Chapter four: The nature of the Wallach cue and MVP localization

Of all the sources used in the experiments reported so far, those in or near the MVP have been associated with the strongest effects of head motion. The greatest effect for head motion, in terms of elevation judgement, has consistently been associated with the source positioned directly overhead, which is perceived at elevations substantially above apparent positions for those directly in front and behind. There is also a strong effect of head motion for the source positioned directly beneath, as it is often judged to be elevated well above the HP sources, and although such responses are highly inaccurate, the effect is nevertheless in line with what would be expected according to Wallach's theory, assuming purely rotational movements. Likewise, of the 14 sources employed by Thurlow and Runge (1967), head motion produced its greatest increase in elevation accuracy with the source positions near the MVP (at 41° elevation, in front). Experiment 5 in the present report provides evidence that the effect of head rotation on resolving front-back ambiguity is strongest for sources in or near the MVP. With the 500-Hz pure tone, 8° of rotation produced a substantial reduction in front-back confusion for the sources in or near the MVP but not elsewhere.

The data Wallach (1939; 1940) provides as evidence for head motion cues, showing highly accurate perception of simulated source elevations, involved artificially producing the changes in interaural differences that would normally arise from sources positioned within the MVP. In light of evidence for strong effects of head movement involving sources in that region, it is appropriate to examine head movement effects specifically with respect to MVP sources.

4.1. EXPERIMENT 6

In the sixth experiment, the effect of head rotation on accuracy of elevation judgement, and on front-back discrimination, was tested using sources positioned in the upper MVP. Attention was given to replicating the rotation movement occurring in Wallach's (1939; 1940) experiments. Details of how much Wallach's listeners moved are not clear, but information from one experiment in Wallach (1940) tells how listeners sat on a rotatable chair while the experimenter turned the chair and the listener back and forth a 'few' times before the signal was interrupted and the listener made a response. Also, the apparatus he employed meant that movement was limited to 60° of rotation. In an attempt to achieve a close correspondence with the movements of Wallach's listeners, the listeners in the present study were required to rotate the head back and forth between two points 60° apart, 30° to the left and right of the plane of the vertically arrayed loudspeakers, until the signal ceased.

The sixth experiment involved the use of various low- and high-pass noises, as well as broadband noise, to investigate further the frequency-dependent nature of the Wallach cue. To aid such an investigation, some of the conditions involved disruption of pinna function so that the effect of head rotation in company with distorted and undistorted pinnae function could be gauged.

Distortion of pinna function provides the opportunity to test Wallach's claim that his success in simulating source elevation using sources confined to the HP, was evidence that head motion cues could override information derived from the pinnae. The signal he used was piano or orchestral music reproduced from victrola records. The music itself probably did not provide strong pinna cues, however, it is possible that the equipment he used could have introduced hiss and switching transients into the signal. Such a signal may therefore have been relatively rich in pinna cues. Suggestive evidence that pinnae cues could be overridden by competing cues is provided by Wightman and Kistler (1992), who used headphones to present virtual sound sources with static ITD cues specifying a different direction to static ILD and pinna cues. Listeners in their study showed a strong tendency to indicate apparent directions consistent with the ILD cues.

There is also evidence that the cues provided by the pinnae can override low-frequency information. A study by Musicant and Butler (1984), with motionless listening, involved temporary disruption of pinnae function (cavities filled with ear mould material). It was found that front-back discrimination was more accurate with 4-kHz low-pass noise than with broadband noise. This outcome suggests that if a signal contains the range of frequencies (4 kHz and up) that are necessary for pinna function, spectral information from this range, even if it is distorted, overrides shoulder/torso generated spectral information available in lower frequency ranges. If head motion cues can override pinna cues it is expected that disruption of pinna cues would not weaken the head motion effect, but if pinna cues override head motion cues, distortion would be expected to reduce the effect of head motion.

4.1.1. Method

Ten female and six male listeners (average age 26 yrs.), with no previous experience in such experiments, all reporting no abnormalities of hearing, were tested using a series of seven different signals, in four different listening conditions, giving 28 experimental conditions per listener. The signals used were broadband (white) noise — constant sound pressure level across all frequencies from 0.25 to 18 kHz — and various low- and high-pass noises, filtering providing a rejection slope of approximately 90 dB/octave. For half the sample, the order of signal presentation was: 1, 2, and 4-kHz low-pass noise; broadband noise; 1, 2, and 4-kHz high-pass noise. The reverse order was used for the other half of the sample. As in Experiment 4, signals were inverse filtered to compensate for the transfer function of each loudspeaker. They were presented at a nominal level of 60 dBA, with random variation, in 0.375 dB steps, over a range of ±3 dB, from trial to trial. Each signal was ramped on and off over 90 ms, with total signal duration of 3 s. Signals were produced from each of seven loudspeakers placed in a hemicircumference of 1.25-m radius, at 30° intervals, in the upper MVP, from 0° elevation directly in front, through 90° (overhead) to 0° directly behind. In each condition, the loudspeakers were activated in a random order across seven trials. Testing occurred with the listener completely enclosed by the same spherical screen described for the fourth experiment. The technical features of signal generation, signal filtering and delivery were also the same.

The four listening conditions were: 1), normal, motionless listening; 2), normal, rotation listening; 3), distorted (short open tubes by-passing pinna function), motionless listening; 4), distorted, rotation listening. In all conditions, listeners wore the unobtrusive head harness with laser light pointer, and head tracking receiver, as in the fourth experiment. In normal listening there was no encumbrance of the outer ears. In motionless conditions, while the sound was on, the listener kept the light of the laser pointer aimed at a dot created by a light emitting diode (LED) back-projected onto the spherical screen at 0° elevation and azimuth. In distorted listening, the listener wore tapered open plastic tubes, 3 cm in length, which they inserted in their ear canals to achieve a snug but comfortable fit. The tubes had the effect of excluding the directional filtering architecture of the pinnae, thus distorting any high-frequency component of the signal (Fisher & Freedman, 1968). In rotation, after initially facing the LED dot at 0°, the listener, in response to signal onset, oscillated their head, moving the laser light back and forth between two other LED dots back-projected onto the screen at +30° and –30° azimuth in the front HP. With a signal duration of 3-s, all listeners achieved at least two complete (~60°) oscillations. The orders of the four listening conditions (normal, motionless; distorted, motionless; normal, rotation; distorted, rotation) were counterbalanced within the two overall orders of signals; thus each person went through the seven-signal series four times, starting with either motionless or rotation conditions, and either normal or distorted (tubes) conditions.

At the beginning of each trial, the listener lined up the laser light with the dot at 0°. When ready, they pushed a hand-held button, which began head-tracker recording; within 1-2 s after that, the sound began, and the listener moved or remained still as the condition required. All testing was under TV surveillance, and listeners were able to comply readily with all instructed conditions. Following the offset of the sound, the listener made a response as described for the fourth experiment. Prior to the start of each listening condition, listeners were provided with practice trials involving signals presented from an eighth loudspeaker situated directly to their left. Practice trials were repeated until listeners demonstrated they understood what they were required to do. As in all previous experiments, no feedback on localization accuracy was given during practice or at any other time during the experiment.

