An Adjacency Effect in Auditory Distance and Loudness Judgments

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Abstract

This study investigated whether the adjacency principle, demonstrated in a perceived visual space, can be applied to auditory space. In order to demonstrate an auditory adjacency principle, multiple sound sources were varied in direction and distance in an acoustically absorbant space. Specifically, a NEAR sound source was located 10° to the left of the listener's midline at a distance of 2 meters; a FAR sound source was located 10° to the right at a distance of 5 meters. These sources served as perceptual reference points with respect to the localization of three test sounds, all at a distance of 3 meters. Two of three test sounds were directionally closer to the NEAR and FAR reference sounds, respectively. The other was between the reference sources directionally. The listener was asked to judge the perceived distances and the loudness of the three test sounds and the two reference sounds. The results indicated that the apparent distances of the test sounds were most determined by the disparity of distance between each test sound and the reference sound most directionally adjacent to it. Therefore, the findings offer evidence that the adjacency principle can be applied to the auditory space.

I. Introduction

Traditional investigations of auditory space perception have often employed an experimental paradigm in which listeners occupy a fixed listening point and report the appearance of a test sound presented in a uniform surround. However our everyday perceptual environment includes multiple "sounds." Obviously, we should not rely solely on findings from studies dealing with an isolated object, if we wish to explain veridical perception in our normal environment. The present study describes how sound sources interact in multi-source situation and how humans combine discrepant information from objects to perceive unified events.

With regard to the interaction between multiple sources, consider a situation in which an object is seen in isolation or with other objects. Will the perception of the object be stable without any change? Suppose a single light moving repetitively up and down in a dark room. The light is obviously perceived as moving vertically. Now suppose that another light moving repetitively right and left is introduced nearby. The perceived motions of the two points will differ from their physical directions motions. Gogel[1-3] introduced a perceptual organizational factor, termed the adjacency principle, to explain this perceptual phenomenon.

Specifically, the adjacency principle states that the effectiveness of any relationships occurring between objects (or parts of objects) is inversely related to the perceived separation of the objects (or parts of objects). Even when there are effective cues to depth between objects in the visual field, the perception of those objects can be modified by the degree of their separation. That is, the adjacency principle predicts that when two objects are separated sufficiently in a frontoparallel plane or in depth, the effectiveness of relative or exocentric cues (those variables that change the perception when other objects are introduced) between them is reduced the observer tends to rely on absolute or egocentric cues (those variables that determine the perceived characteristics of an object independently of other objects).

Adjacency effects can be measured by changing the apparent position of the test object between two separated and opposing inducing objects (thus creating a two end-points situation)[3-5]. As an example, a change in the effectiveness of relative cues for motion with changes of separation is demonstrated in Figure 1. An observer is presented with the test light (T) either at different separations from opposing induction (or reference) lights (I_1 and I_2). Both the test and induction lights subtend the same size on the observer's retina. Lights move along paths defined by the length and direction of the solid or broken lines. The test light appears to move between upper right and lower left when it is near the induction light I_2, even if the test light physically moves on horizontal path (see Figure 1A). When the test light, however, is about equally separated from both induction

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lights, it appears to move approximately horizontally (see Figure 1B). These results are consistent with the adjacency principle in that the test light is more affected by the induction light to which it is closer and is about equally affected by both induction lights when it is equidistant from each.

