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Research Paper

Auditory Spatial Illusion – A Psychoacoustic Study in Young Adults

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The Franssen illusion, or Franssen effect (FE), is one of the auditory spatial illusions. Few studies have explored the FE, and the mechanisms underlying it remain unknown. The present study was conducted to clarify the FE occurrence with different tasks and presentation modes in young adults. It also sought to investigate possible neurophysiological similarities between interaural time difference (ITD) cue processing and FE perception. FE perception was evaluated using two different tasks and two presentation modes (i.e., insert phones and loudspeakers). Sound reflections (reverberation) were presented in the diffuse field (loudspeaker mode). ITD performance was investigated using different stimuli delivered via insert phones. No significant difference between the two FE perception tasks was found ($F_{1,25} = 0.138$, $p = 0.713$). However, the FE perception showed a significant difference between the two presentation modes ($F_{1,25} = 434.03$, $p < 0.001$). Spearman's correlation did not reveal a significant relationship between FE perception and ITD scores ($p > 0.05$).

The current findings show the importance of reverberation in the FE occurrence. Also, the non-significant correlation between the results of the behavioral binaural temporal resolution test and FE perception in young people with normal temporal resolution may indicate that room reflections (reverberation) complicate the ability to process ITDs (rather than poor ITD processing for the "steady state" portion of signal).

Keywords: auditory spatial illusions; the Franssen effect; interaural time difference; binaural temporal resolution.

1. Introduction

Illusions are valuable tools for studying perception mechanisms since one can relate neural responses to both the physical aspects of the stimuli and subject's answers (Rajala *et al.*, 2013). In contrast to visual illusions (e.g., change-blindness illusion (O'Regan *et al.*, 1999)) and multisensory illusions (such as kappa and tau effects (Schroeger *et al.*, 2022)), which are well-known and extensively studied, there is limited understanding of spatial auditory illusions and the mechanisms underlying them (Rajala *et al.*, 2013). As the spatial representation of auditory signals does not occur at the receptor level (Grothe *et al.*, 2010), this may make designing experiments a challenge. The Franssen illusion, or Franssen effect (FE), is one of the auditory spatial illusions named after Nico Valentinus Franssen, who found and presented this phenomenon in 1960 in his Ph.D. dissertation. This illusion occurs when a sound is divided into two components: a transient onset – (first few milliseconds) characterized by a smooth rising, and a sustained tone. These components are simultaneously presented from different loudspeakers (Franssen, 1960). Indeed, in the Franssen illusion perception, the onset predominates over other cues (Franssen, 1960; Higgins *et al.*, 2017), and this domination of the onset cue continues throughout the entire sound perception process. Therefore, the entire sound is perceived as originating from the onset loudspeaker, even though it is the other loudspeaker that delivers nearly all of the sound energy (Franssen, 1960). The perception of this illusion may last for tens of seconds (Rajala *et al.*, 2013).

A previous study proposed a possible relationship between the FE and a more widely known phenomenon, i.e., the precedence effect (Yagcioglu, Ungan, 2006). Due to the precedence effect, similar sounds are localized by directional cues carried in the first-arriving sound, resulting in their perception as a single auditory event (fusion) (Wallach *et al.*, 1949). Litovsky and Godar (2010) introduced several different psychophysical tasks to investigate different aspects of the precedence effect, including discrimination-based task, fusion, and localization. Notably, studies on the impacts of these tasks on precedence effect assessments yielded inconsistent results. Previous studies (Donovan *et al.*, 2012; Saberi, 1996; Seeber, Hafter, 2011) showed that the temporal (fusion) and spatial (localization/discrimination) aspects of the precedence effect probably have different mechanisms. On the other hand, Seeber and Hafter (2011) investigated fusion and both lead and lag localization using virtual auditory space stimuli across different conditions. They concluded that the fusion and localization aspects of the precedence effect share similar time courses. However, until now, the effect of various tasks on FE perception has not been investigated.