4.1.2. Results

Front-back discrimination. As in the previous experiments front-back errors were recorded whenever a listener chose an apparent source position in the opposite hemisphere, front or back, to where the sound had originated (the source directly overhead was not included in this analysis). Figure 18 shows the proportion of front-back errors occurring in each of the conditions. The general outcome is clear. With every type of signal, the motionless condition produced front-back confusion for a substantial proportion of trials, whereas the rotation conditions produced virtually none. The varying pattern of front-back errors, as a function of signal type, merits further analysis.

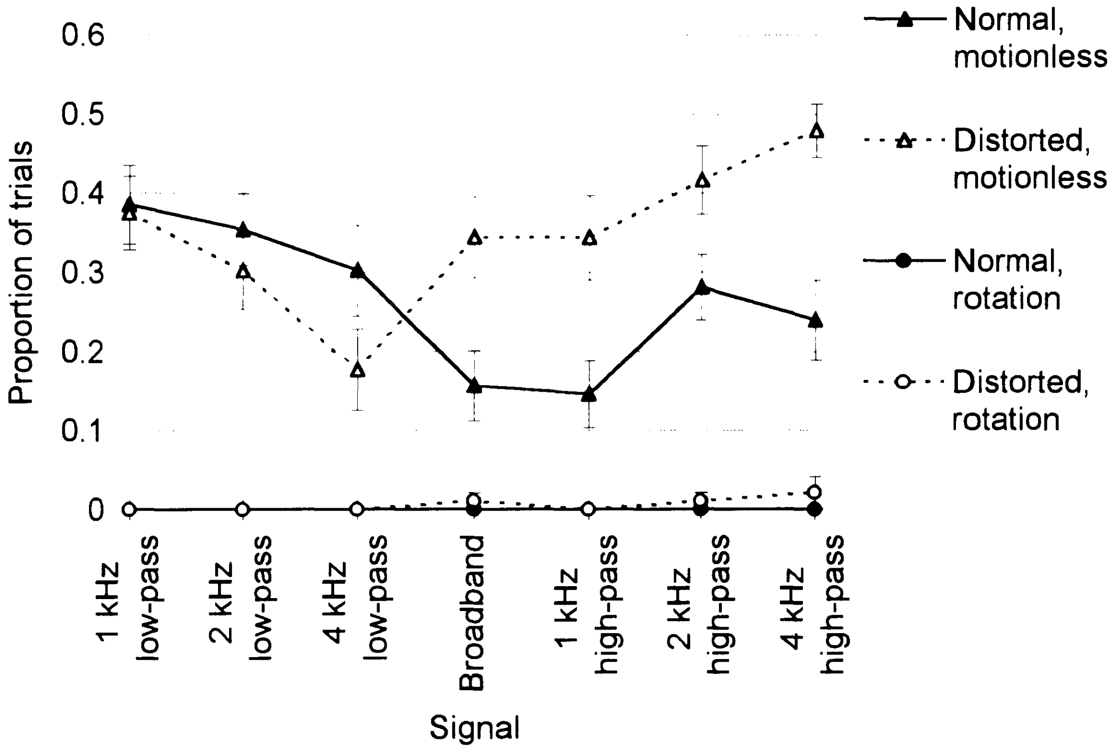

Figure 18. Front-back errors occurring for each condition in Experiment 6. Error bars indicate standard error of the mean.

Non-parametric tests (Wilcoxon matched-pairs signed-ranks) were used for the front-back error analysis to overcome distribution problems in the data. On average, 27% of all motionless trials in normal listening conditions and 35% of all motionless trials with tubes inserted in the ear canals, resulted in front-back errors. As expected, an increase in the number of front-back errors due to distortion of pinna function became apparent when the signal contained high-frequency acoustic energy. The addition of tubes had no significant effect on motionless listening with the low-pass signals. Compared with normal listening, the tubes condition produced significantly greater proportions of front-back errors for broadband noise ($p<0.01$), 1-kHz high-pass noise ($p<0.01$), 2-kHz high-pass noise ($p<0.05$) and 4-kHz high-pass noise ($p<0.01$). In the rotation conditions, no front-back errors occurred for normal listening while only 0.6% of distorted listening (tubes) trials resulted in front-back errors. For each signal, whether listening was with or without tubes, motionless trials produced significantly more front-back errors than rotation ($p<0.01$).

Apparent elevation. Figure 19 displays the average apparent elevation of each of the sound sources under each of the four listening conditions. The three low-pass signals produced similar results. Listening while motionless afforded little or no perception of the true elevation of the sound sources in the MVP. By contrast, rotation did provide such information, with individual source elevations being discriminated well. As expected, the presence of tubes made no obvious