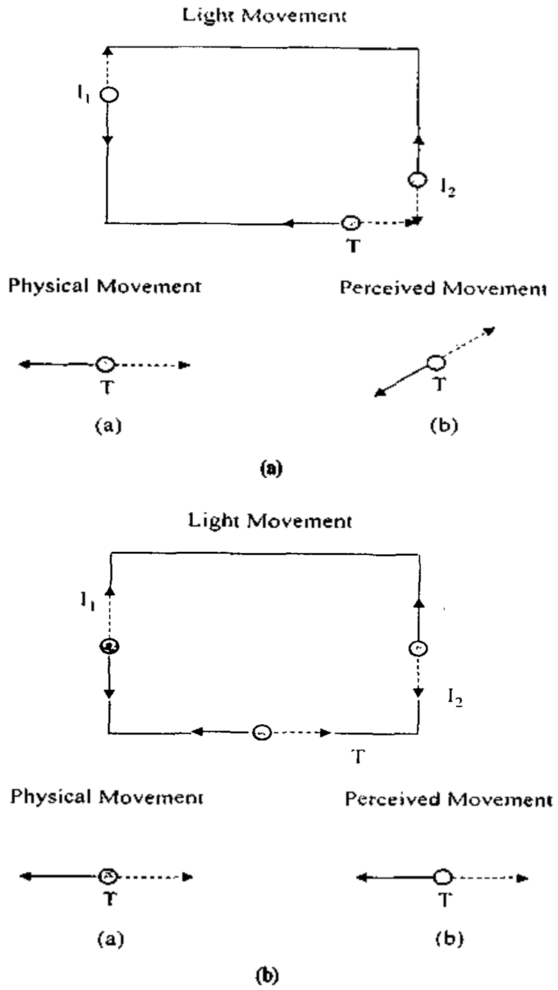


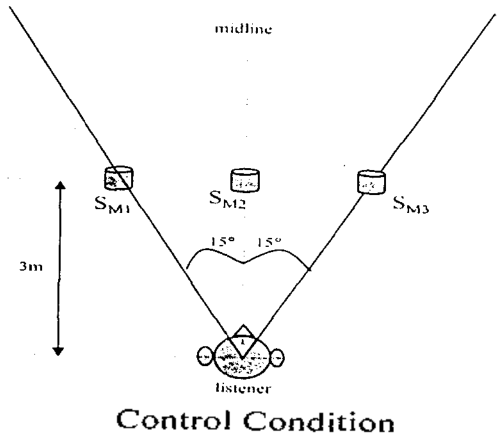
Figure 1. The effectiveness of relative cues to motion may be demonstrated by placing a test object (T) at different distances from opposing objects (I_1 and I_2) or midway between the induction objects. Points of light move along paths defined by the length, direction and phase (defined by solid or broken line). When T is near to induction object (I_2), it appears to move between upper right and lower left (A). However when T is midway between the induction objects, it appears to move approximately horizontally (B).

Clearly, the effectiveness of relative cues is reduced as the distant between the test object and the induction object increases. It seems clear that the adjacency principle can be successfully applied to a wide range of phenomena, and it also must be considered in any attempt to explain the processes involved in the perception of a variety of object characteristics. However this principle has been demonstrated only in visual space. Thus the present research attempts to identify whether the adjacency principle also applies to auditory phenomena, particularly to the perception of auditory depth.

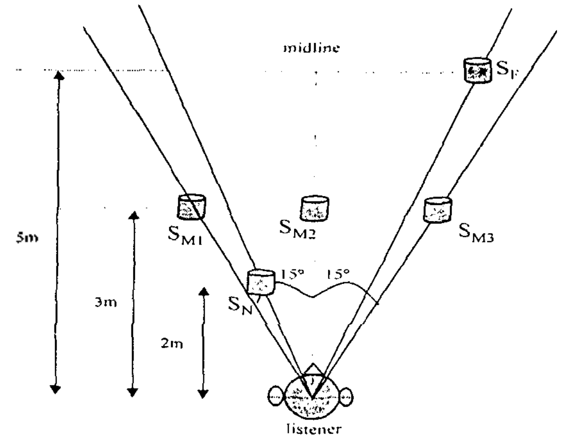
II. Research Paradigm and Hypothesis

This study was intended to demonstrate the adjacency principle in auditory space by examining whether the changed distances of sound stimuli can influence the perceived distance adjacent sound stimuli and whether variation in the perceived distances of the adjacent sound stimuli influence the perceived loudness of those stimuli.

The present study employed the research paradigm shown in Figure 2. Under a control condition, the listener was presented just the test sounds without the referent sounds. For an experimental condition, the research employed two reference stimuli (thus establishing two end-points). The induction reference sound sources were located in different directions and distances to examine the changes which might occur in the depth of three test sounds located at the same distance between the two reference sounds. All sounds were presented just below the height of the listener's ears, and the presentation of sounds was in the order $S_N \rightarrow S_F \rightarrow$ (S_{M1} or S_{M2} or S_{M3}) for the experimental condition. A higher sound level was employed for SN than for the test sounds or SF. This sound level difference was expected to help establish a clear variation in the distances of the sound[6-9].