In the Franssen illusion perception, stream separation based on spatial cues does not occur as intended (Van Deun *et al.*, 2009), which may be related to incorrect processing of ITD and interaural intensity difference (IID) cues, required for sound localization, particularly due to sound reflections and reverberation (Hartmann, Rakerd, 1989; Stevens, Newman, 1936). In sound localization, ITD holds greater significance (Babkoff *et al.*, 2002). ITD cues can be divided into ongoing envelope, fine structure, and transient onset (Haqqee *et al.*, 2021; Verschooten *et al.*, 2019). In pure tone signals, ITD is processed up to 1500 Hz, referred to as fine-structure ITD (ITD_{FS}) (Brughera *et al.*, 2013; Delphi *et al.*, 2017; Verschooten *et al.*, 2019). In complex sounds, ITD at higher frequencies (beyond 1500 Hz) is perceived through the difference in the sound's envelope timing, known as envelope ITD (ITD_{ENV}) (Yost, 2017); and transient onset ITD cues, which refer to the difference in the arrival time of the sound to the perceiver's different ears ($\text{ITD}_{\text{ONSET}}$) (Scharf *et al.*, 1976).

Yost and Zhong (2014) investigated sound localization by stimuli with a bandwidth ranging from 1/20 to two octaves. Their findings revealed that sound localization accuracy in noise burst stimuli is higher than that in pure tone. Soeta and Nakagawa (2007) conducted a study on binaural hearing filters. Their results showed that N1m amplitudes increase with the increasing frequency separation to above 200 Hz. Hafter *et al.* (1979) indicated that, for tones with extended durations, onsets and offsets were unnecessary for detecting ITD or IID with earphones. On the other hand, Hartmann and Rakerd (1989) showed that the sustained component of a stimulus does not provide valuable localization information in a room. Thus, they introduced the plausibility hypothesis. In this hypothesis, reflections make ITDs unreliable as cues for localizing steady-state stimuli (Hartmann, Rakerd, 1989). Previous studies showed that the Franssen illusion exists in live (reverberant) rooms (Hartmann, Rakerd, 1989; Yost *et al.*, 1997), and it is particularly strong for midfrequency tones (near 1500 Hz) (Yost *et al.*, 1997). With regard to previous studies on onset dominance, questions arise whether the presentation of FE stimuli with earphones causes FE perception, and whether there is any similarity in the underlying neurophysiological mechanism between FE and ITD cues processing.

The present study was designed to clarify the Franssen illusion occurrence in young adults. For this purpose, the perception of the FE was evaluated through two different tasks conducted under the insert phones mode and the diffuse field mode within a typical room (in which reverberation times ranged from ~0.2 to roughly 1.3 seconds (Gelfand, 2016)). Since the abnormal ITD cues are implicated as the cause of the FE occurrence, in line with the plausibility hypothesis, the correlation of the illusion with ITD scores (around frequency 1500 Hz where all ITD cues are weak and do not overcome each other) was investigated using tone burst and noise bursts.

2. Material and method

2.1. *Participants*

A total of 26 young adults aged between 19 and 32 years old (mean = 23.30 ± 3.18) participated in the research. They had no history of ear and hearing problems, head trauma, or neurologic disease. Audiometric thresholds were equal to or less than 10 dB hearing level (HL) at octave frequencies ranging between 250 to 8000 Hz. Interaural audiometric threshold asymmetry was usually less or equal to 5 dB at all frequencies tested. The average gap in noise threshold was obtained at 4.41 ms in the right ear and 4.54 ms in the left ear. The experiment was administered in accordance with the ethical guidelines of the Iran University of Medical Sciences (ethics code: IR.IUMS.REC.1400.1099).

2.2. Stimuli, experimental design, and procedure

Experiment 1: The Franssen illusion investigation with identification/discrimination tasks at 1500 Hz tone burst stimuli using insert phones and diffuse field modes.

