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Audio–Ocular Response Characteristics[1]

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The characteristics of eye movements elicited by auditory stimuli, the audio–ocular response (AOR), differ from those made in response to visual stimuli. Their latencies are longer, their accuracies slightly worse, and their velocities slower. In addition, AOR latencies decreased with increasing stimulus eccentricity; this is opposite to the latency variation of visually evoked saccades.

Anatomical and physiological studies indicate that the visual and auditory fields project onto the superior colliculi, thereby forming a sensory map of visual and auditory space (Gordon, 1972; Syka & Straschill, 1970). An ocular motor map also exists in the colliculus (Robinson, 1972). Thus, it is not surprising that individuals respond to auditory as well as to visual stimuli with eye movements.

The latency, accuracy, and velocity characteristics of eye movements elicited by visual stimuli have been extensively investigated (Becker & Klein, 1973; Boghen, Troost, Daroff, Dell'Osso, & Birkett, 1974; Täumer, Lemb, & Namislo, 1976). Much less is known about eye movements elicited by auditory stimuli (audio-ocular response, AOR). Previous studies (Dodge, 1923; Hennebert, 1960; Lackner, 1977) noted the presence of nystagmus when sound was rotated about the head of subjects, and Paulsen and Ewertsen (1967) reported that the eye could be positioned to within 5° of a 20° auditory stimulus. The characteristics of the eye movements elicited by auditory stimuli have not been reported, nor have comparisons been made to eye movements elicited by visual stimuli. The present experiment was performed to investigate these points quantitatively.

METHODS

Four subjects—two men and two women—between the ages of 26 and 31 years with normal auditory, visual, and ocular motor function participated in this experiment. None of the subjects had any previous eye movement test experience or practice prior to testing.

Eight auditory stimuli and one visual stimulus were used. The auditory stimuli were narrow-band noise bursts (2 octaves wide at the 3-db points) centered at 750, 1500, 3000, and 6000 Hz and presented at 65 and 85 db as measured at ear level (General Radio Co. Sound Level Meter Type 1565A). These stimuli were gener-

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ated by an Amplaid 300 audiometer (referenced at 0.0002 μbar, sound pressure level) driving a Teledyne Model R-618 amplifier and were presented through 9-cm loudspeakers located on a 228-cm diameter perimeter at 10 and 20° right and left of a 0° stimulus position. At no time during testing or calibration were the loudspeakers visible to the subject. No sound-deadening procedures were used since noise stimuli do not generate standing waves and we wished to simulate real-life conditions. The visual stimuli were red light-emitting diodes located on the perimeter directly below the loudspeakers and driven by previously described circuitry (Dell'Osso, Troost, Patterson, & Sacerio, 1974).

The subject was seated in a modified dental chair at the center of the perimeter. His head was firmly fixed with a chin cup and head brace. The subject's task was to "look" as quickly and as accurately as possible from his fixation position (a continuously illuminated red light at 0°) to the position of the auditory or visual stimulus. The subject was to "hold" this position for about 1 sec, then return his eyes to the fixation position, wait for the next stimulus, and repeat the task.

To monitor and record the horizontal eye movements of both eyes, an infrared eye monitoring system (Biometrics, Model 200), linear to plus or minus 20°, and an eight-channel dc-coupled recorder (Beckman Instruments, Inc., Type R. Dynograph) with a 100-Hz bandwidth were used. Velocities were obtained by electronic differentiation of the eye position signals. It was possible to measure the latency, accuracy, and velocity to 10 msec, 0.5°, and 10°/sec, respectively.

For each subject, a complete block of trials consisted of the presentation of the five auditory stimulus positions at each of the eight combinations of frequency and intensity, plus the visual stimulus, for a total of nine subsets. Four of these subsets, selected randomly, were presented at one experimental session and five at the other. All of the stimuli were randomly presented at each position for 400 to 600 msec, with an average interstimulus interval of 2.5 sec. Calibration was checked and a rest period given prior to each new stimulus presentation. Testing of each subject required two 45-min sessions.

RESULTS

The data showed that the form of eye movements elicited by auditory stimuli (as shown in Fig. 1 for one subject) compared well to eye movements elicited by visual stimuli. Initial statistical analyses revealed that the trends of the data for all subjects were similar and that there were no significant differences across the eight auditory stimuli or between the first and last five eye movements to each position for each stimulus. These observations permitted us to combine the responses for all subjects and auditory stimuli and to discount the possibility of a practice effect.

