. A paired t-test revealed no significant differences between the 2 conditions ($p > 0.10$).

While the values of our upper limits are very much in line with those of [Féron et al., Exps. 1,2] [6], we failed to observe the beneficial effect of reverberation on upper limit that they reported in the reverberation condition. The source of difference could be methodological as participants in Féron et al. [6] were slightly off-center resulting in additional motion cues such as Doppler shifts of the direct sound that could have enabled participants to track motion at higher velocities. Also, the circular array used in [Féron et al., Exp. 3] had a larger diameter. But the difference may also be attributed to our reverberation model which simulated primary early reflections only. Experiment 2 extends the reverberation simulation to model secondary reflections and maximize differences between source images by contrasting wall frequency-dependent reflection coefficients. In addition we provide a direct comparison with the set-up used in [Féron et al., Exp. 3] but with participants sitting in the center of the circular array. We further add a control condition in the natural reverberation environment with a smaller circular array identical to the one used in the dry condition.

3. EXPERIMENT 2 - COMPARISON OF DRY, REFINED SIMULATED REVERBERATION AND NATURAL REVERBERANT CONDITIONS

3.1. Apparatus

Experiment 2 consisted of 4 sessions, 2 in the previously described dry room and 2 others in the reverberant room used by Féron et al. [6].

In the dry room using the same circular array as in Exp. 1, the dry condition was identical to the one in Exp. 1. The simulation of reverberation uses different spectral absorption coefficients based on wall manufacturer references [11, 12] on the 4 different walls and introduces asymetry in the virtual walls geometry as summarized in Table 2.

In the reverberation conditions, two concentric circular loud-

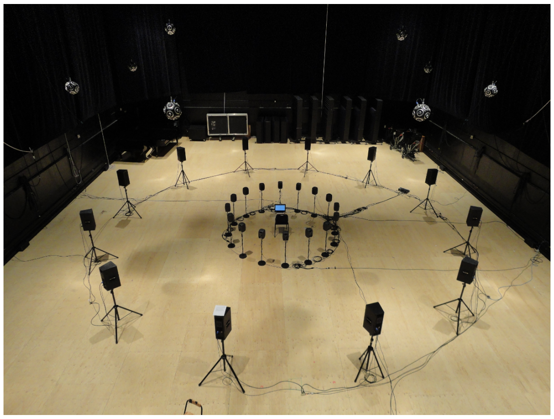

Figure 4: Set-up in the Music Multimedia Room at CIRMMT where took place Experiment 3.

speaker arrays were in the reverberant room described above. The large circular array was the one used in [Féron et al., Exp. 3] with 12 Meyer Sound VariO UPJ-1P loudspeakers regularly spaced on a 6-m radius circle. The smaller circular array was the same as the one used in Exp. 1 and in the dry room of Exp. 2. The stimuli were presented in all conditions to fit a Leq Level at 67 dB, measured with a B& K sound level meter at the listening position.

3.2. Procedure and participants

Experiment 2 consisted of 4 sessions of 10 minutes each, corresponding to the dry condition (in dry room), the simulated reverberation (in the dry room) and 2 loudspeaker arrays in the natural reverberation condition. Each session uses the same adaptive procedure and task as in Exp.1. The order of presentation of the 4 different sessions was counterbalanced across participants.

A new set of fifteen McGill students, aged 19 to 50 years, with self-reported normal hearing participated in Experiment 2.

3.3. Simulation

We hypothesize that a potential beneficial effect of reverberation on upper limits could be due to Doppler pitch shifts in the mirror images. To test this hypothesis, we decided to use a band-pass noise instead of white noise in Exp. 2 based on measured Frequency Response Functions (FRFs) in the dry room.

By minimizing differences in loudspeaker responses and acoustical paths, we ensure that we are evaluating the effect of the reverberation of the virtual asymmetric wall geometry. Two 40 dB/octave high-pass and low-pass filters were used to filter the white noise generated by the Max/MSP program with cutoff frequencies of 100 Hz and 10 kHz respectively. These cutoff frequencies were selected to leave frequency ranges exhibit the largest differences among speaker FRFs.

3.4. Results

The upper limits averaged over all participants are presented in Fig. 5 for the dry, simulated reverberation, natural reverberation

WALL	Location [m]	Filter	Cutoff Freq. [Hz]	Gain [dB]	Q
A	$(2, 0)$	High-pass	1500	0	0.7
B	$(0, 2)$	Band-pass	1000	0	1.2
C	$(-2, 0)$	Low-pass	500	0	0.7
D	$(0, -8)$	Low-pass	800	0	0.7

Table 2: Geometrical and filter parameters of the reverberation simulation in Experiment 2.