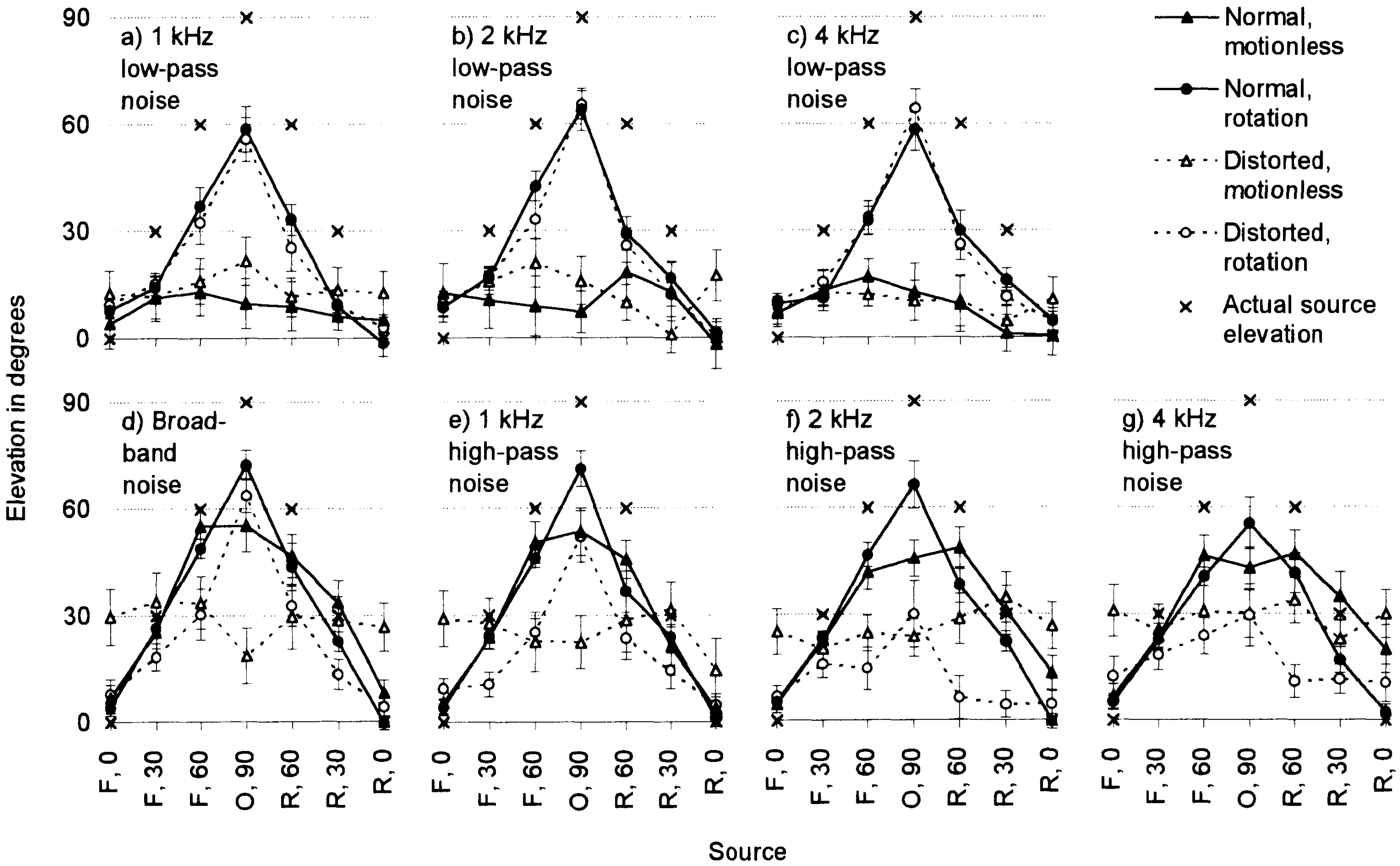

Figure 19. Apparent elevation for the seven types of noise under four different conditions in Experiment 6. Actual source positions are at 0°, +30°, +60° in front (F, 0, etc.); Overhead (O, 90), and +60°, +30°, 0° (R, 60, etc.) and actual elevations are indicated by crosses (×). Error bars indicate standard error of the mean.

difference with low-pass signals, in either the motionless or rotation conditions. The failure of listeners to derive any noticeable advantage from normal over distorted pinna function, confirms that the effect of rotation did not implicate the pinnae.

A broadband noise changed the response pattern, such that normal, motionless listening was associated with more accurate elevation detection, whereas the presence of tubes in motionless listening, as expected, disrupted the vertical plane response. Rotation nonetheless served to restore vertical plane discrimination, despite the distorting effect of tubes on pinna cues, although the most accurate response pattern occurred under rotation conditions with normal pinna function.

The foregoing picture is clarified by the further changes in response pattern that arose when an increasing proportion of low-frequency energy was removed from the signal. Now, rotation could not compensate for a distorted high-frequency signal, the collapse in performance under rotation-plus-tubes being particularly noticeable between the 1 and 2-kHz high-pass conditions. There was also a slight decrement in normal conditions with an increasingly high-frequency cut-off.

Absolute elevation error. All major effects observed in the apparent elevation data were confirmed by statistical analyses of the absolute elevation error collapsed across loudspeakers. The data for each type of signal were analyzed

Table 7. Mean absolute elevation error, in degrees, for seven different signals under four different listening conditions (standard deviations in brackets).

Signal	Pinna function	Rotation		Motionless	
1 kHz low-pass	Normal	20.3	(7.8)	39.3	(9.9)
	Distorted	22.4	(7.7)	36.0	(9.9)
2 kHz low-pass	Normal	18.2	(7.5)	41.3	(13.9)
	Distorted	20.1	(5.3)	35.4	(9.1)
4 kHz low-pass	Normal	20.9	(7.5)	36.7	(12.2)
	Distorted	20.2	(7.4)	36.5	(10.2)
Broadband	Normal	11.1	(7.7)	17.9	(10.4)
	Distorted	19.5	(8.1)	36.2	(9.0)
1 kHz high-pass	Normal	12.6	(6.5)	17.1	(9.3)
	Distorted	24.3	(11.4)	36.7	(9.8)
2 kHz high-pass	Normal	13.5	(7.2)	14.4	(5.7)
	Distorted	32.0	(13.2)	33.5	(6.6)
4 kHz high-pass	Normal	16.8	(7.0)	22.3	(8.9)
	Distorted	30.7	(12.1)	32.6	(8.0)

separately using a two-factor, repeated measures ANOVA (movement: rotation vs. motionless × pinna: normal vs. distorted). Table 7 shows the mean values. Again the three low-pass signals yielded similar results. Unexpectedly, the movement × pinna interaction effect was found significant ($p=0.01$) for the 2-kHz signal, but not significant for the 1-kHz or 4-kHz signal. Post-hoc analysis of the 2-kHz low-pass data, using Tukey's HSD, revealed that under motionless conditions, absolute elevation error was significantly greater when participants listened normally than when they listened with tubes ($p<0.05$). As expected, the main effect for pinna was not significant for all three low-pass signals. The main effect for movement was highly significant ($p<0.001$) for these signals; rotation producing less error than motionless listening.

With a broadband signal the movement × pinna interaction effect was significant ($p=0.006$). Post-hoc testing revealed that normal listening produced significantly more accurate elevation judgement than distorted listening in either motionless ($p<0.01$) or rotation conditions ($p<0.01$). Rotation produced significantly greater accuracy than motionless listening in both the distorted ($p<0.01$) and the normal conditions ($p<0.05$). Indeed the distorted, rotation listening condition was not significantly different from the normal, motionless listening condition. The main effect for movement was significant ($p<0.001$).

The 1-kHz high-pass noise analysis reveals a similar set of results to that for the broadband signal, although due to somewhat more error in the distorted rotation condition, the pinna × movement interaction was not significant. The main effect for movement was significant ($p=0.001$), with rotation producing more accurate elevation judgements than motionless listening. The main effect for pinna was also significant ($p<0.001$), with normal pinna function producing more accurate elevation judgement than distorted pinna function.

Results for the 2-kHz and 4-kHz high-pass signals did not show any effect for rotation. The movement × pinna interaction effects for these signals were not significant. The main effects for movement were also not significant, confirming that when signals do not provide acoustic energy below 2 kHz the rotation cue fails. Both signals produced significant main effects for pinna ($p<0.001$), there being greater accuracy with normal than with distorted pinna function.

