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BINAURAL FUSION AS A SPECIAL CASE OF AUDITORY OBJECT FORMATION

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ABSTRACT

Binaural fusion reflects the percept of a single auditory image when a signal is presented to both ears. Research on binaural fusion has primarily focused on two key properties of the signal: interaural coherence (i.e. the statistical similarity of the sound at the two ears, independent of interaural time differences) and interaural frequency similarity (i.e., the similarity in frequency of the sound delivered to the two ears), both of which improve binaural fusion. Like binaural fusion, auditory object formation involves grouping multiple sounds into a single percept. We hypothesize that the cues that foster auditory object formation also foster binaural fusion. Two recently published studies will be discussed along with one ongoing study. In one of the recently published studies, we reduced binaural fusion using partially interaurally decorrelated sounds and used harmonicity to foster binaural fusion. In another study, we manipulated interaural coherence and then fostered binaural fusion using shared lateralization cues. In our ongoing study, to determine if the effect of lateralization cues were limited to countering decreased interaural coherence, we manipulated interaural frequency similarity alongside shared lateralization cues. The results of these studies support the hypothesis that cues that foster auditory object formation also foster binaural fusion.

Keywords: *binaural fusion, auditory object formation, common location, harmonicity.*

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1. INTRODUCTION

Binaural fusion reflects the percept of hearing a single auditory image originating from a spatially punctate sound source when sound is presented to both ears. Binaural fusion likely plays a critical role in binaural benefits such as sound source localization and speech understanding in noisy environments. Investigations on the cues that affect binaural fusion have largely focused on interaural coherence (i.e., the similarity of the signal at the two ears after accounting for interaural time differences), and interaural frequency similarities, and have demonstrated that both cues are important for binaural fusion [1-4].

This limited set of cues contrasts with the much larger set of cues for another phenomenon that involves grouping sounds together: auditory object formation [5]. Cues such as similar frequency [6], common temporal modulation [7], common onset/offset [8], timbre [9], harmonicity [10], and common location [11] all affect auditory object formation. With auditory object formation, multiple sounds are grouped together perceptually. While both auditory object formation and binaural fusion group sounds together, with auditory object formation a single sound source is perceived, whereas with binaural fusion a single sound location is perceived, but that location may include multiple sound sources.

Although the focus in the binaural fusion literature has primarily been on interaural coherence and interaural frequency similarity, there is emerging evidence that these are not the only cues that can foster binaural fusion. Additionally, this evidence suggests that some of the cues that foster auditory object formation also foster binaural fusion. We hypothesize that the same cues that foster auditory object formation also foster binaural fusion. Three studies will be discussed that investigate this hypothesis.

2. RECENT STUDIES SUPPORTING THE HYPOTHESIS

2.1 Harmonicity

Harmonicity plays an important role in creating auditory objects [13, 12]. If one tone of a tone complex is not harmonically related to the other tones in the complex, it will be heard as a separate auditory object. To see if a similar effect occurs with binaural fusion, Aronoff et al. [11] used two harmonic two-tone complexes, one in each ear. Each two-tone complex consisted of an fundamental frequency (F0) and its second harmonic. All four tones across both two-tone complexes were either harmonically related, or the tones within each two-tone complex were harmonically related but the tones in the different two-tone complexes were not harmonically related. The F0 of one of the two-tone complexes was manipulated to vary the harmonicity across two-tone complexes. As the F0 of that two-tone complex increased, the tones across two-tone complexes because spectrally further from being harmonically related. Consistent with the effects of frequency similarity, increasing the F0 of only one two-tone complex decreased binaural fusion. However, if the reduced frequency similarity resulted in all tones across both two-tone complexes to be harmonically related, binaural fusion was restored (see Figure 1). This suggests that harmonicity can foster binaural fusion.

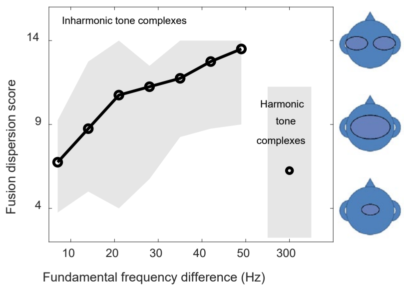

Figure 1. The effect of harmonicity on binaural fusion. Grey shading indicates 95% confidence intervals

2.2 Shared location

Sounds coming from a shared location are typically perceived as being part of the same auditory object [12]. To determine if this also facilitates binaural fusion, Aronoff et al. [13] presented normal hearing listeners with stimuli that varied in interaural coherence where different ILDs were added to the entire signal. While ILDs near 0 dB had little effect on perceived lateralization, suggesting a weak lateralization cue, large ILDs significantly shifted the perceived lateralization of the sound and increased the likelihood of binaural fusion occurring, especially when the interaural coherence was low (see Figure 2). This suggests that shared location can foster binaural fusion.