(a)



Experimental Condition

(b)

Figure 2. Schematic drawing illustrating the locations of the induction and the test stimuli. Three test sounds are placed at the same distance (3m from the listener) but in different direction. A near reference sound (S_N) is placed at the near distance (2m) but in the adjacent direction as S_{M1} and a far reference sound (S_F) at the far distance (5m) but in the adjacent direction as S_{M3}. In a control condition, only three test sounds are presented to the listener. In an experimental condition, all sound sources are presented to the listener.

The main concern to be examined by this experimental design was a comparison of apparent depth of the three test sounds in the different conditions. The three test sounds were expected to vary systematically in depth. That is, all three were predicted to be varied in the perceived distance although these were at the same physical distance. In other words, the perceived distances of the three test sounds (S_{M1}, S_{M2}, S_{M3}) were expected to change due to the distances of the reference sounds. This sort of change in the depth of the three test sounds would confirm the importance of auditory adjacency effect. That is, the test sounds presented at the same physical distance would perceptually seem to originate from different distances, since each test sound would be heard in depth in relation to its position with respect to the directionally nearest reference sound.

Mershon et al.[10] reported that variations in the perceived distance to a test sound could also influence its loudness, even for a constant sound level at the ears. The present results were expected to reflect similar findings. Therefore, the second hypothesis was that perceived distance and perceived loudness would be directly related. Specifically, the perceived loudness of the test sounds would vary in terms of variations in their perceived distances.

2.1. Listeners

The listeners consisted of 24 college students (12 men and 12 women). Their mean age was 19.8 years. All participants were requested to have normal hearing and vision, although no audiometric or vision tests were performed to verify this. No observer had any prior experience in the test room and all were naive with respect to the aims of the present experiment.

2.2. Environment and experimental setting

All experiments were conducted in an enclosed, windowless test room consisting of a 7.3 x 7.3 x 3.6m (l x w x h) space covered with sound-absorbing panels to reduce reflections. The T_{60} reverberation time was approximately 0.36s for frequencies between 0.5 and 8.0kHz.

An hearing booth was made by blocking off parts of the test room with thin dark blue cotton cloth. Therefore, the listener could not see any of the loudspeakers, nor any of the experimental structure beyond the curtain. The listener was seated in an adjustable chair in the hearing booth. The experimenter was seated to the listener's left and instructed and operated the experimental equipment. The observer could not see the experimenter because of a second curtain between them. Sonex 4 inch acoustical foam (1.2 x 1.2m) was attached to the wall approximately 1.2m behind the observer. This panel was intended to eliminate early reflections which could otherwise have been produced by the wall behind the listener.

Two referent speakers (S_N and S_F) were placed 10° to the left and right of midline at 2 and 5m from the listener, respectively. Test speakers S_{M1} and S_{M3} were placed 15° to the left and right of midline at 3m from the listener. The middle test speaker (S_{M2}) was placed in the listener's midline at the same 3m distance.

2.3. Stimuli

A number of experiments have demonstrated several auditory distance cues. With regard to sound level, judgments of distance systematically increase as the level at the listener's ear decreases with changes in physical distance[7, 8]. Also the existence of direct and reflected sound energy, which occurs in most natural acoustic environments, facilitates the perception of sound-source distance. That is, the ratio of direct to reverberant sound decreases with distance[8, 11].

There is another distance cue, spectral content cue. Sounds lacking high frequency components usually seem farther away than sounds containing high frequencies [11-13]. To create sounds which would produce perceptual differences in distance, three auditory distance cues (sound level, frequency spectrum and reverberation) were manipulated simultaneously.

Two referent sounds were noise bursts with a relatively wide-band frequency spectrum; a similar sound was employed for the three test sound sources. All sound stimuli were created using Cool Edit (a software program for designing sounds) and were saved as WAV files in a windows-pentium computer.

The near referent sound (S_N) was presented at a sound level of 53dBA (measured at the normal position of the listener's head by using a Rion NA-61 sound level meter); the far referent sound (S_F) was presented at 43 dBA. To allow the listener to discriminate easily the two reference sound stimuli, given that the same noise was employed for each of them, a different pulse rate was applied to each reference sound. That is, S_N pulsed with a nominal on-time of 100 msec and off-time of 50 msec, and SF pulsed with an on-time of 200 msec and off-time of 100 msec.