Two types of stimuli (generated digitally in MATLAB) were used. The Franssen stimuli (including a transient component (total duration was 50 ms), a sustained (steady state) component with a 50 ms linear onset, 100 ms linear offset, and a 350 ms plateau), and a single sound non-Franssen stimulus. Both stimuli had a total duration of 500 ms. The stimuli were presented with two loudspeakers (Pejvak Ava Corporation, Tehran, Iran) and ER-2 insert earphones (Etymotic Research, Inc., El Grove Village, IL, United States) to subjects seating in a typical room (reverberation time (RT) = 0.827 s, estimated through Sabine's reverberation equation (Fig. 1)). The ER-2 insert earphones were calibrated at 1000 Hz without any frequency-dependent correction. The level of stimuli presentation was at 70 dB sound pressure level.

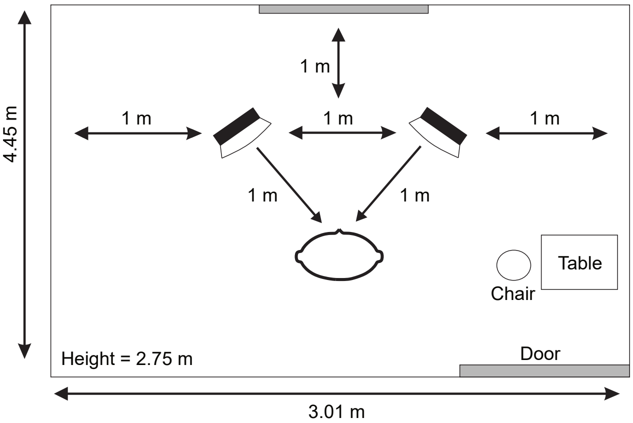

Fig. 1. Sketch of the test room and the relative positions and orientations of the speakers and the listener. Dimensions of the room: length – 4.45 m, width – 3.01 m, height – 2.75 m, positions of the speakers: height from the floor – 1 m, distance from the side and back walls – 1 m, facing of loudspeakers – medially 45°; height of the listener's ears from the floor – 1 m, and reverberation time with Sabine's equation (RT) = 0.827 s.

Procedure for the Franssen effect identification task: stimuli were presented alternately, and in each trial, the participants were asked "which speaker/insert phones presented the stimuli? right, left, or two sounds from both speakers" and the participant identified the direction of presentation (Fig. 2). A block of 50 trials was used to estimate the Franssen illusion for each mode (under insert phones and loudspeakers). The number of Franssen and non-Franssen stimuli were equal, and their distribution was random. Finally, the number of illusions was calculated and reported in terms of total Franssen stimuli numbers (i.e., 25).

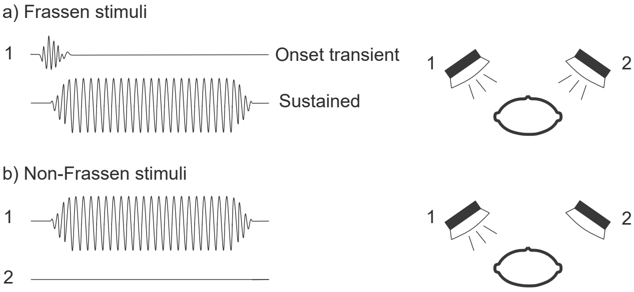

Fig. 2. Identification task procedure in diffuse field: a) in the Franssen stimuli, the onset transient was presented from one loudspeaker (1) and quickly cross-faded to a second loudspeaker (2); b) in the non-Franssen stimuli, the whole tone was presented from one loudspeaker (1), and the other loudspeaker was off (2).