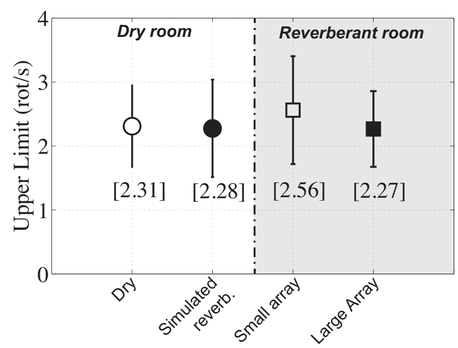

Figure 5: Thresholds resulting from Experiment 2 relative to no reflection simulation and reverberation simulation conditions in the dry room, DRY and SIMULATED REVERB. respectively and relative to the corresponding to the small diameter loudspeaker array configuration and the large diameter loudspeaker array configuration taking place in the reverbrant room, SMALL ARRAY and LARGE ARRAY, respectively.

with the small array and natural reverberation with the large array conditions. They are respectively equal to 2.31, 2.28, 2.58 and 2.27 rot.s^{-1}.

A one-way ANOVA revealed no significant differences across conditions (F(3,59)=0.73, p $>$ 0.54), which does not provide support for our hypothesis. A follow-up study was piloted with 3 participants using 2 different signals: white noise and white noise with pure tone. Indeed, one potential explanation is that the Doppler effect additional cues may not be perceptible on wide band-pass noises. The result of the pilot study seemed to support this idea. Furthermore, the Doppler cues may only be beneficial at very high velocities above the upper limit, in which case the effect would not be observable using ascending adaptive staircases (restricted to velocities below the upper limit). Experiment 3 was designed to test this new hypothesis with the addition of a pure tone on a wider range of velocities using a discrimination task.

4. EXPERIMENT 3 - COMPARISON OF TWO DIFFERENT AUDIO SOURCE TYPES

The same apparatus as in Experiment 1 was used in Experiment 3.

4.1. Procedure

To test the validity of this hypothesis for high velocities, we chose to measure motion detection with a constant comparison ABX discrimination task. On each trial, participants were presented with 3 sounds labeled A, B and X and asked to indicate X was identical to A or B. The only difference between A and B was the direction of the rotation (CW or CCW).

We used the same reverberation simulation as in Exp.2 (sec. 3) (dry room, simulated reverberation). We used two audio source types to generate the stimuli. One was the filtered white noise used in Exp.2, the second one was the same signal with the addition of a sinusoidal tone at 1000 Hz and 10 dB above large band noise level. The number of rotations was randomized across trials between 4 and 6.

Seven discrete velocities (1.5; 2.0; 2.53; 3.05; 3.57; 4.08; 4.60 rot.s^{-1}) were selected to cover a wider range of velocity values extending well-above the thresholds measured in Exp. 1 to allow for a potential increase in performance if Doppler cues become more noticeable at very high velocities. The experiment was divided into 2 sessions of 12 to 15 minutes. The order of presentation of the 168 trials was randomized across sessions to avoid any order effect.

4.2. Participants

Six subjects, aged 22 to 35 years, participated in Experiment 3. They were musicians, researchers in audio laboratories or audiophiles with self reported normal hearing.

4.3. Results

The percentage of correct answers collapsing over all participants for each signal condition (*Noise* and *Noise + Tone*) is presented in Fig. 6 as a function of source velocity and for each signal condition. Also reported is the chance level around 50% correct in which answers are not considered random according to the binomial test. All the observations are above chance level even for

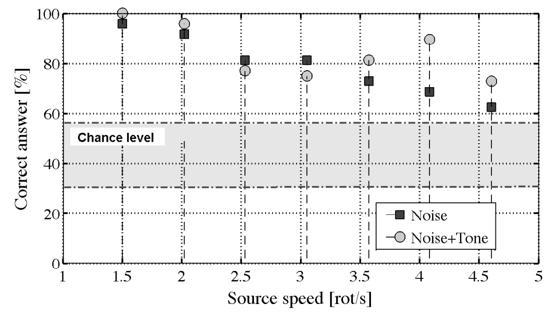

Figure 6: Percentage of correct answers collapsing over all participants (N=6) in Experiment 3.

the white noise. This suggests that participants were able to discriminate between sounds rotating in different directions at velocities well-above the upper limits measured in Exps. 1 and 2 and in [Féron et al., Exps. 1-3] . In this ABX discrimination task, participants have to match the last sound heard to one of the 2 first sounds presented. While the sounds differ in the direction of motion, participants may be able to perform the task at hand relying on cues that are not related to direction but rather to changes in coloration. Moreover, a 7 (velocities) $\times$ 2 (audio source types) $\times$ 6 (subjects) factorial-ANOVA reveals a significant main effect of velocity (F(6,30)=4.93, p=0.0013) and a significant interaction effect *subjects* $\times$ *velocities* ((F(30,83)=2.06, p=0.0261)). No effect of audio source type was observed contrary to our hypothesis.

