Auditory localization: The importance of eye movements and a textured visual environment*

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Two experiments were designed to investigate the factors involved in the visual facilitation of auditory localization. In both experiments, adult human Ss pointed to targets in a variety of visual conditions. The results of the first experiment showed that target-directed eye movements were important. In the second experiment, eye localization was assessed, along with pointing localization. Both eye and hand localization of the hidden auditory targets were better when target-directed eye movements were made in a lighted environment than when made in the dark. Data also suggested that Ss have better knowledge of their eye position in the light. Possible mechanisms for the involvement of eye movements were suggested, and the theoretical importance of the results was discussed.

Several studies have shown that auditory function in humans is influenced by visual stimulation. For example, Hartmann (1934) and Child and Wendt (1938) demonstrated that pitch and intensity discriminations were better in the light than in the dark. Auditory localization is also affected by visual stimulation. Jackson (1953) showed that localization of an auditory target was biased toward the position of a discrepant and simultaneously presented visual stimulus. Similarly, Pick, Warren, and Hay (1969) found that judgments of the position of an auditory target were biased toward the discrepant apparent visual position of the same target.

Another aspect of visual involvement in auditory localization was demonstrated by Warren (1970), who showed that adult Ss were better at localizing an unseen auditory target with the eyes open than with them closed. This phenomenon, called visual facilitation, was operationally defined as a smaller variability of localization with the use of vision than without it. Facilitation is thus a relative performance concept.

In the original set of experiments, Warren attempted to determine what conditions of visual stimulation were necessary to produce facilitation. Free vision, where S could look wherever he wanted in a lighted visual environment, produced the best localization. Having the eyes open and

free to move in a completely dark environment did not produce better localization than did having the eyes closed. Restricting eye movements by requiring a straight-ahead fixation in a lighted environment produced localization that was not significantly worse than that in the free vision, lighted environment condition. This result was surprising, since it was expected that eliminating target-directed eye movements would interfere with the facilitating effect of vision.

The experiments reported here were designed to investigate in more detail the possible involvement of eye movements in auditory localization. In the first experiment, eye movement involvement was standardized in one condition by requiring S to look toward the auditory target before pointing. Performance in this condition was compared to that in two other conditions, one where S maintained a straight-ahead fixation in a lighted environment, and another where S kept his eyes closed. If eye movements are involved in the facilitation phenomenon, the compulsory involvement of eye movements should produce better localization than in the fixation condition or in the eyes-closed condition.

EXPERIMENT 1 Method

Subjects. Twenty-four college students served as Ss. No S reported any hearing abnormality, and those Ss who normally wore glasses or contact lenses wore them during the experiment.

Apparatus. The apparatus consisted of two semicircular shelves. The S sat on an adjustable chair with his chin on a chinrest on the lower shelf at the

center of the semicircle described by the parallel shelves. Above S's head, the second shelf extended out and hid from view the boom from which the targets were suspended. The boom rotated about a center point directly above S's head and could be moved by E, by means of a pulley system, to any of the target positions. A khaki-colored burlap cloth screen was stretched from the circumference of the top shelf to that of the bottom shelf. This screen was perpendicular to S's line of sight, and it hid the target speaker from his view. The interior of the apparatus was illuminated by four 24-V bulbs that were not visible to S. The illuminated cloth screen thus provided a textured visual field.

The auditory target was a repetitive clicking sound, presented with a frequency of 2 clicks/sec, which remained on until S completed his pointing response. The 12 target positions were located at ± 30 , ± 25 , ± 20 , ± 15 , ± 10 , and ± 5 deg laterally along the outer circumference of the lower shelf, where 0 deg represents S's straightahead.

Under the bottom shelf, a response array consisted of bare wires along each degree ray from 0 to 90 deg out on either side. The center of emanation of these rays was a point directly below S's chinrest, and the rays extended out beyond pointing range. When S reached out and pointed up underneath the board toward the target, a wire on his right forefinger touched one of the rays and completed an electrical circuit. The E read the response to the nearest degree from a display panel.

Eye position was monitored by placing small Beckman skin electrodes at the external canthus of each eye. Eye position was recorded as a dc potential, which caused the deflection of a Beckman Dynograph recorder pen: the pen deflection was linearly related to the amount of eye movement well beyond the range of targets utilized. The Dynograph record for all Ss also contained a record of the onset and termination of the clicks and a marker when S touched the response array with his pointing finger.