Figure 2 shows the latency for eye movements to visual and auditory stimuli at the 10 and 20° positions. The auditory response latency at all positions was longer than the visual latency and, although the latency *increased* for the visual stimuli, it *decreased* for the auditory stimuli from the 10 to 20° positions. These differences were statistically significant ($p < .001$). These data would indicate that, in contrast to auditory reaction time (hand-held switch) studies (Andreassi & Greco, 1975), auditory stimuli take longer to be processed by the eye movement system than do

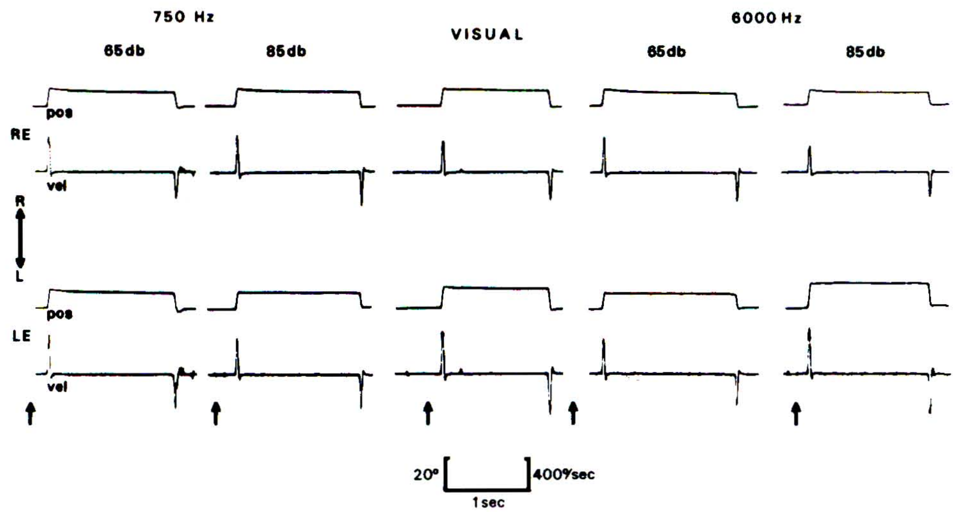

FIG. 1. Typical eye movement responses to both visual and auditory stimuli. All stimuli were at 10° to the right of center; shown are examples of the responses to two auditory intensities at each of two center frequencies. Arrows indicate stimulus onset.

visual stimuli. Methodological differences between laboratories require care in making interlaboratory comparison. Perhaps localization of an auditory stimulus, as well as its discrimination close to the midline, requires more "decision time" prior to initiation of the response.

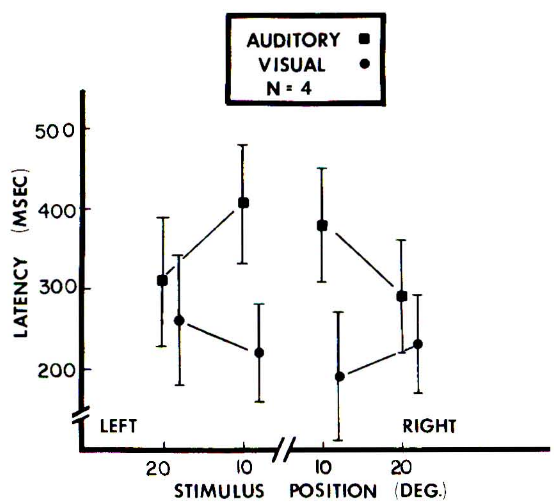

FIG. 2. Eye movement latencies to both visual and auditory stimuli. Each mean, here and in subsequent figures, represents 640 responses to the auditory stimuli and 80 responses to the visual stimuli. The visual data have been shifted along the abscissa for clarity. Vertical bars indicate plus or minus one standard deviation, here and in the following figures.

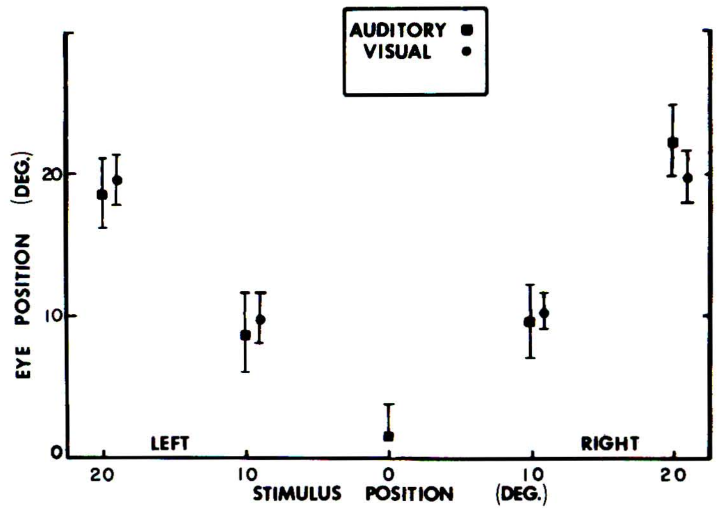

FIG. 3. Eye movement accuracies to both visual and auditory stimuli.

