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Auditory Induction: Perceptual Synthesis of Absent Sounds

Abstract. *Within certain auditory patterns, fainter sounds may be "heard" clearly when replaced by louder sounds having appropriate spectral compositions. This auditory induction of fainter by louder sounds can cancel the perceptual effects of masking. Phonemic restorations, which have been reported previously, appear to be a specialized application to speech of the much broader phenomenon of auditory induction. The rules governing auditory induction indicate that it helps maintain stable auditory perception in our frequently noisy environment.*

When a speech sound or syllable within a sentence is deleted and replaced by a louder extraneous sound, listeners believe they hear the excised portion and cannot detect which part of the sentence is missing (*1*). When we reported this ability to perceptually synthesize missing phonemes, we did not suspect that it could be considered as a special case of a much broader auditory phenomenon. Speech components are not the only types of sounds that can be "heard" when they are not present. There appear to be at least two other types of perceptual synthesis that can be grouped under the generic term of auditory induction (AI).

We discovered the second type of AI when we repeated without pauses sequences consisting of three intensity levels of the same sound. Thus, when a 2000-hz octave band noise was presented through headphones at three intensities (for example, 60, 70, and 80 db above 0.0002 μbar) with each successive level lasting for 300 msec, and the sequence was recycled without pause, then the faintest sound appeared to be on continuously, coexisting with each of the two louder sounds. This is a puzzling and seemingly paradoxical auditory effect, for were the fainter sound to remain on, it should fuse with the louder sounds of the same spectral characteristics. Nevertheless, all subjects (20 undergraduate students, 8 graduate students and staff) reported this AI whether or not they were aware of the physical nature of the auditory pattern and the paradoxical implications of perceiving the faintest sound as continuous. The order of the three sounds was not crucial (the position of the middle and loudest intensities could be interchanged), nor was the spectral composition of the sound. However, temporal contiguity was important, and 50 msec of silence between successive sounds prevented AI.

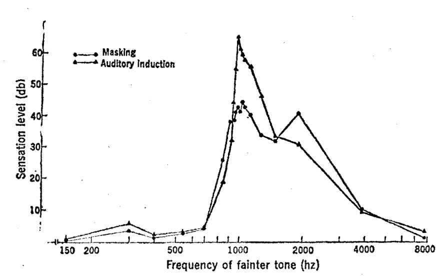

Fig. 1. Auditory induction and masking for tones in the presence of a louder 1000-hz tone presented at a sound-pressure level of 80 db. The values are the means for six subjects.

This type of AI involving spectrally identical sounds did not require that the repeated sequence consist of three intensities; 300-msec presentations of a 2000-hz octave band noise alternating between sound-pressure levels of 70 and 80 db resulted in illusory continuity of the fainter sound. Presenting other narrow noise bands, broad noise bands, and tones at alternating intensities also produced AI. These observations suggested the possibility that alternating the intensity of spectrally different sounds (for example, tones of two frequencies, or a tone and a noise) might give rise to a third type of AI having illusory persistence for durations comparable to those of the other two. There have been reports that this type of illusory continuity exists at rapid alternation rates (*2*). In these experiments, the illusory persistence of the fainter of two qualitatively different sounds was limited to about 5 to 90 msec, with most reports well below the upper limit. However, we have found it possible to induce illusory continuity for much longer durations (from a few hundred milliseconds up to some tens of seconds).

The first example of this type of AI which we studied in some detail involved alternation of a 1000-hz tone with a fainter tone of different frequency (*3*). Each tone lasted 300 msec. The 1000-hz tone was always at a sound-pressure level of 80 db, and six listeners adjusted the intensity of the fainter tone to the highest level at which it seemed continuous for the frequencies from 150 to 7800 hz shown in Fig. 1. The means of these maximum intensities for AI are expressed as sensation levels [or decibels above threshold of audibility (*4*)]. It can be seen that virtually no AI occurred up to 700 hz. At frequencies close to the 1000-hz inducing tone, AI was found at relatively high intensities of the fainter sound. When the frequency of the fainter tone matched that of the inducing tone (1000 hz), the special type of AI described earlier occurred, and four of the six subjects reported AI when the intensity of the fainter tone was only 3 db below that of the louder.