4.1.3. Discussion

<u>Front-back discrimination.</u> Under normal listening conditions without head movement, much front-back confusion was evident, even when the signal was rich in the complex acoustic energy known to produce pinna cues (4 kHz and above). Rotations of the head completely eliminated this confusion across all

signals. Even when pinna function was disrupted, head rotation eliminated or virtually eliminated front-back confusion for all signal types. The virtual elimination of front-back errors with 4-kHz high-pass noise, when pinna cues are distorted, suggests that a rotational front-back cue can be derived from transformations of ILD information, but it has been shown that interaural time information can be extracted from ongoing changes in amplitude occurring in a high-frequency signal (Yost & Hafter, 1987), so that changing ITDs may form the basis for front back discrimination even for high-pass signals. The changes that occur over time in random noise, may have been enough to allow extraction of ITDs from the 4-kHz high-pass noise. As with the previous elimination of front-back confusion with low-pass noise and the substantial reduction of them with a 500 Hz pure tone, results with the various low-pass signals strongly implicate transformations of ITD information as a major source of the rotational front-back cue.

Elevation. In the absence of pinnae transforms, horizontal head rotations can allow elevation judgement of sources in the upper MVP that is just as proficient as when pinna cues are available. Even with distorted pinna cues, head rotation can permit such proficiency, provided there is audible low-frequency energy in the signal. The implication of that finding is that the dynamic cue for source elevation requires acoustic energy below 2 kHz. When only high-frequency energy is provided, distortion of input cannot be remedied by head rotations, suggesting the transformation of interaural level differences is not a strong counter cue to source elevation.

By contrast, when low-frequency energy is provided along with such distorted high-frequency input (broadband or 1-kHz high-pass signals, tubes inserted in the ear canals), rotation serves to overcome the distortion effect. Taken with the finding that the elevation of low-pass signals is detectable under rotation conditions, this strongly indicates that the dynamic 'Wallach cue' to elevation relies on transformations of interaural time/phase. The failure of high-frequency spectral pinna cues to disrupt the effect of rotation on judgement of elevation suggests that low-frequency spectral information (shoulder/torso) may not be involved in the rotational effect. This conclusion is possible if distortion of pinna cues is assumed to disrupt all potential forms of spectral information derived from low-frequency energy, in the way distortion of pinna cues disrupted front-back discrimination in the study by Musicant and Butler (1984).

In Experiment 4, which included sources arrayed vertically throughout the LVP (i.e., above and below the HP), there were clear signs, in the rotation and even the motionless conditions, that listeners could discriminate between sources above and below the HP, suggesting they may have recruited other spectral cues, perhaps related to the shoulders and torso (Gardner, 1973; Kuhn, 1987) to help disambiguate sources above and below the HP. It was also apparent, however, that elevated sources coinciding with the MVP, i.e. those directly above and below, were not well discriminated in either condition. A seventh experiment, including sources throughout the MVP, would determine whether the up-down confusion extends throughout the MVP, as a strict reading of Wallach's theory would suggest.

General. The results from the sixth experiment revealed a somewhat more impressive effect for rotation than was evident for the LVP in Experiment 4. It is not clear whether the difference was due to the rotation cue being more useful for MVP localization than for LVP localization, or due to procedural differences, such as the use of a single 45° head rotation in the fourth experiment, compared with the repeated 60° oscillations used in the present experiment. To determine if head rotation assists accuracy in elevation judgement differently depending on whether sources are in the MVP or LVP the seventh experiment was conducted with sources arrayed in both the LVP and MVP.

4.2. EXPERIMENT 7

In the seventh experiment, localization of low-pass noise was tested under motionless and rotation conditions with sources positioned throughout the MVP and the left LVP. Head rotation in this experiment was the repeated 60° oscillations employed in the previous experiment.

4.2.1. Method

The second experiment involved 22 people (9 female, 13 male students — average age 37 yrs.), reporting normal hearing function. None had prior experience in auditory localization experiments. The sounds, 2-kHz low-pass noise, were presented from each of 17 loudspeakers positioned, as shown in Figure 20, at 30° intervals, throughout the entire MVP and at 30° intervals through the left LVP (extending from directly overhead, through directly left on the interaural axis to directly below). Each loudspeaker was selected once in a random sequence, resulting in 17 trials in each of four blocks (two motionless blocks and two rotation blocks). The number of trials was kept low in an endeavour to sample unpracticed responses, so that the findings would represent, as closely as possible, listeners' real sensitivity to localization cues in novel situations. To compensate for the low number of trials per listener, the number of participants (22) was relatively high for an experiment of this kind. To control for possible practice and order effects, block orders were counterbalanced between- and within-subjects. The sequence of blocks was:

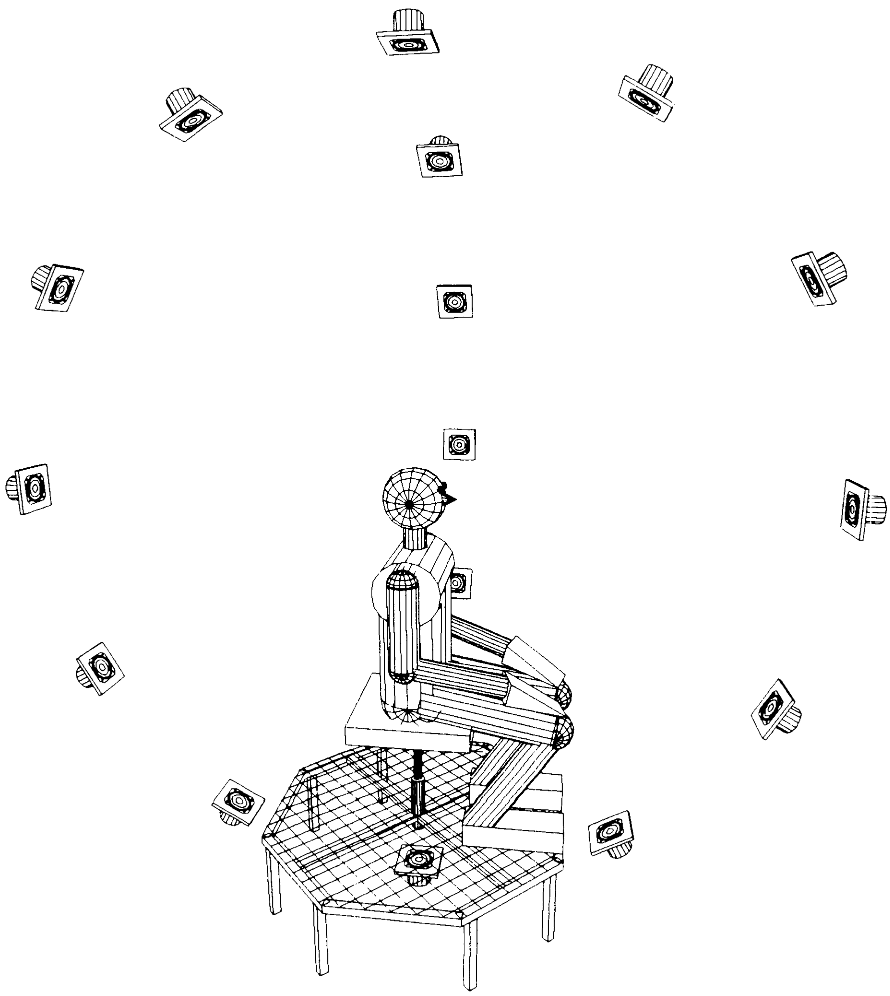

Figure 20. Loudspeaker array used in Experiment 7. Displayed is the complete circle of loudspeakers positioned in the median vertical plane and the semicircle lying in the lateral vertical plane.

motionless-rotation-rotation-motionless for half the listeners, and rotation-motionless-motionless-rotation for the others. To acquaint and re-acquaint listeners with the required movements, three practice trials involving the loudspeakers directly in front, directly behind and directly left were provided before the first, second and fourth blocks. All other technical and procedural details were the same as described for the previous experiment.

