LOCALIZING SOUNDS REVOLVING AT VERY HIGH VELOCITIES: AN AUDITORY WAGON-WHEEL EFFECT

Noa Kemp *[1,2,3], **Ulysse Lefeuvre** †[2,3], **Cynthia Tarlao** ‡[2,3] **et Catherine Guastavino** ♦[2,3]
[1] Department of Physiology, McGill University, Montreal, QC, Canada.
[2] School of Information Studies, McGill University, Montreal, QC, Canada
[3] Centre for Interdisciplinary Research in Music Media and Technology, Montreal, QC, Canada

1 Introduction

The mechanisms involved in the localization and perception of static sound sources have been extensively studied. As for moving sound sources, studies are often restricted to low velocities, mainly due to laboratory limitations. A few studies from our team have investigated circular sound trajectories at high velocities (several rotations per second) [1] to identify the velocity threshold above which a sense of direction is no longer perceptible (around 2.5 rot/s [2,3]). Explorations at extremely high velocities well above this upper limit [4,5], show that a sense of direction might re-immerge when the number of rotations per second approaches the fundamental frequency f_0 of the sound. Furthermore, we observed in this range of velocity what can be described as an auditory wagon-wheel effect: the sound appears to move in one direction when the velocity (number of rot/s) is above f_0, and in the opposite direction when it is below f_0. We hypothesize that this effect is due to interference between the frequency of the stimuli and its velocity. When two slightly different frequencies are presented simultaneously, they create a periodic variation in amplitude or "beat" whose frequency is the difference between the two frequencies. Here the frequency at which the sound is revolving (in rot/s), a frequency in space, interferes with the frequency of the sound. We thus introduce the notion of a 'spatial beat', that has an apparent 'pseudo-direction' revolving at a 'pseudo-velocity'. Set f_v to be the velocity of the sound, that is its frequency of revolution, we have that in one second, the sound travels f_v rotations in space, that is $f_v \cdot 2\pi$. Thus in $1/f_0$ seconds, the sound travels $2\pi \cdot f_v / f_0$ around the physical space. The sound's phase also completes a full cycle, that is 2π, in that time. The difference in phase between the distance travelled by the sound in space ($2\pi \cdot f_v / f_0$) and the sound's phase (2π) is $2\pi \cdot f_v / f_0 - 2\pi = 2\pi(f_v - f_0)/f_0$. We call it the pseudo-distance, or perceived angular distance travelled by the 'spatial beat' in $1/f_0$seconds. When $f_v < f_0$, the pseudo-distance is negative, thus the 'spatial beat' could be perceived as rotating in the opposite direction as the actual one. And when $f_v > f_0$, the pseudo-distance is positive, so the 'spatial beat' could be perceived as rotating in the same direction as the actual one. This effect was first identified informally in [4,5] and used in music creation [6]. A first study [7] validated perceptually that a sense of motion re-immerges at velocities approaching f_0. However, the change of perceived direction was ambiguous for the velocities tested by [7]. Here, we test this perceived change in direction with velocities closer to f_0.

2 Method

2.1 Participants

Twenty-two subjects (7 women, 14 men, 1 non-binary; Age =[20;47], M=29.45), reporting normal hearing, participated in this experiment. Their experience in music and/or sound varied from 0 to 36 yrs (Median=5).

2.2 Apparatus and stimuli

Laboratory setting. The experiment was conducted in the Performance Research Lab (W7.7m x L9.3m x H4.95m) at the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT) in Montreal, Canada, acoustically treated laboratory. 16 loudspeakers Genelec 8050A were evenly spaced on a circle with a 3.3 m radius at ear level.
Stimuli. A complex sound was generated in MAX/MSP (Cycling '74, San Francisco, CA) with a center frequency of 200Hz and 20 harmonics. Stimuli was created by revolutions at the following eight velocities (in rot/s): 199.75, 199.80, 199.85, 199.875, 200.125, 200.15, 200.20, 200.25. Stimuli duration was randomized to be [1:1.25] pseudo rotation, which, depending on its velocity, lasted [4:8]+[1:2]s. The starting position was randomized across trials.

2.3 Procedure

The experiment lasted 1.5 hours and was divided into five sessions. Only the second to fifth sessions, lasting approximately 7 minutes each, are discussed in this paper. Using a 2AFC task, participants were asked to judge if the sound was revolving clockwise (CW) or counterclockwise (CCW) by pressing the right or left arrow keys, respectively, and the next trial launched automatically. Participants were seated with their head centered in the array asked to keep their head still and upright during the stimulus presentation. For each velocity, the stimulus was presented 24 times (12 CW and 12 CCW) from a random starting position, in randomized order within each session. In total, 192 trials were presented for each participant, divided into 48 trials per session.

* noa.kemp@mail.mcgill.ca
† u.lefeuvre@gmail.com
‡ cynthia.tarlao@mcgill.ca
♦ catherine.guastavino@mcgill.ca

However, due to a technical error, one data point per session is missing, as well as an extra data point for P2, resulting in 188 data points per participants, for a total of 4135 datapoints.

3 Results

3.1 Experimental results

We computed the proportion of times the sound was judged to rotate in the same direction as the actual direction. In Figure 1, we observe that at velocities below the fundamental frequency of the stimulus (200 Hz), the participants perceive the direction of the ‘pseudo-rotation’ that is opposite to the actual direction of the stimulus. Furthermore, for velocities above 200 rot/s, participants perceive the ‘pseudo-rotation’ in the actual direction of the stimulus. In sum, we observe a strong shift of perceived direction between velocities below and over 200 rot/s.