Conditions. Ss pointed to auditory targets in four conditions. Fixation straight ahead (F): S had his eyes open in the lighted environment, but he maintained fixation on a small light straight ahead of him during the task. Split fixation (S): S kept his eyes open in the lighted environment, but he fixated a light at $+35$ deg for half the trials and a light at -35 deg for the other half. Eye movement (E): with his eyes open, S was instructed to look toward each auditory target before pointing to it. No vision (N): S kept

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Table 1
Group Means of MAE and SD Scores
(Degrees) for Pointing Localization
in Experiment 1

Condition	MAE Score		SD Score	
	Mean	SD	Mean	SD
E	4.4	2.3	4.5	2.2
N	5.9	2.1	6.3	2.3
F	5.7	1.9	6.0	2.6
S	6.1	2.5	5.8	2.7

his eyes closed, with no instructions about where to look.

A replication of the basic facilitation phenomenon should be provided by finding better performance in E than in N. To the extent that eye movements are a vital component of the facilitation phenomenon, E performance should be better than F, where eye movements were restricted. Eye position was monitored during the F task to ensure that S maintained fixation within 2 deg either side of straightahead. The record was also monitored during the E task to ensure that a stable fixation was attained before the onset of the pointing response.

In the S condition, half the Ss (termed "near split") fixated a light at -35 deg (i.e., to S's left) while performing the trials in which the target was on the left side of straightahead, and they fixated a light at +35 deg while performing the trials on which the target was on the right. The other 12 Ss (termed "far split") fixated a light at +35 deg while localizing the targets to the left, and a light at -35 deg while localizing those to the right. Thus, for the far split Ss, the fixation point was 35 deg further from the average target position than for the near split Ss. The S condition was included for two purposes. First, the near split Ss were compared with the far splits to provide information about the effect of the distance between fixation and target area. Second, the possibility of a central tendency effect of fixation on the pointing responses could be assessed by comparison of the mean response in F with that in S for the near split Ss. Analysis of the data revealed no differences in performance in either of the comparisons.

In each of the four conditions, each target position was used once, with presentation in a random order. Each of the 24 Ss performed in all four conditions, with condition order counterbalanced between Ss. It was not possible to use a bitebar to restrain head position because of the noise that such an arrangement introduces into the eye movement records. However, head position was restrained by the

use of a chinrest, and S was instructed to keep his head directed straight ahead without movement in all conditions.

Results

There are several meaningful measures of localization performance. In this experiment, both standard deviation of error (SD) and mean of the absolute values of error (MAE) scores were calculated. The SD provides a measure of S's response consistency, while MAE provides a measure of localization veridicality from trial to trial. The MAE score was calculated for each S in each condition by averaging the absolute values of the errors of localization for the 12 trials.

The SD scores were entered into a one-way analysis of variance, with the four conditions as levels of a within-Ss variable. The effect of condition was significant, $F = 4.53$, $df = 3,69$, $p < .01$. The condition means appear in Table 1. Newman-Keuls contrasts showed that performance in the E condition, with compulsory eye movements, was significantly less variable than performance in the N condition, $p < .01$, or in the S or F conditions, $p < .05$ in both cases.

The MAE scores were entered into a similar analysis of variance, and the results were quite similar to those for SD. The effect of condition was significant, $F = 5.09$, $df = 3,69$, $p < .01$. Contrasts showed that localization was more veridical in the E condition than in any of the other conditions, $p < .01$ in all cases.

Thus, for both measures, the facilitation phenomenon was replicated, and further, the expectation that target-directed eye movements would lead to better localization was confirmed. The results thus support a visuomotor involvement in auditory localization.

Two differences between the present experiment and that reported by Warren (1970) may account for the different results. First, the maintenance of fixation in the F condition was carefully monitored in this experiment, while Warren had no way to do this. Performance in the fixated condition in that study may have been better because eye movements may, in fact, have occurred. Second, target-directed eye movements were required and monitored in the present experiment, while only "free vision" was instructed in the previous experiment. In spite of the Ss' reports of target-directed eye movements in the previous study, it seems quite possible that the intentionality of the movements required here made them more effective.

EXPERIMENT 2

The second experiment was designed to investigate further the nature of the visuomotor involvement. How does the facilitation occur, and what is it about eye movements that aids localization? The most obvious possibility is that S has more precise control over his eye movements than over his hand movements and can thus make better localizations with his eyes. Thus the proprioceptive information about eye position may serve as a more effective target for the hand response than the original auditory source does. This formulation relies on S's ability to use proprioceptive information about his eye position. Merton (1964) and Festinger and Canon (1965) review the evidence and suggest that such proprioceptive information is not available. Festinger and Canon go on to suggest, however, that eye position information may be gained by monitoring the efferent commands that produce target-directed saccadic movements. Accordingly, the visual involvement in auditory localization may be formulated as follows: S localizes the auditory target with his eyes, and he gains efference information (rather than position information) from the eye movements which helps to specify the target position.