The sound level (47dBA) for the test sounds (S_{M1}, S_{M2}, S_{M3}) was selected to fall approximately midway between those used for S_N and S_F, since it was important for the test sounds to appear somewhere between S_N and S_F in distance. For each test sound, a single sound burst was presented for 1.5 sec (including linear rise and fall times of 600 msec). The long rise and fall times employed for the test sounds were intended to minimize the usefulness of reverberation cues for distance, thereby emphasizing the role of relative cues such as changes in sound level and spectral content across the test and referent stimuli.

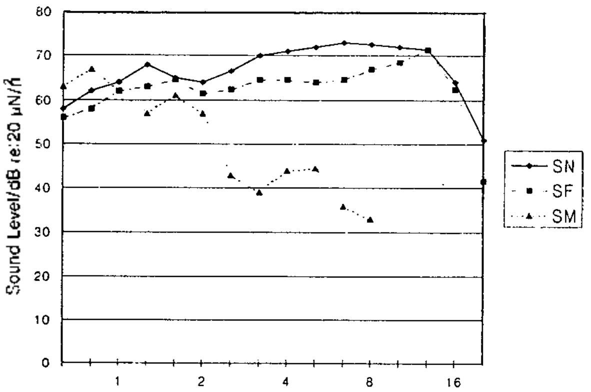


Figure 3. One-third-octave band spectral composition of the sound.

Figure 3 shows spectral analyses of the stimuli generated for this experiment. The spectral analysis for the referent sounds shows that decibel values increased steadily from approximately 58 to 71dB for S_N and 56 to 71dB for S_F (between 0.63 and 12.5kHz). Above and below these values, signal energy decreased sharply. For the test sound, decibel values increased from approximately 63 to 69dB between 0.63 and 8kHz, above which signal energy decreased steadily.

For measuring the perceived loudness, another sound burst was generated as a standard against which the test sounds could be evaluated. The average difference in level between the test sound and the standard sound (i.e., averaged across all frequencies between 0.63 and 8kHz) was approximately 7dBA.

2.4. Presentation of sounds and measurements

All sounds, saved as WAV files, were managed by Visual C++. The program provided 24 basic options for presenting sounds (2 presentation orders of the reference sounds x 6 orders of the three test sounds x 2 conditions). For the experimental condition, all presentation sequences included the following eight trials for judging distance and loudness (see Figure 4): first, there were 3 trials in which the listener judged the perceived distances of the three test sounds; second, there were 2 trials in which the listener orally judged the perceived distances of two reference sounds; and third, there were 3 trials in which the observer judged the perceived loudness of the three test sounds. For the control condition, the listener was asked to judge only the perceived distances to the three test sounds. Thus, the perceived distances to the three test sounds were obtained from the same listener in both the experimental and control conditions, respectively.

The sounds were amplified through a Vector Research amplifier (model VR-2300) and the amplified sounds were sent to the each loudspeaker through a switch box placed in the test room. The speakers were Art Audio speakers (model BAW-50) for the reference sounds and Jensen 3½" cone speakers (model J135FR) for the test sounds.

For each trial, sounds were presented in the following order: 3 repetitions of S_N and S_F (alternating), followed by a single presentation one of the three test sounds. During trials 1-3, the listener judged the perceived distance of each test sound; during trials 4-5, the perceived distances of the two reference stimuli. For one presentation sequence, S_N, consisting of 5 noise bursts (each nominally 100 msec in duration with successive inter-burst intervals of 50 msec), was presented for 700 msec. S_F, consisting of 3 noise bursts (each 200 msec in duration with 100 msec inter-burst delays), was presented for 900 msec. Three such sequences were presented, followed by a single presentation of the test sound for 1.5 sec (including linear rise and fall times of 600 msec). Each delay between sounds was 150 msec. Additional presentation sequences began 1 sec after the preceding test sound, until the listener made a judgment.