Procedure for the Franssen-effect discrimination task: a block of 48 trials was used to estimate the Franssen illusion perception for each mode (under insert phones and loudspeakers). In each block, experimental and catch trials were presented randomly. In each trial, pairs of stimuli were presented. For example, in the Franssen right and non-Franssen right experiment, the onset of the Franssen stimuli was presented to the right earphone/speaker, and the sustained part of the Franssen stimuli was presented to the left earphone/speaker. Then, the second stimuli (non-Franssen right) were presented to the right earphone/speaker. The participant was asked to determine whether the stimuli were the same or different (Fig. 3). A "same" response indicated that both stimuli presented in each trial were similar in terms of perceived spatial location. The distribution of stimuli was random. To ensure that participants attended to the requested task, 16 catch trials (~30% of all stimuli) were used in which pairs of non-Franssen stimuli were presented in the same or different directions. Finally, the number of illusions (a condition in which a person does not differentiate between the Franssen and non-Franssen stimulus pairs) was calculated and reported in total real trials (i.e., 32).

Experiment 2: ITD assessment at 1500 Hz tone burst and as a function of bandwidth (1/200 to 1/2 octaves wide).

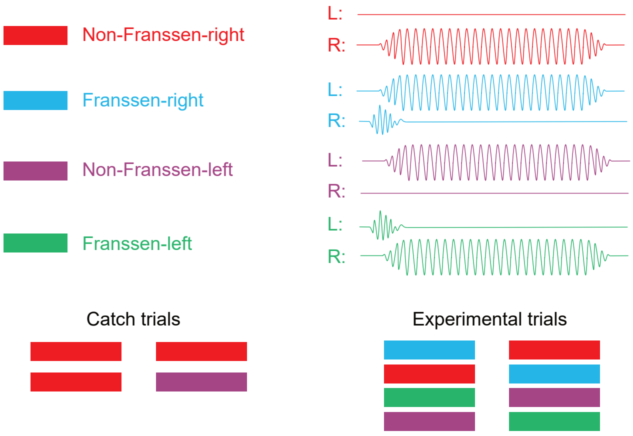

Fig. 3. Discrimination task procedure: in catch trials, pairs of the same (two non-Franssen stimuli from the right loudspeaker) (red) or different (two non-Franssen stimuli from the right and left loudspeakers) (red, purple) stimuli were presented randomly; in experimental trials, pairs of Franssen and non-Franssen stimuli were presented.

Stimuli were generated digitally in MATLAB (including 1500 Hz tone burst and filtered noises of various bandwidths (1/200, 1/100, 1/50, 1/20, and 1/2 octaves wide), filtered with a six-pole elliptic filter with passband ripple 3 dB and stopband ripple 20 dB, geometrically centered at 1500 Hz). Two durations were used: 250 ms and 20 ms rise and fall time to investigate ITD. In ITD tests, stimuli were presented binaurally with ER-2 insert earphones (Etymotic Research, Inc., El Grove Village, IL, United States), with delay times of 700, 300, 100, 0, −100, −300, and 2700 μs between the two ears at an intensity level of 70 dB SPL. Therefore, the sounds could be perceived to be coming from seven different positions in a semicircle. To understand each position, a pair of stimuli was presented with an interval of 500 ms. In stimulus pairs, the first signal (standard signal) always shows the midline position, and the second signal (test signal) indicates the position that the person must understand and point to its position. The participant was asked not to respond to the first stimuli and determine the position of the second stimuli orally after each stimulus, which was presented randomly. Each position was evaluated twice, and errors (i.e., wrong answers) were calculated. Hence, the maximum number of true or wrong answers was 14. All participants were trained before the main test, and after becoming familiar with the response method, they proceeded with the main test.

3. Results

Table 1 shows the minimum, maximum, mean, and standard deviation of the number of errors in experiment 1 for each of the tasks and modes. In the present study, a two-way repeated measures ANOVA did not reveal a significant difference in the Franssen illusion perception between the two different tasks ($F_{1,25}$ = 0.138, p = 0.713). The total number of Franssen stimuli presented in each procedure/task were converted into a ratio and then compared due to different stimuli numbers. However, the Franssen illusion perception showed a significant difference with two different presentation modes, under insert phones and diffuse field ($F_{1,25}$ = 434.03, p < 0.001). Also, the interaction of the two factors was not significant ($F_{1,25}$ = 2.609, p = 0.119). The minimum, maximum, mean, and standard deviation of the number of errors for each of the stimuli used in experiment two are given separately in Table 2.