There is some question as to whether efference alone is sufficient to explain the type of facilitation found in Experiment 1. Warren (1970) reports an experiment in which Ss pointed to unseen auditory targets in lighted and dark visual environments. The Ss were free to make whatever eye movements they wished, and, in fact, most Ss did report that they moved their eyes toward the targets in both conditions. In spite of the eye movements, localization by pointing was much better when the lighted environment was available. Eye movements alone were not sufficient: there was something vital about the visual environment in which the eye movements took place. It may be that when an eye movement is made in a lighted, textured visual environment, S obtains useful information about the position of his eyes by comparing the efferent commands with the amount of change in the visual field produced by the movement.

In this experiment, localization by eye position was analyzed, in addition to localization by pointing. Eye localization of unseen auditory targets in a lighted, textured visual environment was compared to that in a completely darkened environment. If the efference notion alone is sufficient, the eye localization under these conditions should not differ.

In addition to testing for the necessity of visual texture information, the experiment was designed to provide more information about the eye-hand relation in auditory localization through an analysis of trial-to-trial eye-hand correspondence.

Method

Subjects. Eighteen college students served as Ss. S requirements were the same as in Experiment 1.

Design. The apparatus was identical to that used in Experiment 1, with one modification. For the second group of nine Ss, a switch was mounted under the chinrest. Ss in the second group were instructed to grasp the switch between trials. Thus, when S began his pointing response, the switch was released and a mark appeared on the Dynograph record. Each S in the first group was instructed to place his right hand on his lap between trials. This procedure was identical to that of the first experiment.

Two experimental conditions were identical to those of Experiment 1: fixation straight ahead in a lighted environment (F), and eye movements before pointing in a lighted environment (E). In a third condition (D), S was required to keep his eyes open and make eye localization before pointing, but the visual environment was completely dark except for a dim light at S's straightahead. This light was on only between trials. Thus, S had a fixed, known eye position when each trial began. Monitoring of the eye position record again insured that S did make an eye localization before pointing in E and D and that fixation was maintained in F. In the E and D conditions, it was emphasized to S that he should not begin to point until he had completed his eye localization of the target. Eye position was analyzed by reference to a calibration graph, obtained for each S separately, by having S fixate on a series of visual targets both before and after the experimental conditions.

Each S performed all three conditions, with condition order counterbalanced between Ss. Each of the 12 target positions was used once in each condition, with target order randomly determined.

Results

Both SD and MAE scores were calculated as reported for Experiment 1. Analysis of variance was performed on the SD scores, with condition as a within-Ss variable and with handle/no-handle as a between-Ss variable. The effect of the handle procedure was not significant, $F < 1$, nor was the interaction, $F = 2.86$, $df = 2,32$. The effect of condition was significant, $F = 12.05$, $df = 2,32$,

$p < .01$. The condition means appear in Table 2. Newman-Keuls contrasts showed that performance in the E condition was significantly better than in D, $p < .01$. Performance in E was also significantly better than in F, $p < .01$. Thus, when S made target-directed eye movements in a lighted, textured visual environment, his pointing localization was less variable than when he made target-directed eye movements in the dark or when he maintained fixation in the lighted environment.

A similar ANOVA was performed on the MAE scores, and the pattern of results was the same. The effect of the handle procedure was not significant, $F < 1$, nor was the interaction, $F = 3.03$, $df = 2,32$. The effect of condition was significant, $F = 8.26$, $df = 2,32$, $p < .01$. Contrasts showed that E performance was better than D, $p < .05$, and E was better than F, $p < .01$. Thus, the pattern for localization veridicality was identical to that for localization consistency, and again the joint effect of eye movements and visual texture was demonstrated.

DISCUSSION

Localization by Eye Movements

For the eye localization analysis, the records of the second group of nine Ss were examined in detail. For these Ss, the record contained the following information: stimulus onset, initial saccade, adjustment of eye position after the initial saccade, onset of pointing response, and end of pointing response. MAE scores were calculated for the accuracy of eye position after the initial saccade in the E and D conditions. Comparison of mean MAE showed that eye localization was significantly more veridical in E than in D, $t = 2.67$, $df = 8$, $p < .05$. Thus, saccadic eye movements in the lighted environment were more accurate than in the dark.