The perceived loudness was evaluated on trials 6-8, following the completion of the measurements of perceived distance. Measurements of the perceived loudness used a magnitude estimation task[14, 15]. The listener was presented first with a standard sound stimulus that was defined as having a loudness of "100" (a numerical value of the sensation produced by the standard). Then the whole "typical presentation sequence" was presented for each of the test stimuli, and the listener was asked *to assign a number to the perceived loudness of the test* sound, relative to the standard. For example, if a particular test sound seemed to have twice the loudness of the standard, the listener was told to assign the value "200." For each presentation sequence, the standard stimulus was presented for 1.5 sec, followed after 500 msec by the presentation sequence for measuring the perceived distance. A new presentation sequence was begun 3 sec after the preceding sequence had finished, until the listener reported his/her judgment.

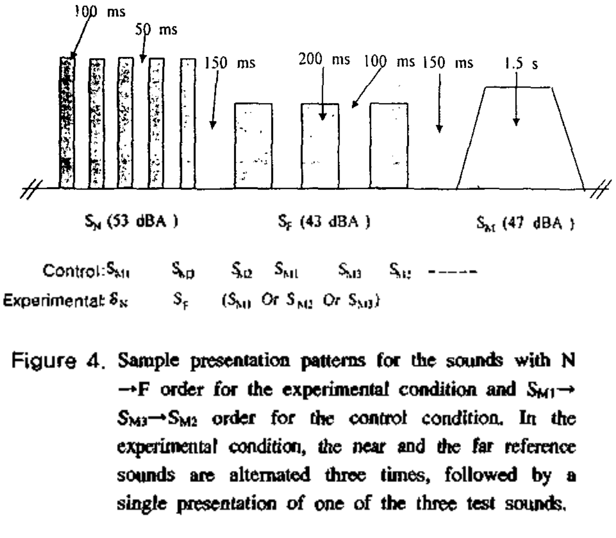


Figure 4. Sample presentation patterns for the sounds with N →F order for the experimental condition and S_{M1}→ S_{M3}→S_{M2} order for the control condition. In the experimental condition, the near and the far reference sounds are alternated three times, followed by a single presentation of one of the three test sounds.

III. Experimental Results

Each listener made a judgment of the perceived distance (D') to the five sounds and the perceived loudness (L') of the three test sounds using a verbal report. Main statistical analysis (ANOVA) was performed on D' values of the two reference sounds and the three *test* sounds and L' values of the test sounds, separately.

3.1. Perceived distances of the sound sources

The common experimental question was whether D' values of the three test sounds, located at the same physical distance (3m) from the listener but in different directions, could be affected by including the referent sounds (two end-points). To examine the difference among the test sounds within each condition, One-way ANOVA was carried out. D' values of the test sounds were significantly different only in the experimental condition ($F_{2,69}$ =72.37, p<.001). Such changes in D' values were consistent with the adjacency principle and were in the predicted direction.

Our experiment clearly demonstrated that though the three sounds were always located at the same physical distance from the listener, their D' values were affected by the referent sounds. The D' values of S_{M1} was influenced by the adjacent S_N and that of S_{M3} by the adjacent S_F.

On the other hand, it was expected that the average D' values might be approximately the same for the three test sounds in the control condition, since the test sounds were essentially similar (differing only as a consequence of loudspeaker signature) and the auditory cues were such that the test sounds should have fallen between S_N and S_F references in distance.

To provide an overall analysis, 2 (condition) x 3 (location of S_M) x 2 (gender) x 6 (orders for presenting SM) repeated ANOVA was carried out. The results revealed significant main effects for Condition ($F_{1,36}$=5.26, p<.05), Location of SM($F_{2,132}$=40.43, p<.001), Gender ($F_{1,36}$=14.86, p<.001) and a significant interaction of Condition and Sound Location ($F_{2,132}$=42.24, p<.001). Figure 5 provides an overview of the results showing condition and sound location variables. As can be seen in Figure 5, the distances of the three test sounds in the control condition were underestimated relative to their physical distance of 3m.