Statistical analysis of the ITD score was performed between stimuli. Results of the pairwise comparison with the Bonferroni post hoc test between tone burst stimuli (1500 Hz) and noise burst stimuli with

Table 1. Statistics of the Franssen illusion perception test results with insert phones and diffuse field modes.

Franssen illusion perception tasks	Presentation modes	Participants [n]	Number of errors			
			Minimum	Maximum	Mean	Standard deviation
Identification task	Diffuse field	26	11.00	25.00	21.11	4.79
	Insert phones	26	00.00	13.00	4.34	4.70
Discrimination task	Diffuse field	26	13.00	32.00	28.03	6.15
	Insert phones	26	00.00	20.00	4.00	5.34

Table 2. Statistics of the ITDs test results at 1500 Hz and as a function of bandwidth (1/200 to 1/2 octaves wide).

Types of stimuli	Participants [n]	Number of errors			
		Minimum	Maximum	Mean	Standard deviation
Tone burst 1500 Hz	26	4.00	13.00	9.61	2.26
Noise burst with 1/200 octave wide	26	00.00	8.00	2.73	2.30
Noise burst with 1/100 octave wide	26	00.00	7.00	3.11	2.02
Noise burst with 1/50 octave wide	26	00.00	9.00	3.23	2.15
Noise burst with 1/20 octave wide	26	00.00	6.00	3.19	1.67
Noise burst with 1/2 octave wide	26	00.00	3.00	1.07	0.93

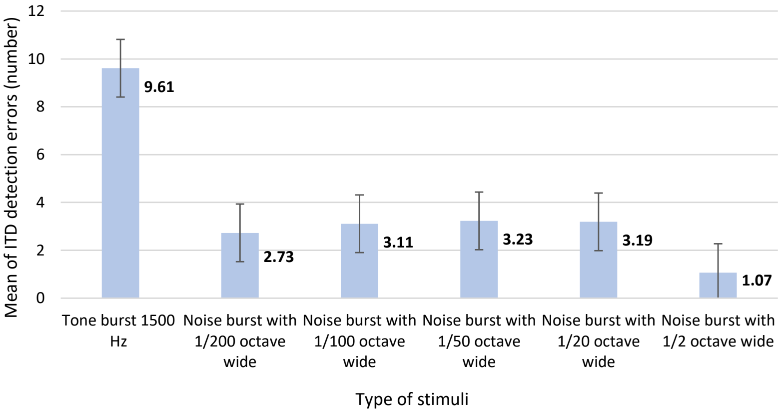

Fig. 4. ITD scores for the six different stimulus waveforms using a stimulus level of 70 dB SPL. The rectangular bars and the error bars indicate the mean and standard deviations of the data across the twenty-six participants.

bandwidths of one-half to $^1/_{200}$ octaves showed a significant difference. The one-half octave wide noise burst differed from other noise bursts as well (Fig. 4). Additionally, Spearman's correlation did not show a significant relationship between the Franssen illusion perception and ITD scores ($p > 0.05$).

4. Discussion

In the present study, Franssen illusion perception was evaluated using two different tasks (the sound source identification task/the Franssen discrimination task) to investigate the impact of different task types on Franssen illusion outcomes. Statistical analysis did not show any significant differences between the results of these two task types, which is in accordance with the study of Seeber and Hafter (2011). The average error number for the identification task in diffuse field mode was 84.44%, and for the discrimination task with a similar presentation method, it was 87.59%. This shows the similar performance of these two procedures in the Franssen illusion investigation. On the other hand, prior studies (Donovan *et al.*, 2012; Saberi, 1996; Seeber, Hafter, 2011) indicated that temporal (fusion) and spatial (localization/discrimination) aspects of the precedence effect probably have different mechanisms. This discrepancy may be due to binaural fusion dependence on the task. Also, interpreting the percentage of fused responses is complicated (Suneel *et al.*, 2017). In general, both tasks appear to have the same ability in investigating the occurrence rate of the Franssen illusion, and the probability of illusion occurrence in a typical room is almost the same for both types of procedures. Fusion and spatial mechanisms probably have the same contribution to the occurrence of FE. This seems reasonable, considering that fusion stimuli perception correlates with localization performance (Suneel *et al.*, 2017).