The general shape of the AI curve in Fig. 1 resembles that of a masking function, since it is greatest at frequencies close to the 1000-hz inducing tone and asymmetrical with a greater effect for frequencies higher than 1000 hz. Another clue to the possible relation of AI to masking was the observation reported for phonemic restorations that the illusory perception of the missing speech sounds required the extraneous sound to be at an intensity which could mask the speech (*1*). We therefore obtained masking judgments from the subjects in the AI experiment. A 1000-hz masking tone was kept on continuously at 80-db sound-pressure level, while a pulsed fainter tone was on for 300 msec and off for 300 msec. The listeners adjusted the intensity of the pulsing fainter tone until it could just be heard. The simultaneous masking thresholds for the same frequencies employed for AI are shown in Fig. 1. Values are expressed as sensation level (*4*). It can be seen that AI corresponds closely to masking for frequencies up to 975 hz. At exactly 1000 hz (*5*), the special AI for spectrally identical sounds occurred, and AI differed significantly from masking for this tone and for the neighboring frequencies from 990 through 1300 hz ($P < .05$, two-factor analysis of variance, repeated measures on both). At 1500 hz and above, AI and masking remain quite close, except for a second peak in the masking curve at 1950 hz, corresponding to the increase reported for frequencies close to one octave above the masker (*6*). The difference between AI and masking is significant at this frequency ($P < .05$, dependent *t*-test), indicating some basic distinction between the mechanisms underlying these two auditory effects.

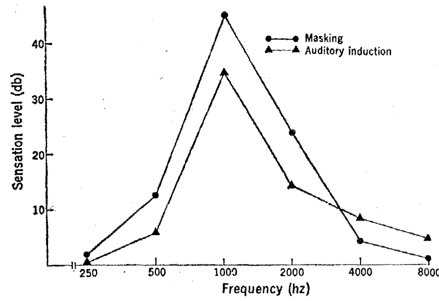

Fig. 2. Auditory induction and masking for tones in the presence of a louder one-third octave band noise which was centered at 1000 hz and presented at a sound-pressure level of 80 db. The values are the means for six subjects.

The generally close correspondence between the values for AI and masking has some interesting implications. Masking refers to the ability of a sound to perceptually obliterate another, but AI is in some ways an opposing effect—the ability of a louder sound to evoke the illusory perception of a simultaneous sound.

In order to verify whether AI can selectively cancel the effects of masking, we undertook two additional experiments in which noises were substituted for the louder 1000-hz tone used in the previous experiment. Noises of appropriate spectral characteristics are efficient maskers for some tones and not others, and the correspondence between masking and AI can thus be tested directly. Conditions were similar to those used in the experiment with pairs of tones. In the first experiment with noise, six subjects (five of whom had served in the earlier experiment with tone pairs) heard a narrow (one-third octave) band of noise centered at 1000 hz and presented at 80-db sound-pressure level. The results for both masking and AI are shown in Fig. 2. It can be seen that masking is maximal at the center frequency of the noise band, as would be anticipated, and that the masking function is paralleled by AI.

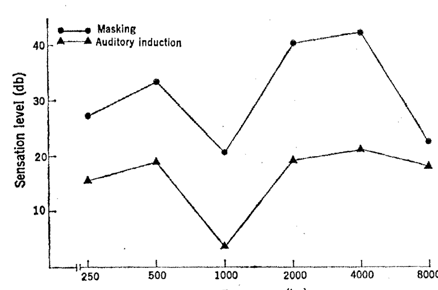

Fig. 3. Auditory induction and masking for tones in the presence of a louder pink noise lacking a band of frequencies from 700 to 1400 hz. This broad-band pink noise with a one-octave frequency notch was presented at a sound-pressure level of 85 db. The values are the means for 15 subjects.

The narrow band noise is perceived to have a discrete pitch corresponding to the center frequency, and it is possible that AI depends upon a direct comparison of the pitch of the noise and the fainter tone. For that reason, another experiment was undertaken with noise lacking a discrete pitch but having special masking characteristics. The stimulus was prepared by passing pink noise (noise having equal energy per octave) through filters which rejected a band of frequencies from 700 through 1400 hz, with maximum attenuation (40 db) at 1000 hz. This broad-band noise with a frequency notch was played at an overall sound-pressure level of 85 db, and conditions were similar to those used in the experiment with narrow-band noise. The results for 15 subjects (none of whom had served in earlier experiments) are shown in Fig. 3. It can be seen that masking at the frequency corresponding to the notch (1000 hz) was low and that a corresponding drop in AI occurred. It appears that AI does not depend upon a similarity of apparent pitches but upon overlap of spectral composition of the louder and softer sounds.