5. DISCUSSION

The findings of Experiments 1 and 2 converge to show that reverberation (be it simulated with modeled early reflections or natural) does not affect the upper limit. Indeed the thresholds of velocity above which participants could no longer detect the direction of motion ranged between 1.98 and 2.56 rot.s^{-1} with a standard deviation of 0.138 rot.s^{-1} across conditions. No significant differences were observed across the different reverberation conditions. In Experiment 2, we also compared upper limits obtained with 2 concentric circular arrays and found no significant differences. Together these findings indicate that the upper limit is robust to reverberation and across the different sound reproduction configurations tested when using white or large-band noises. Through pilot testing, we observed that in extreme asymetrical reverberation conditions using pure tones, one could hear subtle differences that could attributed to Doppler shifts patterns on the reverberated soundfield. Subsequently, Experiment 3 extended our investigation to two signal types: white noise and white noise with a sinusodial tone. The hypothesis was that reverberation could provide additional cues (Doppler shift patterns on the mirror images) that would only be available at very high velocities above the upper limit and more perceptible on tones. To test this hypothesis, we used a different procedure with a discrimination task on predefined velocities extending the range of velocities well-above the upper limit. In terms of audio sources, the differences between the noise and noise + tone conditions did not reach statistical significance but this could be due to the small sample size. Furthermore, participants were able to perform the ABX discrimination task above chance level even at all velocities, including the ones above the upper limit. One reason could be methodological, as this task is a recognition task as opposed to the direction detection one used in Experiments 1 and 2. Participants could rely on cues related to the comparison of soundfields between A and B introduced by the specific location of different Doppler effects on the mirror images as a function of the direction. In other words, this discrimination task might be easier than the task used in previous experiments and may not involve actual motion detection.

The upper limits observed in [Féron et al., Exp. 3] were 2.6 rot.s^{-1} for the dry condition and 3.5 rot.s^{-1} for the natural reverberation condition suggesting a beneficial effect of the reverberation for dynamic sound source localization, which could be attributed to a reinforcement of the spatial definition through mirror images also rotating around the listeners. However several differences between the dry and reverberation conditions should be noted: in addition to the acoustics (RT60 is 11 times longer in the reverberant condition), the rooms also differed in size and speakers array configuration in the reverberation condition, the loudspeakers were approximately 2.5 times further away from the listener in the reverberant condition (resulting in different direct-to-reverberation ratios) and the participants were seated slightly off-center. As proposed by Féron et al., we hypothesize that the off-center position resulted in additional cues for motion perception. Indeed, off-center circular trajectories of the mirror image could produce perceptible Doppler shifts with reflections enlarging spatial width and frequency content. We tested this hypothesis in Experiment 2 by varying independently the audio (size of the loudspeaker array) of one acoustic (reverberation) parameters while ensuring that participants sat at the very center of the loudspeaker arrays. We did not find differences across loudspeaker arrays of different sizes. In addition, contrary to Féron et al., we did not observe significant differences between the reverberant and dry conditions using the exact same room and speaker configurations, suggesting that the increased upper limit observed in Féron et al. was attributable to the off-center position of the participants rather than to a beneficial effect of reverberation.

6. CONCLUSION

In a series of experiments, we measured listeners' ability to track circular motion at high velocities in various reverberation conditions. We also compared two audio source types as well as as two loudspeaker array configurations using adaptive procedures experiments and ABX discrimination tasks to measure the velocity threshold above which listeners are no longer able to track circular trajectories.

The different reverberation conditions included a dry room, simulated reverberation (with primary and/or secondary early reflections) and with different wall reflection coefficient geometries, and a natural reverberant room (with an RT60 of 1.82 s). Audio source types involved were white noise, large band limited white noise and large band limited white noise added with a pure tone. The different loudspeaker configurations were a small 16-loudspeaker equally spaced circular array and a large 12-loudspeaker equally spaced circular array.

The main finding is that the upper limit, defined as the velocity thresholds above which participants can no longer detect the direction of circular motion is robust to variations in reverberation conditions, audio source types and loudspeaker configurations. Indeed :

1. There is no effect of the reverberation (dry, different simulations, and natural reverberation) on the upper limits for the audio source types tested (white noise, band-pass filtered white noise, white noise + tone).
2. There is no effect of loudspeaker configuration (different sizes and numbers of speakers) on the upper limit.

In terms of robustness to the task at end, the thresholds obtained in Exps. 1 and 2 by asking participants to indicate the direction of the rotation are comparable with those obtained by Féron et al. and Aschoff [5] though using different tasks, suggesting the the upper limit is also robust for different motion detection tasks. However, the ABX discrimination task used in Exp. 3 yields higher performance, suggesting that other perceptual mechanisms are at play for detecting motion direction and for discriminating soundfields produced by sounds rotating in different directions.

A recent study by Frissen et al. [13], in the same range of velocities, shows that reverberation does not affect velocity discrimination thresholds. Together these findings provide converging evidence for the robustness of auditory motion perception to reverberation. Future direction include investigating other aspects of auditory motion perception such as the perception of spatial trajectories in different reverberation conditions.

7. ACKNOWLEDGMENTS

This research was supported NSERC (RGPIN 327392-13) grant and a William Dawson award (McGill University) to C. Guastavino. The authors would like to thank Ilja Frissen, Daniel Steele, for their assistance and François-Xavier Féron for relevant discussions.

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