The perception of the FE with both tasks in diffuse field and insert phones mode exhibited a significant difference. In other words, the average Franssen illusion (i.e., the average percentage of errors (number) in both procedures/tasks) decreased from 86% in the diffuse field mode to 14.93% with insert phones. These errors arise because individuals tend to localize the stimulus using the onset cue and have difficulty in identifying the location of the sustained part of stimuli. This observed result is consistent with previous studies (Hafter *et al.*, 1979; Hartmann, Rakerd, 1989; Yost *et al.*, 1997). Hartmann and Rakerd (1989), and Yost *et al.* (1997) investigated the FE in the diffuse field mode. They showed the occurrence of the Franssen illusion in a reverberant room, and observed a reduction in the Franssen illusion when it was performed in a dead room. It seems that in typical listening environments, the ITD cue in identifying the sustained part of the Franssen stimulus becomes abnormal due to reverberation.

Hafter *et al.* (1979), in a study on stimulus onset, demonstrated that people could lateralize stimuli in the absence of abrupt onset, which can be a justification for reducing the occurrence of illusions and the non-dominancy of onset in the insert phones condition (a state in which there were no environment reflections) in the present study. It seems that the onset predominance or, in other words, interaural onset difference leads to the Franssen illusion perception in the diffuse field mode. However, this onset dominance is lost in the insert phones mode, and people can distinguish the onset and sustained parts individually. Studies on the role of onset dominance in the precedence effect occurrence showed that if the delay between onset and post-onset pulses is less than 5 ms, participant's spatial judgments are dominated by onset cues (lead). However, if the inter-pulse interval is 12 ms, it causes the same sensitivity to the onset "leading" and post-inset pulses "lagging" in spatial judgment (i.e., failure in precedence effect) (Brown *et al.*, 2015; Saberi, 1996). In the present study, despite the sustained part of the stimulus reaching its maximum value after 50 ms and continuing up to 500 ms, we still have the predominance of onset in diffuse field presentation, which may be due to the gradual and progressive onset of the Franssen stimuli or the different origins of these two effects (i.e., precedence effect and the Franssen illusion).

The statistical analysis showed a significant difference between the ITD score with tone burst 1500 Hz stimulus and noise burst stimuli (including bandwidths of 1/200 to 1/2 octave) so that the average number of errors decreased from 9.61 to 1.07, which is in accordance with previous studies (Pierce, 1901; Stevens, Newman, 1936; Soeta, Nakagawa, 2007; Yost, Zhong, 2014). Yost and Zhong (2014) investigated the accuracy of sound localization using stimuli with a bandwidth of 1/20 to two octaves and center frequency of 250, 2000, and 4000 Hz. The study's findings showed that sound localization accuracy in noise burst stimuli is higher than in pure tone. This suggests that modulations or oscillations around the center frequency over time help participants to use the difference in arrival time of the stimulus envelope (ITD_{ENV}) and ITDFS for sound lateralization.