4.2.2. Results

Front-back errors. In the motionless listening condition 35% of trials resulted in front-back errors. In the rotation condition 0.5% of trials resulted in front-back errors; results confirming those from the sixth experiment.

Apparent elevation. Figure 21 displays the average apparent elevation of each of the sound sources under rotation and motionless conditions. Figure 21a shows performance for sources in the LVP and Figure 21b for sources in the MVP.

It is evident that rotation provides an advantage over motionless listening for judging the elevation of upper hemisphere sources. Comparison of the upper MVP data points with those of the previous experiment suggests slightly poorer

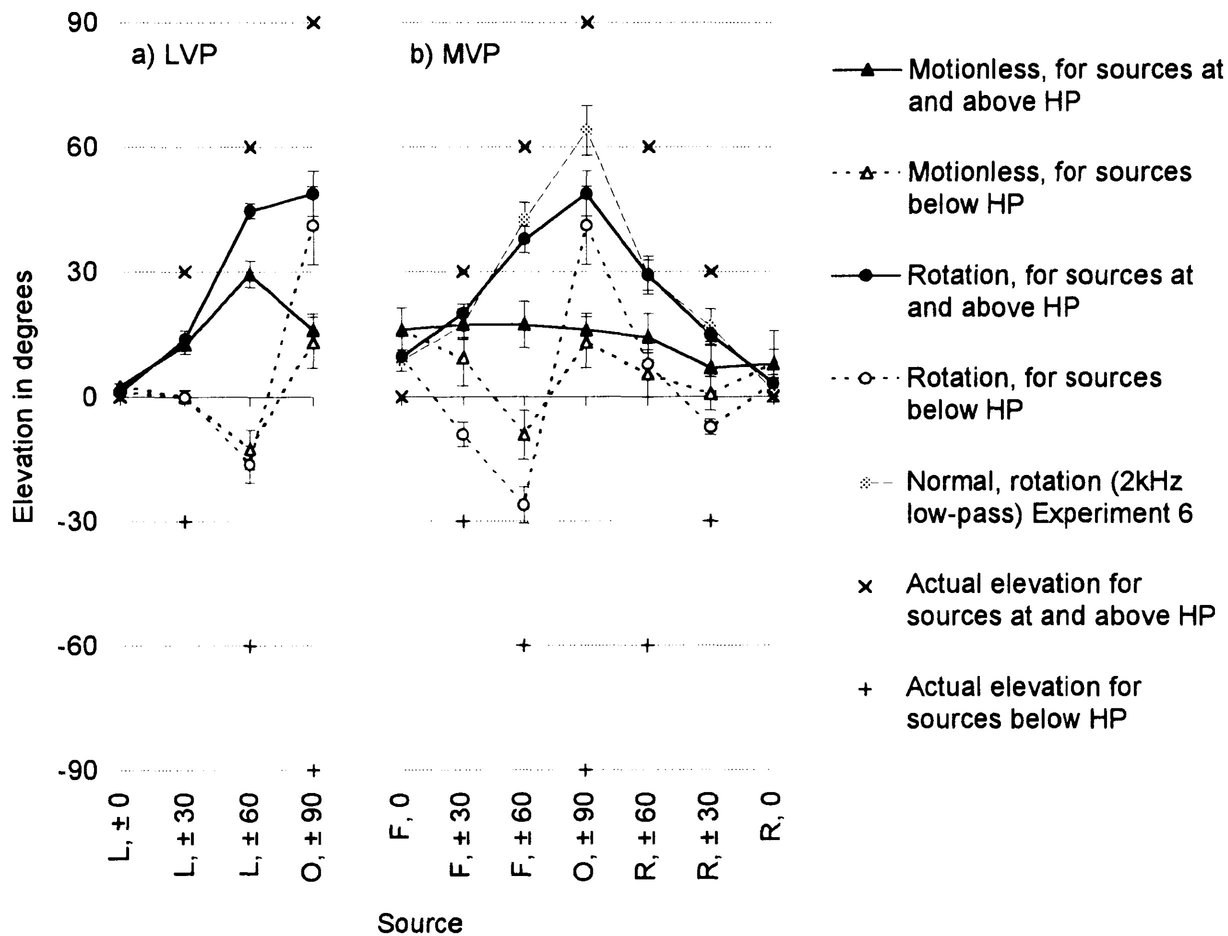

Figure 21. Apparent elevation under rotation and motionless conditions in Experiment 7. Actual source positions are at 0°, ±30°, ±60° elevation, leftward (L, 0, etc.); forward (F, 0, etc.); overhead and below (O, ±90), and ±60°, ±30°, 0° elevation, rearward (R, ±60, etc.). The symbol "×" indicates the actual elevation of sources at and above the HP; the symbol "+" indicates sources below. Error bars indicate standard error of the mean.

performance in experiment 2; this was due to responses to the loudspeaker directly overhead, performance at other locations being identical with that of the first experiment. Rotation can also be seen to have produced substantially greater accuracy for some sources in the lower MVP but it failed to deliver any benefit for MVP sources that were directly below (-90°) or rearward at -60° elevation.

Rotation appears not to have provided any advantage for judging the elevation of lower LVP sources (Figure 21a). Generally, listeners were able to discriminate fairly well between sources above and below the HP, in both the LVP and front MVP, in both the motionless and rotation conditions. Back MVP sources, below the HP, were localized inaccurately in both rotation and motionless conditions, but listeners distinguished upper sources from lower sources more clearly in the rotation condition than in the motionless condition. The regions of greatest benefit from rotation were the front MVP and upper back MVP.

Comparing experiments and the effects of test order and practice. The absolute elevation error data for the sixth experiment were compared with those for the corresponding sources in the upper MVP of the present one (see upper section of Table 8). Repeated measures ANOVA with one within-subjects factor (movement: rotation vs. motionless) × one between-subjects factor (experiment: experiment 1 vs. experiment 2) revealed a non-significant interaction effect for movement × experiment and a non-significant main effect for experiment. The main effect for movement was significant ($p<.001$), with rotation, as expected, producing significantly less absolute elevation error than motionless listening. This indicates that the inclusion of the additional sources below the HP and in the LVP did not have a significant impact on upper MVP elevation judgement generally.