The data in Fig. 3 show that eye movements to auditory stimuli are only slightly less accurate than eye movements to visual stimuli. The accuracy of the AOR is, however, substantially better than the response indexes used in previous localization studies (e.g., pointing or verbal reporting) (Merton, 1951; Paulsen & Ewartsen, 1967; Sanchez-Longo & Forster, 1958). Unlike studies using pure tones (Deatherage, 1966), we found accuracy to be independent of the center frequency or intensity of the stimulus. Thus, it seems clear from these data that the eyes can be directed to a narrow-band noise burst with a considerable degree of accuracy (i.e., $\pm 3°$).

Figure 4 shows that visual and auditory stimuli elicit eye movements that lie on parallel but separate velocity–amplitude curves, with the auditory movements being significantly slower. This is consistent with data which show that saccades made in the dark or in a Ganzfeld are slower than those made in a structured visual environment (Bahill, Clark, & Stark, 1975; Becker & Fuchs, 1969; Ron, Robinson, & Skavenski, 1972; Sharpe, Troost, Dell'Osso, & Daroff, 1975).

DISCUSSION

Eye movements made toward noise sources have, then, been found to be slower, slightly less accurate, and, for small gaze angles, slower to initiate than refixations made toward visible targets. Their accuracy, however, is still much better than that obtained through the use of other localization paradigms such as pointing or verbal estimation (Jerger, Weikers, Sharbrough, & Jerger, 1969; Sanchez-Longo, Forster, & Auth, 1957). This may be due to the fact that turning one's eyes toward a sound is a very natural response; both pointing to a sound and verbally estimating its deviation from center are artifical laboratory procedures. Directing one's gaze toward a sound (AOR) is a basic response with obvious survival value, and is also an integral part of the orienting response (Gogan, 1970) and might logically be expected to be a better measure of localizing ability

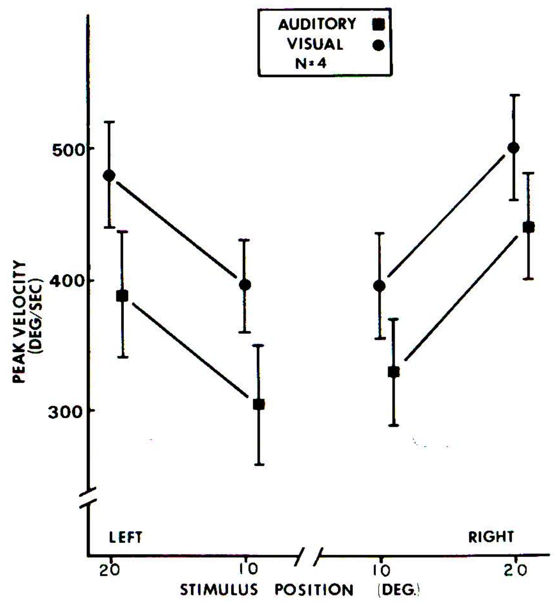

FIG. 4. Eye movement peak velocities to both visual and auditory stimuli.

than some more artificial indicator. This technique might therefore be useful in audiology or neuro-otology as a more sensitive test for localization defects.

As mentioned previously, the superior colliculus is the primary anatomical site of convergence of the visual and auditory pathways. Gordon (1972) has reported on cells in the cat superior colliculus that responded to moving lights and noise sources, with visual and auditory receptive fields that were at least roughly overlapping. There was a smaller number of cells that responded to the turning on and off of stationary stimuli, such as were used in the experiments described here, with the visual response being more frequently dependent on stimulus movement.

The superior colliculus seems to be the region most directly concerned with allowing an organism to find and follow objects moving around it. When sensory modalities are mixed, such as the case when the eyes are moved toward a sound, an interesting conflict arises. The visual world is mapped retinotopically in the superior colliculus; the auditory world is represented in reference to the body. If the eyes are pointed straight ahead, the two mappings are equivalent. If, however, the head remains straight but the eyes are directed laterally, the two representations shift apart. If the AOR is examined under these conditions, it is not clear what effects this change in reference frame orientation will have on accuracy and latency. A series of experiments is currently under way to investigate this point. Specifically, the interaction between visual and auditory representations of the world should provide an understanding of the spatiotemporal transformation required to generate the neural control signal responsible for the saccadic eye movement.

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