A comparison of the ITD scores between the noise burst stimulus with a 1/2 octave bandwidth and other noise burst stimuli showed a significant difference. However, it did not show any significant difference between 1/200 to 1/20 octave bands, probably due to the stimulation of the same auditory filters. Soeta and Nakagawa (2007) performed a study on binaural hearing filters with auditory-induced magnetic fields. Their results showed that N1m amplitudes remain roughly constant if frequency separation is below 100 Hz, but they increase with increasing frequency separation to above 200 Hz. Given that only the frequency bandwidth changes in stimuli with different octave bands, Soeta and Nakagawa's findings (2007) can justify the present study's results. Based on their study results, ITD discrimination improves with an increase in bandwidth, even as small as 1/200 octaves. However, when the difference in frequency separation between two stimuli is such that they are placed in the same physiological filter, it will not create a significant difference in the listener's performance in ITD discrimination.

This study showed no significant correlation between ITD scores and the Franssen illusion occurrence. This finding can be explained in several ways. First, the probable site of the mechanism leading to the Franssen illusion remains ambiguous and controversial. Higgins *et al.* (2017) concluded that the perceptual representation of auditory space occurs at the higher level of the auditory cortex, which gives the basis for the formation of the FE. Yagcioglu and Ungan (2006) introduced the primary auditory cortex as a possible site for the FE mechanism. On the other hand, Rajala *et al.* (2013) showed a considerable correlation between the neural activity of the inferior colliculus in rhesus monkeys and behavioral responses to Franssen stimuli, indicating a possible subcortical origin of the Franssen illusion. Likewise, Haqqee *et al.* (2021) recently indicated the high sensitivity of the inferior colliculus to interaural onset difference in bats, which is remarkable considering the dominance of onset in perceiving the Franssen illusion. Therefore, if the FE is assumed to be a perceptual illusion, the absence of a significant correlation between the illusion perception and ITD, which has a subcortical origin and is considered a bottom-up process, is justifiable. Secondly, the different sensitivity of mammal's auditory system to onset and envelope cues (Haqqee *et al.*, 2021) may lead to the illusion occurrence in diffuse field conditions. The participants in this study were young adults with normal monoaural and binaural temporal resolution and normal ITD processing. It seems that the possible role of abnormal ITD cues in Franssen illusion perception is not due to a deficiency in neural processing of ITD but rather to the reverberation and its interference with ITD perception.

The current study demonstrated that Franssen illusion perception occurs in a typical room and is reduced in the insert phones condition. Moreover, the task variety does not affect the results, and it seems that the illusion occurrence does not depend on behavioral ITD discrimination. It is important to note that this research was conducted on listeners with a normal temporal resolution, fixed ITD (i.e., 100, 300, and 700 µs), and a constant center frequency. Performing a study on people with abnormal monaural and binaural temporal resolution, such as the elderly, across the entire human frequency range, and employing different ITDs in diffuse field conditions, could provide more information about the importance and role of ITD cues in the Franssen illusion perception. On the other hand, correlation is a type of statistical analysis that depends on individual participants' data rather than overall average, and thus a significant correlation may be observed with a large sample size. Based on the present study results and considering the onset dominance in the diffuse field mode, it may be possible to use the FE in examining the tone onset time (TOT), which is vital in understanding plosive (stop) consonants (Pisoni, 1977). Furthermore, the study suggests that the effect of age, hearing loss, and training on the Franssen illusion may be investigated with behavioral and nonbehavioral tools (e.g., electrophysiological tests) in order to obtain more information about the mechanism of the Franssen illusion perception, the precedence effect, and its potential applications in clinical settings.

5. Conclusion

This study investigated the impacts of different tasks and presentation modes on the Franssen auditory-spatial illusion perceptual aspect. Subsequently, the relationship between illusion perception and the listener's ability in binaural temporal resolution was studied. The findings of the present study, in accordance with previous works, showed the importance of reverberation in the Franssen illusion occurrence and onset's non-dominancy under insert phone conditions. Furthermore, there was no significant correlation between the results of the behavioral binaural temporal resolution test (with a fixed interaural difference and center frequency) and the Franssen illusion perception among young people with normal temporal resolution, which may suggest that room reflections (reverberation) complicate the ability to process ITDs (rather than poor ITD processing for the "steady state" part of signal).

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