Table 8. Mean absolute elevation error across experiments and test orders. (standard deviations in brackets).

Experiment		Rotation		Motionless	
6		18.2	(7.5)	41.3	(13.9)
7		20.1	(6.7)	36.9	(9.6)
Both experiments		19.3	(7.0)	38.7	(11.6)

Blocks	Test order group	Rotation		Motionless	
1-2	Rotation first	33.1	(6.5)	40.5	(4.9)
	Motionless first	30.6	(3.8)	42.8	(7.2)
	Both groups	31.9	(5.3)	41.6	(6.1)
3-4	Rotation first	31.1	(6.8)	39.9	(4.9)
	Motionless first	28.9	(5.0)	39.0	(4.4)
	Both groups	30.0	(6.0)	39.5	(4.5)

The overall absolute elevation error data for the seventh experiment were analyzed to check for possible order or practice effects, to determine whether these factors had a significant impact on listeners' response patterns. A repeated measures ANOVA was conducted, with two within-subjects factors (practice: blocks 1-2 vs. blocks 3-4; × movement: motionless vs. rotation) and one between-subjects factor (order: motionless first vs. rotation first). The relevant means are reported in the lower section of Table 8. No significant interaction effects were observed. The main effect for order of conditions was also not significant. The main effect for practice was significant ($p=0.028$) with the mean absolute elevation error being slightly but significantly greater in blocks 1-2 than in blocks 3-4. As expected, the main effect for movement was significant ($p<0.001$).

Ability to distinguish sources above from those below. To test for ability to distinguish sources above the HP from those below, two two-factor, repeated measures ANOVAs (hemisphere: upper vs. lower hemisphere × region: front MVP vs. LVP vs. back MVP) were conducted on the apparent elevation data. One ANOVA was on the rotation listening condition and the other on the motionless listening condition. Data for sources in the HP and those directly overhead and directly below were not included. Means are shown in the third and fourth columns of Table 9. Significant hemisphere × region interaction effects were observed for both the motionless ($p=0.005$) and rotation ($p<0.001$)

conditions. For motionless listening (fourth column of Table 9), post-hoc comparisons revealed significant differences between upper and lower sources for the front MVP ($p<0.01$) and the LVP ($p<0.01$), but not for the back MVP. For rotation listening, post-hoc tests showed significant differences ($p<0.01$) between upper and lower sources in all three regions.

Table 9. Apparent elevation and benefit from rotation for three different regions and two hemispheres (standard deviations in brackets).

Region	Hemisphere	Rotation		Motionless		Benefit	
LVP	Upper	28.9	(10.7)	21.3	(13.9)	8.7	(7.4)
	Lower	-8.2	(13.0)	-6.4	(13.8)	1.8	(9.4)
					*	5.3	(4.9)
Front MVP	Upper	29.3	(7.1)	17.3	(18.3)	16.2	(13.7)
	Lower	-19.9	(15.8)	-2.7	(24.6)	21.2	(17.1)
					*	18.7	(11.1)
Back MVP	Upper	22.0	(11.9)	10.6	(24.9)	16.5	(20.5)
	Lower	-4.1	(9.5)	1.0	(21.4)	4.5	(16.4)
					*	10.5	(9.0)

* Mean benefit for upper and lower sources combined.

Region of greatest benefit from rotation. To determine if the benefit of head rotation, in judging elevation more accurately, is dependent on the position of the source, a 'benefit-from-rotation' variable was derived. This was done by subtracting the absolute elevation error for rotation trials from that for motionless trials. Again, a two-factor, repeated measures ANOVA (hemisphere: upper vs. lower hemisphere × region: front MVP vs. LVP vs. back MVP) was conducted, this time on the benefit from rotation data. As before, data for HP sources, and for those directly overhead and directly below were excluded. Means are shown in the rightmost column of Table 9. The hemisphere × region interaction effect was significant ($p=0.005$). Post-hoc testing revealed that the benefit from rotation was not significantly different across regions of the upper hemisphere. Across regions in the lower hemisphere, significantly more benefit was obtained from rotation with sources in the front MVP than with those in either the LVP ($p<0.01$) or the back MVP ($p<0.01$). Benefit from rotation was not significantly different between upper and lower hemisphere sources when each region was considered separately. The main effect for hemisphere was also not significant. The main effect for region was significant ($p<0.001$). Post-hoc testing showed that greater benefit was gained from rotation for front MVP sources than for LVP sources ($p<0.01$). No other differences between regions reached levels of significance.

4.2.3. Discussion

The findings about the efficacy of head rotation with low-pass sounds reported in the sixth experiment, with source positions restricted to the upper MVP, were replicated in the seventh experiment, with sources arrayed throughout the whole MVP. It was observed that listeners clearly distinguished frontal sources above the horizon from those below in rotation conditions, and to some extent even in motionless conditions. As previously suggested with respect to localization of LVP sources, an involvement of the shoulders and torso (Gardner, 1973; Kuhn, 1987) may account for the ability to make such distinctions.

The results of the seventh experiment demonstrate that head rotation assists judgement of elevation more for some spatial regions than for others. The only sources in the MVP for which rotation failed to deliver any benefit were those directly below (-90°) or rearward at -60° elevation. The direct path of the sound from the source at -90° to the ears, would have been obstructed by the listener's seat, hence disrupting any potential cue. Sounds from the source at -60° behind, will interact similarly with the obscuring surface of the listener's back. Benefit from rotation was also found to be greater for sources in the front MVP than for those in the LVP. These outcomes suggest that the rotation cue to elevation is most useful when listeners are oriented such that the source lies roughly in their front MVP. Indeed, if rotation occurs, listeners are more able to achieve such an orientation, as indicated by the virtual elimination of front-back confusion, and the reduced horizontal error, reported for Experiment 4. In normal circumstances, auditory localization involves the visual system. Once oriented in the general direction of an unseen source, visual scanning is likely, involving horizontal rotations of the head. The present findings show that such head rotations afford listeners useful auditory information concerning the elevation of a sound source, provided the sound includes low-frequency acoustic energy.

Chapter five: An exploration of the functional limits of head rotation

This chapter reports on two experiments designed to investigate aspects of the functional limits of head rotation cues. These experiments feature conditions in which the listener rotates the head from right to left in one continuous sweep. As the head rotates in this manner, a brief low-pass signal is presented which the listener is required to localize. The objective was to assess the functional limits of the head rotation cue in terms of the parameters of velocity, duration and (derivatively) the extent of head rotation, by controlling the velocity of head rotation and the duration of the signal. The purpose of Experiment 8 was to investigate effects on front-back discrimination, while that of the final experiment (Experiment 9) was to investigate effects on elevation judgement.

5.1. EXPERIMENT 8

As with Experiment 5, the focus of the present experiment was to investigate the lower bounds of the operation of the head rotation cue for resolving front-back positions. The present experiment differs from the earlier one, in that brief signals were used while head rotation proceeded at various predetermined velocities.