We also employed pairs of noises of different spectral composition. Auditory induction was found if the louder sound had a broader spectrum which included that of the fainter sound. Rather long durations were observed for illusory carry-over with such noise pairs. We obtained AI's of 20 seconds for 8 of 15 subjects when a band of pink noise from 500 to 2000 hz was alternated slowly with a fainter, one-third octave band of noise centered on 1000 hz. Six of these subjects heard the fainter sound carry through 50-second bursts of the broader band noise

Our observations with the three types of AI (phonemic restorations, sounds differing only in intensity, and sounds differing in both intensity and spectral characteristics) suggest a general rule: If there is contextual evidence that a sound may be present at a given time, and if the peripheral units stimulated by a louder sound include those which would be stimulated by the anticipated fainter sound, then the fainter sound may be heard as present.

Auditory induction appears to be a quite useful perceptual phenomenon permitting a highly selective reinstatement of sounds which would otherwise be lost through masking. The listener can thus establish a simpler and more stable interpretation of his auditory environment than the intermittent extraneous sounds present in our noisy world would otherwise permit.

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3. Listening was through matched TDH 49 headphones, and subjects controlled intensity by adjusting a visually shielded attenuator. Frequencies from separate oscillators were measured with the aid of quartz crystal time base, and the intensities were measured with an artificial ear connected to a Brüel and Kjaer model 2204 sound level meter. Timing was accomplished with a Grason-Stadler model 829E electronic switch set at a rise/decay time of 5 msec (which eliminated audible clicks).
4. The threshold of audibility in this and all other experiments corresponded to the minimum intensity at which the fainter tone (adjusted by the listener) could be heard while alternating with the fixed louder sound at the rate employed for measuring AI.
5. The same tone generator was used for the masked and the masking sounds when both were at 1000 hz to provide exact correspondence of frequency and phase. Hence, this measurement was equivalent to a just noticeable difference in intensity.
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Endothelial Projections

Smith *et al.* (*1*) describe endothelial projections which have been previously "overlooked." While not denying the presence of these structures in their photographs and the intriguing speculations which they have elicited, considerable caution is warranted lest Smith *et al.* also be guilty of having overlooked an important consideration. Their method described fixation of the pulmonary vessel *after* its removal; many artifacts can be introduced by loss of extension and distention of an elastic vessel such as this. Absence of distending pressure causes an increase in wall thickness of about 40 percent; an elastic vessel shrinks in length about 40 percent on removal which causes even further wall thickening and distortion of the organization of constituent elements (*2*). The endothelium is not spared, for others have shown a marked difference in its appearance when measures are taken to preserve distention and extension during fixation (*3*). The endothelium of distended arteries and veins is greatly thinned, and the published photographs of such vessels give little evidence for the presence of endothelial projections (*3*).

This is not to gainsay the findings of Smith *et al.* for the pulmonary artery; but it does seem premature to speculate about new structures seen at 14,000-fold magnification until attention is paid to the maintenance of gross functional architecture of the entire arterial wall.

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While there is no doubt that shrinkage and contraction occur in muscular arteries upon removal, we have been unable to correlate cellular contraction with the occurrence of endothelial projections. Indeed, transmission electron micrographs of the material that we used for scanning electron microscopy show areas of endothelial thickening [possibly due to contraction of the endothelial fibrillar material (*1*)]. However, the number of projections never appears large in thin sections and over the thickened portions is no greater than over the slender arms of the cells [figure 4 of Smith *et al.* (*2*)], making it unlikely that the projections result from gross "crinkling" of the vessel wall.

Furthermore, we have evidence of the existence of endothelial projections in pulmonary capillaries fixed in situ by perfusion at physiological pressures. These vessels appear to have little or no intrinsic capacity for contraction and are not surrounded by muscular or elastic elements.

Finally, once one has recognized the existence of endothelial projections, one finds them in a large number of published micrographs of vessels of a wide variety of sizes [for examples, see (*3*) and figure 4 of Esterly and Glagov (*4*), cited by Wolinsky].

The density of endothelial projections varies in different vessels. In some instances the degree of their proliferation suggests highly specialized functions, for example, in the pecten of the bird's eye (*5*) and in the rat Gasserian ganglion (*6*). The latter study, performed entirely by transmission electron microscopy, led the authors to postulate the existence of endothelial projections nearly 3 years ago.

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