3.2 Data analysis

A repeated measures ANOVA was conducted to evaluate if the proportion of times that the sound was judged to rotate in the same direction as the pseudo direction differed across velocities. The assumption of sphericity was not met (Mauchly’s test $\chi^2(27) = 158.242$, p<0.001), so the results will be reported with the Huynh- Feldt correction (ε = .220). There are significant differences between the proportion of times that the sound was judged to rotate in the same direction as the pseudo direction across velocities using the Huynh-Feldt correction (F(1.539,32.326) =77.149, p<0.001) The velocity factor explains $\omega^2 = 76.9\%$ of the variance in performance. At other velocity comparisons not mentioned, the proportion of correct answers do not significantly differ.

Post-hoc tests using the Bonferroni correction revealed significant differences in perceived direction between velocities below and over the fundamental frequencies, but no significant differences among all frequencies below, nor among all frequencies above the fundamental frequency (see Table 1)

4 Conclusion and future research

Our experiment validated perceptually the auditory equivalent to the wagon-wheel effect by demonstrating that a sound spinning around the listener will be perceived to be moving in opposite directions when its velocity (in number of rotations per second) is below or above its fundamental frequency. This study contributes to the small but growing body of literature on dynamic sound localization and further offer opportunities for artistic exploration [5]. Future research is needed to extend this investigation to other stimuli to generalize the concept of spatial beats, and determine the limits and possibilities of this phenomenon.

Acknowledgments

We thank Prof. Suresh Krishna, Cédric Camier and François-Xavier Féron for their insightful comments, CIRMMT for technical assistance, and NSERC for financial support (RGPIN/06121-2019).

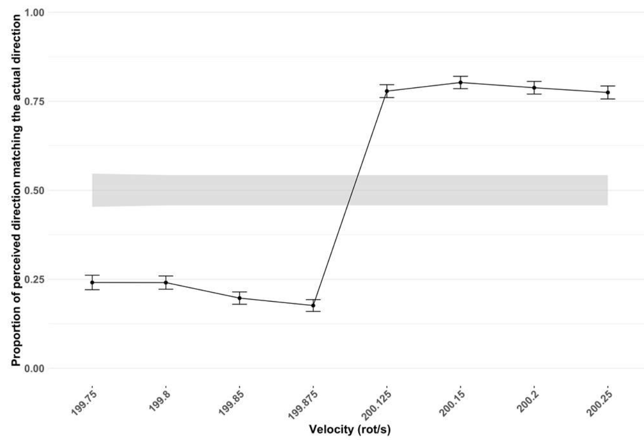

Figure 1: Proportion of perceived direction matching the actual direction, pooled plot with standard error. Chance level (binomial test, p-value = 0.05) represented in grey.

Table 1: Post-hoc test results using the Bonferroni correction. P-values are above the diagonal and Cohen’s d below the diagonal.

In rot/s	**199.75**	**199.8**	**199.85**	**199.875**	**200.125**	**200.15**	**200.2**	**200.25**
199.75		1.000	1.000	0.292	<.001	<.001	<.001	<.001
199.8	0.002		1.000	0.701	<.001	<.001	<.001	<.001
199.85	0.281	0.279		1.000	<.001	<.001	<.001	<.001
199.875	0.415	0.412	0.133		<.001	<.001	<.001	<.001
200.125	-3.441	-3.443	-3.722	-3.856		1.000	1.000	1.000
200.15	-3.599	-3.601	-3.880	-4.013	-0.158		1.000	1.000
200.2	-3.502	-3.504	-3.783	-3.916	-0.061	0.097		1.000
200.25	-3.417	-3.419	-3.698	-3.831	0.024	0.182	0.085	

References

[1] V. Roggerone, J. Vacher, C. Tarlao, and C. Guastavino, “Auditory motion perception emerges from successive sound localizations integrated over time,” *Sci. Rep.*, vol. 9, no. 1, Art. no. 1, Nov. 2019, doi: 10.1038/s41598-019-52742-0.

[2] F.-X. Féron, I. Frissen, J. Boissinot, and C. Guastavino, “Upper limits of auditory rotational motion perception,” *J. Acoust. Soc. Am.*, vol. 128, no. 6, pp. 3703–3714, Dec. 2010, doi: 10.1121/1.3502456.

[3] C. Camier, J. Boissinot, and C. Guastavino, “On the robustness of upper limits for circular auditory motion perception,” *J. Multimodal User Interfaces*, vol. 10, no. 3, pp. 285–298, Sep. 2016, doi: 10.1007/s12193-016-0225-8.

[4] C. Camier, F.-X. Féron, and C. Guastavino, “Spatial effects induced by circular motion at high velocities,” Montreal, Canada, May 2024.

[5] F.-X. Féron, C. Camier, and C. Guastavino, “Spatial effects induced by a sound centrifuge,” presented at the Proceedings of the Forum IRCAM Hors les murs, Montreal, Canada, Feb. 04, 2021.

[6] C. Camier, “Spatial Beat,” Conservatoire de Montreal Residency, Feb. 2017.

[7] U. Lefeuvre, “Circular auditory motion perception of harmonic sounds at very high velocities,” Master, Sorbonne Université, Paris, 2023.