5.1.1. Method

Twenty four listeners participated in this experiment (13 females, 11 males), all reporting normal hearing, and none with previous experience in localization experiments. They were presented low-pass noise bursts from two loudspeakers, one positioned directly in front and the other directly behind. Both loudspeakers were mounted on a steel framework and faced the centre of the listener's head at a distance of 1.25 m. The loudspeakers were hidden from view by the spherical screen described in the method section for experiment 4.

The signal used was a 1-kHz low-pass white noise, chosen in preference to a signal with a 2-kHz cut-off in an attempt to maximize instances of front-back confusion. The signals were digitally created in the way described in the method section for Experiment 4, with the exception that the pink noise filtering procedure was omitted. The signal was produced in six different durations, 100 ms (practice trials only), 150 ms, 200 ms, 250 ms, 300 ms, and 350 ms with 20-ms rise and fall times.

There were four different movement conditions including a motionless condition in which the listener remained still throughout signal presentation; and three rotation conditions, each involving a different velocity of head movement. In rotation, the head was moved from right to left in one continuous sweep, throughout the signal duration. The three rotation conditions were: 1) rotation at 25°/s, 2) rotation at 50°/s and 3) rotation at 100°/s. These rates were chosen because they covered a range velocities that could achieved.

An array of 20 LEDs was used to assist listeners to achieve the particular velocity of head movement required for each of the rotation conditions. The LEDs of the array were positioned 3.75° apart from 50.625° azimuth to -20.625° in the front HP. Each LED was mounted just behind the spherical screen so that a dot of light was back-projected onto the surface of the screen whenever the LED was illuminated. The computer program controlled the timing of each individual LED illumination. During the rotation movement, the LEDs were briefly illuminated, one at a time, beginning with the rightmost LED, and working incrementally to the leftmost. This created what appeared to the listener as a moving light dot on the HP of the spherical screen. The listener's task was to try to keep the light point, produced by the head mounted laser, aligned with the 'moving' light dot, by rotating the head. The rotation sequence was timed such that accurate tracking of the moving dot would mean the listener's head was rotating at the required velocity throughout the duration of the signal, and that the listener was facing directly forward midway through the duration of each of the signals. Listeners were instructed to continue a smooth rotation of the head, to a comfortable position, well past the leftmost extent of the moving light dot array, and to be absolutely sure that the signal had ceased before they stopped rotating. This ensured that that head rotation would occur throughout the duration of the signal even if the listener's tracking of the moving light-dot was somewhat inaccurate.

At the start of each rotation trial the listener pushed the button on the hand held module as described for the previous experiments. A light dot then appeared at the starting position at 50.625° azimuth. The listener aimed the laser pointer immediately below this light dot which remained for 1.5 s before being switched off for 0.5 s. The listener was then cued to start rotating with a count-in sequence involving a flash of the starting position LED at 2 s and then 1 s before they were to start their rotation. The listener was instructed to count the flashes and on the count of three to begin rotating their head while using the laser to track the 'moving' dot. Once the rotation movement was complete the listener was free to respond as in the previous experiments involving the laser pointer. The procedure in the motionless condition was identical to that used in the motionless condition of Experiment 4, with a LED, back-projected at 0° azimuth in the front HP for head alignment before and during the signal presentation.

During pilot testing for the present experiment it was apparent that the accuracy of listeners responses could change dramatically as testing progressed through the various conditions. The experiment was therefore designed so that any effects arising from different levels of experience could be assessed. Twelve listeners participated in the 25°/s and 50°/s rotation conditions, while the other 12 participated in the 100°/s rotation and 0°/s (motionless) conditions. Each listener participated in a block of 60 trials for each of two rotation velocity conditions. The order of these conditions was counterbalanced across listeners. Six in the 0°/s-100°/s group and six in the 25°/s-50°/s group were tested with the lower velocity first, while the other six in each group were tested with the higher velocity first. Each loudspeaker was activated once in random order within a pair of successive trials. Each of these pairs involved one particular duration of signal, involving all but the 100-ms signal. Over a series of five successive pairs of trials, the duration of the signal was either incremented upward producing an 'up' series, or downward producing a 'down' series. As listeners progressed through a block, the series alternated between up and down, with half the listeners encountering the series in an up-down-up-down-up-down order and the others encountering the series in a down-up-down-up-down-up order. Thus, each listener was tested at each signal duration six times per loudspeaker.

At the start, the experimenter demonstrated to each listener the movements that were required and then guided them through four practice trials for each of the two conditions they were about to encounter. The duration of the signal used in the practice trials was 100 ms. Pilot testing had suggested that a 100-ms signal was virtually impossible to localize under rotation conditions, and so was used in practice trials because it allowed listeners to gain experience with task requirements without gaining experience in using head movement cues. No feedback on accuracy of responses was given during practice or the experiment. Polhemus Isotrak II head tracking and closed circuit TV monitoring were again used as in Experiment 4.

5.1.2. Results

Initial analyses showed, as expected, substantial differences occurring within the same conditions as a function of the order in which conditions were faced and the number of trials completed. To provide greater insight into any effects arising from the various experimental conditions the results are presented in two different ways. First, an overall analysis is provided in which all the collected data are collapsed across the different orders-of-conditions and across time. Second, an analysis is presented in which the data from each group of listeners who faced the conditions in a particular order are kept separate and considered at six different stages of the experiment's progress.

The front-back data were statistically analyzed with non-parametric procedures since much of the data was not normally distributed. Wilcoxon Rank Sum W tests (SPSS) were used for comparisons between groups of different listeners, and Wilcoxon matched-pairs signed-ranks tests were used when comparisons were made within the same group of listeners.

Overall analysis. Figure 22 displays the proportion of trials resulting in front-back errors in each condition with each different signal duration. It is immediately apparent that the greater the velocity of the head rotation the greater the accuracy in front-back discrimination. In the motionless condition, front-back error rates ranged from a mean of 39% for the 200-ms signal to 41% for the 350-ms signal. The 25°/s condition produced significantly fewer front-back errors than the motionless condition (p=.0246), ranging from a mean of 26% with the 150-ms signal to 14% with the 350-ms signal. The 50°/s condition also produced significantly fewer front-back errors than the motionless condition (p=.0037),