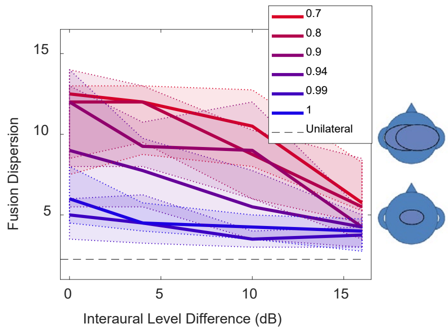

Figure 2. The effects of interaural level differences on binaural fusion for stimuli with varying interaural coherence. Colored shading indicates 95% confidence intervals.

3. ONGOING EXPERIMENT

3.1 Introduction

The experiment on shared location described above relied on decreasing binaural fusion by decreasing interaural coherence. This raises the prospect that the ILD itself directly interacted with the interaural coherence, possibly indirectly improving binaural fusion by effectively lessening the decreased interaural coherence. To determine if that is the case, an experiment was conducted where the effects of large ILDs on binaural fusion were examined but binaural fusion was manipulated using decreased interaural frequency similarity rather than decreased interaural coherence.

3.2 Methods

3.2.1 Participants

Fifteen individuals with normal pure tone thresholds from 250 to 8000 Hz participated in this experiment.

3.2.2 Stimuli

Stimuli consisted of single channel vocoded signals, composed of 20 narrowband noise carriers, with center frequencies equally spaced along the cochlea from 200 to 8000 Hz. For future comparison with cochlear implant users' performance, frequency similarity was manipulated based on the center frequencies used by cochlear implants to process stimuli. The carrier with the maximum amplitude was at approximately 6500 Hz (channel 2 for Cochlear company cochlear implants' default frequency allocation) in one ear. Stimuli for the other ear varied such that the maximum amplitude corresponded to one of the center frequencies for other channels based on that same frequency allocation table.

3.2.3 Procedures

Participants were asked to indicate the number and size of perceived auditory images resulting from the stimuli, as well as the lateralization of the stimuli. They indicated this using a dial (Powermate, Griffin Technology). Participants saw an image of a head on the screen with an oval on it. By turning the dial clockwise, they could make the oval larger. Continuing to turn the dial caused the oval to split into two ovals, one near each ear, indicating that the percept was no longer binaurally fused. Continuing to turn the dial further made the two images smaller. By pushing down and turning the dial, participants could move the oval to the left or right if they perceived a single lateralized image, or change the color of the ovals to indicate if the left or right image was more dominant if they perceived two images.

3.3 Preliminary Results

Consistent with previous research [14], the results demonstrate that fusion becomes less common (i.e., fusion dispersion scores increase) when frequency similarity decreases as indicated by increased frequency mismatch (see Figure 3). In terms of the effects of a common location, preliminary results show a similar pattern as seen in Aronoff et al. [13], with fusion dispersion scores decreasing with the addition of a large ILD. However, there is a critical difference. While Aronoff et al. [13] found that even manipulations that yielded unfused percepts (i.e., fusion dispersion scores of 10 or higher) became more fused when a large ILD was added, this did not occur with large mismatches in the current study.

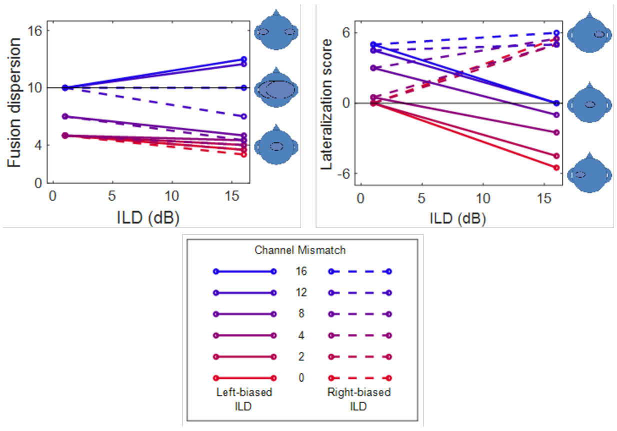

Figure 3. The effects of interaural level differences (ILDs) on binaural fusion (top left panel) and lateralization (top right panel) in the presence of interaural frequency dissimilarity.