The Ss were not prevented from adjusting their eye position after the initial saccade, and such adjustment did occur in 79% of the E trials and in 84% of the D trials. Analysis was also performed on the final eye position, that is, on that eye position when S started the pointing response. Final eye position was also significantly more veridical in E than in D, $t = 3.40$, $df = 8$, $p < .01$. In sum, the lighted environment provided for better saccadic localizations, as well as for better fine-adjusted eye localizations.

Correspondence of Eye and Hand Localization

It remains only to ascertain whether there is a greater correspondence between hand and eye localization in the light than in the dark. If S had

Table 2
Group Means of MAE and SD Scores (Degrees) for Pointing Localization in Experiment 2

Condition	MAE Score		SD Score	
	Mean	SD	Mean	SD
E	4.6	2.4	4.2	1.6
D	6.0	2.3	6.0	2.5
F	7.0	3.6	6.9	3.8

better information about his eye localization position in E, and if eye position information were used to mediate hand localization, then a measure of eye-hand correspondence should show a closer correspondence in E than in D. The score used to assess this correspondence was calculated by taking the difference between final eye position and hand position for each trial and finding the SD of the differences. The smaller the SD score, the closer the correspondence between eye and hand position from trial to trial. The mean SD for the E condition was significantly smaller than that for D, $t = 3.29$, $df = 8$, $p < .01$. Thus, eye and hand position were significantly more correspondent in the lighted visual environment than in the dark.

These experiments show that vision is involved in the pointing localization of auditory targets. Performance was significantly better when vision was allowed. Necessary conditions for this visual facilitation may be summarized as follows: target-directed eye movements within a patterned visual environment produced the best localization. If either the eye movements or the patterned environment was removed, localization was worse.

How does the visual involvement aid auditory localization? No direct visual information about target position was obtained in any of the conditions. In all conditions, the primary basis for localization was interaural time and intensity differences, the traditionally considered auditory localization cues. We suggest that in all conditions, a basic localization judgment was made on the basis of these auditory cues: that is, S assigned a range of possible location on this basis. The size of the range varies inversely with auditory localization acuity, or with S's precision in evaluating the time and intensity differences. S made better eye movements toward the auditory target in the presence of the patterned visual environment. There was no difference in the auditory information itself: the difference in eye localization accuracy must have been produced by the visual environment. Since S was better able to match his eye position to a target position in the light, it follows that he had better

information about his eye position in the light. It is not surprising, then, that S was better at making a pointing response to the auditory target in the light, since he could use the more precise target provided by his eye position to direct his pointing. Following this line of argument, it is reasonable to conclude that pointing in the fixated condition was less precise because S had only the auditory range available as a target, without any target-related eye position information.

While this formulation fits the available data, several questions remain. First, why is the initial saccade more accurate in a lighted environment than in a dark one? Two hypotheses seem reasonable: (1) The presence of texture in the visual field enables a relatively accurate predetermination of the size of the saccade necessary to align the eyes with the auditory target. Predetermination in this usage implies that this judgment occurs while the eyes are still straight ahead, before the saccade is initiated. (2) The saccade initiated is the same under both dark and light conditions. That is, S has no more information to start with in the light than in the dark. In the light, however, S can monitor the extent of the saccadic movement during the movement by assessing the amount of texture passed over by the eye. Thus, in the light, the performed saccade conforms more closely to the planned saccade than in the dark, since in the

dark S has less information about the magnitude of the performed movement. This hypothesis implies that eye movements interact dynamically with texture to structure visual space. The similarity of this formulation to the reafference-exafference notions of von Holst (1954) is apparent. While the present data do not allow a choice between these two alternatives, it should be noted that some research (Volkman, 1962; Volkman, Schick, & Riggs, 1968) does support the occurrence of the type of visual processing during saccadic movements that would be required this question.

A second area needing further work involves the nature of the eye-hand relation under these conditions. In the present study, S was instructed to point to where he was looking, and the experimental conditions allowed only assessment of the effects of the eye on the hand. Results of localization studies using a conflict paradigm, however, typically have demonstrated a reciprocal influence of hand on eye (e.g., Pick, Warren, & Hay, 1969; Warren & Cleaves, 1971). Phrasing the question within the present experimental paradigm, does the act of making a pointing response exert an effect on eye localization of the target? In view of the previous literature, it would seem reasonable to expect a less influential but significant effect of hand on eye. Work is in progress in our laboratory to investigate this question.

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