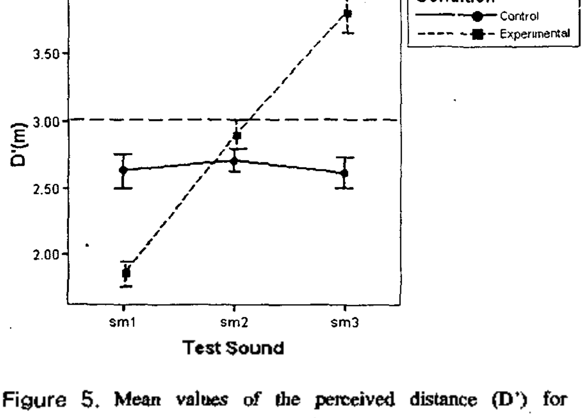


Figure 5. Mean values of the perceived distance (D') for sound sources in verbal judgment. The physical distances of loudspeakers are shown for comparison. (Error bar represents standard error).

3.2. Perceived loudness of the test sounds

The measures of L' were calculated by the mean judgments for each stimulus value. We were interested in examining whether or not D' could influence L' of the sounds. That is, for the constant sound level involved, a monotonic relationship between D' and L' values would be expected. To test whether L' values of each test sound differed significantly within the experimental condition, one-way ANOVA was performed. L' values of the three test sounds were significantly different ($F_{2,36}=13.34$, $p<.001$). These results indicated that the changes of D' affected L', particularly for S_{M1} and S_{M2}. Such changes in L' were in the predicted direction.

Figure 6 presents a summary of the results from the three test sounds. The average L' values are presented as a function of the location of the three test sounds. L' values shown in Figure 6 appears very similar to the variations in D' seen in Figure 5. That is, there was a tendency for values of L' to be positively associated with values of D'.

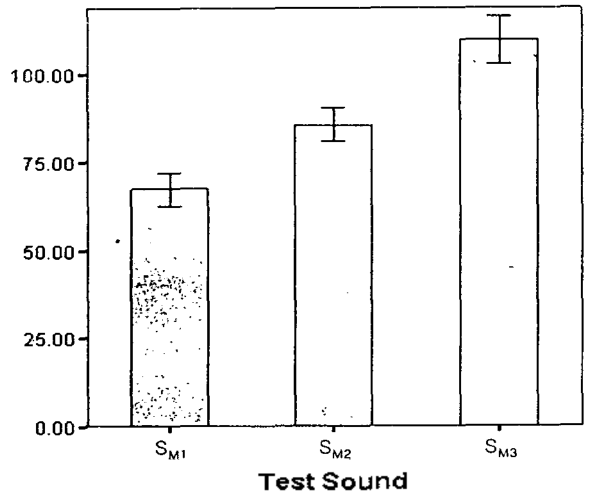


Figure 6. Mean values of the perceived loudness (L') across the test sound sources. (Error bar represents standard error).

IV. Conclusion

The findings that the perceived depth of a sound is changed by an adjacenct is consistent with our prediction based upon the adjacency principle. Although the three test sounds were at the same distance throughout the different conditions, their apparent distances in the control condition were almost equal, whereas they differed significantly in the experimental condition. An interpretation of these results is that the D' of each test sound is determined by relative cues between the test sound and the adjacent reference sound. For example, S_{M1} and S_{M3}, which were physically at the same distance (3m) from the listener, appear to be near by S_N (physical distance of 2m from the listener) and S_F (physical distance of 5m from the listener), respectively.

On the other hand, S_{MD}, which was located directionally mid-way between the two reference sounds, was not affected by the reference sounds. Thus, the results of this experiment are consistent with the adjacency principle that the effectiveness of an exocentric cue is inversely related to the directional separation between the test sound and the reference sounds. This phenomenon is quite similar to the previous findings of Gogel[2] in visual space. Therefore, the results offer evidence of the applicability of Gogel's adjacency principle to auditory space perception.

Finally, this experiment provided data on change in the apparent loudness of the three test sounds. The results of the experiment indicate that the reference sounds can influence the apparent distance (and loudness) of adjacent test sounds. That is, there was a tendency for greater D' values to produce greater L' values. These data are consistent with the previous studies[9, 16]. Such trends are interesting since an identical sound (47 dBA) was employed for each test sound and that sound was presented from the exact same distance.

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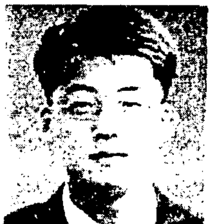

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