3.4 Discussion

While preliminary, these results are consistent with those of Aronoff et al. [13]. Binaural fusion generally increased with the addition of large ILDs, however, the magnitude of the improvement when there was not frequency dissimilarity was the same as when there was a small to moderate degree of frequency dissimilarity. This suggests that large ILDs were not countering the effects of frequency dissimilarity in terms of binaural fusion as they did with interaural coherence.

Frequency dissimilarity resulted in a rightward shifting of the percept in the current experiment. This meant that the addition of the left-biased ILD to these rightward-shifted percepts centered the percept. Such stimuli did not cause the likelihood of binaural fusion to increase. This suggests that it may be the perceived lateralization rather than the presence of a large ILD that is key to fostering fusion.

4. CONCLUSIONS

The results from the experiments described above are consistent with our hypothesis that cues that foster auditory object formation also foster binaural fusion. Harmonicity and common location increase the likelihood of binaural fusion occurring, although it did not counter the effect of interaural frequency dissimilarity.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] J. Blauert, W. Lindemann: "Spatial mapping of intracranial auditory events for various degrees of interaural coherence," *Journal of the Acoustical Society of America*, vol. 79, pp. 806-813, 1986.

[2] B. M. Sayers, E. C. Cherry: "Mechanism of binaural fusion in the hearing of speech," *Journal of the Acoustical Society of America*, vol. 29, pp. 973–987, 1957.

[3] J. M. Aronoff, C. Shayman, A. Prasad, D. Suneel, J. Stelmach: "Unilateral spectral and temporal compression reduces binaural fusion for normal hearing listeners with cochlear implant simulations," *Hearing Research, vol.* 320, pp. 24–29, 2015.

[4] A. Kan, C. Stoelb, R. Y. Litovsky, M. J. Goupell: "Effect of mismatched place-of-stimulation on binaural fusion and lateralization in bilateral cochlear-implant users," *Journal of the Acoustical Society of America*, vol. 134, pp. 2923–2936, 2013.

[5] A. S. Bregman: *Auditory Scene Analysis: The Perceptual Organization of Sound,* Cambridge, Mass: MIT Press, 1990.

[6] M. M. Rose, B. C. J. Moore: "Effects of frequency and level on auditory stream segregation," *Journal of the Acoustical Society of America*, vol. 108, 2000.

[7] A. S. Bregman, J. Abramson, P. Doehring, C. J. Darwin: "Spectral integration based on common amplitude modulation," *Perception & Psychophysics,* vol. 37, pp. 483–493, 1985.

[8] R. W. Hukin, C. J. Darwin: "Comparison of the effect of onset asynchrony on auditory grouping in pitch matching and vowel identification," *Perception & Psychophysics*, vol. 57, pp. 191-196, 1995.

[9] D. L. Wessel: "Timbre Space as a Musical Control Structure," *Computer Music Journal,* vol, 3, no. 2, pp. 45-52, 1979.

[10] M. Fischer, K. Soden, E. Thoret, M. Montrey, S. McAdams: "Instrument timbre enhances perceptual segregation in orchestral music.," *Music Perception,* vol. 38, pp. 473-498, 2021.

[11] J M. Aronoff, J. Deutsch, J. R. LaPapa: "Using harmonicity to facilitate binaural fusion," *Journal of the Acoustical Society of America Express Letters*, vol. 5, 014401, 2025.

[12] C. J. Darwin, R. W. Hukin: "Auditory objects of attention: The role of interaural time differences," *Journal of Experimental Psychology: Human Perception and Performance,* vol. 25, pp. 617-629, 1999.

[13] J. M. Aronoff, J. R. LaPapa, J. Deutsch: "The relationship between interaural coherence, interaural level differences, and binaural fusion," *Hearing Research*, vol, 460, 109241, 2025.

[14] M. J. Goupell, C. Stoelb, A. Kan, R. Y. Litovsky: "Effect of mismatched place-of-stimulation on the salience of binaural cues in conditions that simulate bilateral cochlear-implant listening," *Journal of the Acoustical Society of America,* vol. 133, pp. 2272–2287, 2013.