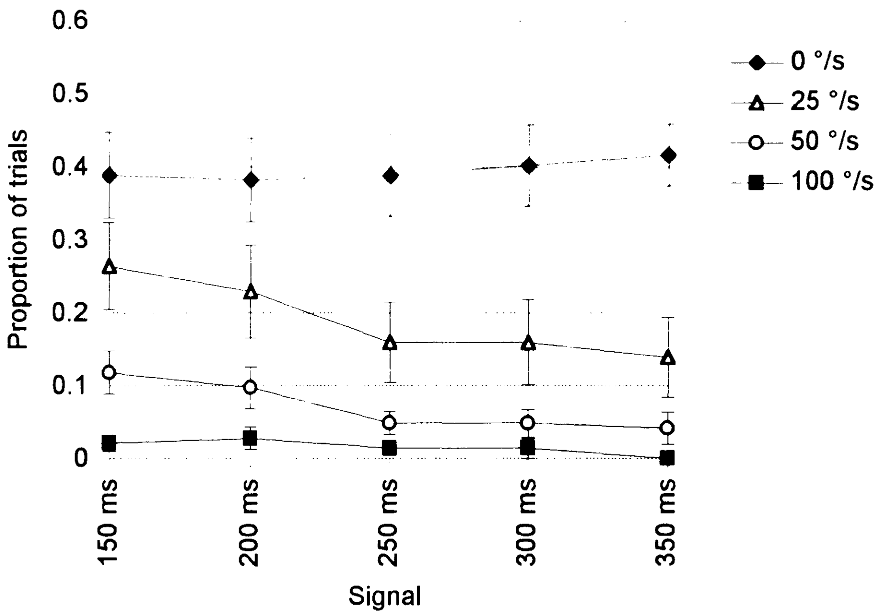

Figure 22. Overall front-back errors for each condition in Experiment 8. Error bars indicate standard error of the mean.

ranging from 12% with the 150-ms signal to 5% with the 350-ms signal. The difference between the 50°/s condition and the 25°/s condition approached significance (p=.0776). In the 100°/s condition, front-back confusion rates ranged from 3% with the 200-ms signal, down to 0% with the 350-ms signal. These were significantly less than the front-back confusion rates occurring in the motionless (p=.0022), 25°/s rotation (p=.0135) and 50°/s conditions (p=.0246). Although there are signs of a reduction in front-back confusion for longer compared with shorter duration signals, particularly in the 25°/s and 50°/s rotation conditions, statistical tests failed to confirm any effect.

Differences due to order of conditions and number of trials. Figure 23 presents front-back error data for each order of condition group at six different stages of the experiment. Each part of Figure 23 represents data arising over one particular stage, comprising 20 trials per listener (2 loudspeakers × 5 durations × 2 series—one 'up', one 'down'). Parts a, b and c show data produced by each of the order of conditions groups in their first block of 60 trials. Parts d, e and f show data arising from their second block of 60 trials. Thus, each data series represents the performance of six listeners, with four trials per listener occurring for each data point.

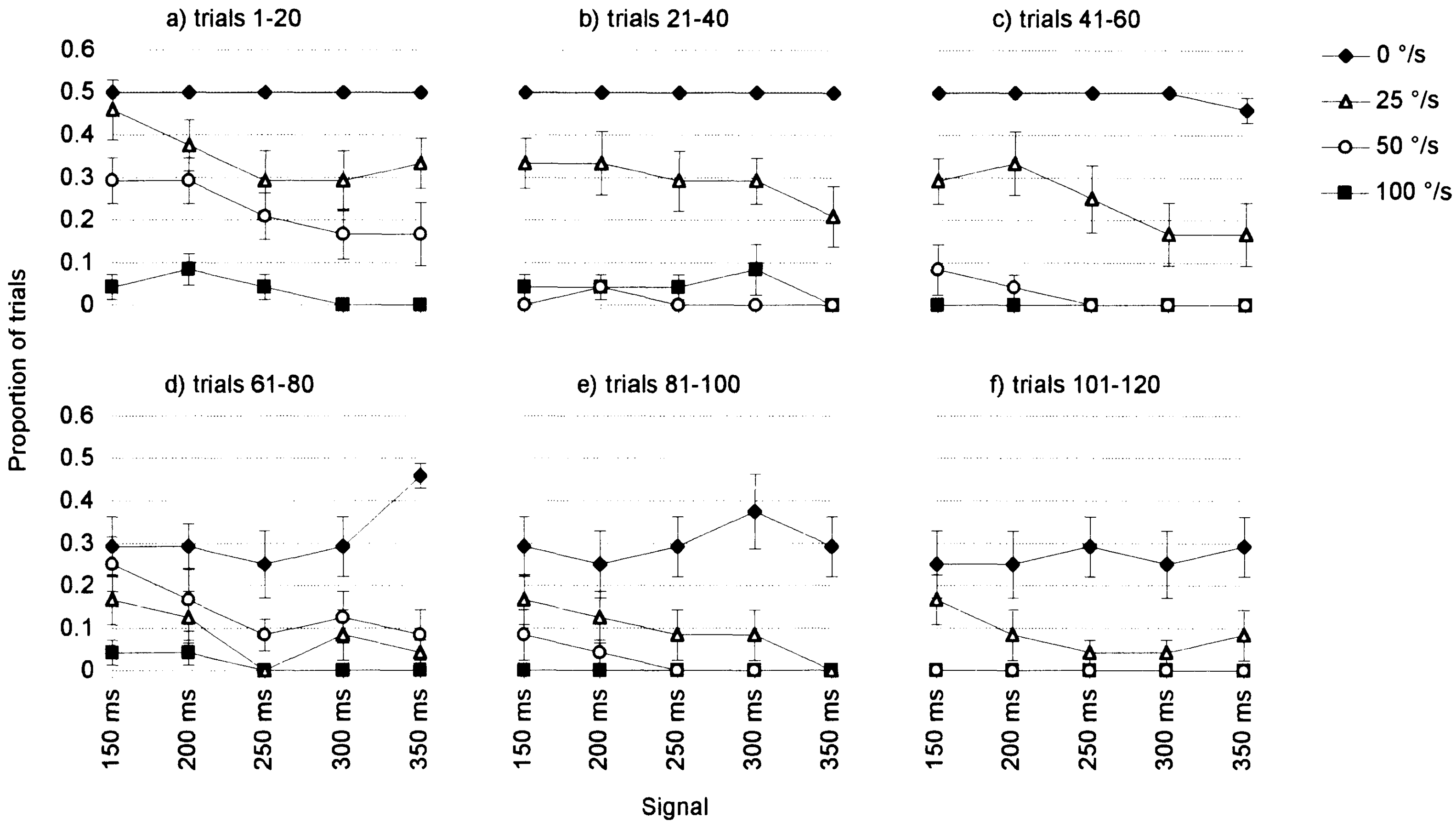

Figure 23. Front back errors over 6 different stages of each condition in Experiment 8. Note that open squares appear where 50°/s and 100°/s rotation data coincide. Error bars indicate standard error of the mean.

When motionless listening was the first condition faced, listeners made front-back errors 50% of the time with only one minor exception (see Figure 23, parts a, b and c). On the other hand, when listeners encountered motionless listening after first completing 60 trials of 100°/s rotation, front-back errors occurred significantly less often (p=.0198), with confusions generally occurring on less than 30% of trials (see Figure 23, parts d, e and f). By contrast, the order of conditions faced had no effect on performance with the 100°/s rotation condition. With the 25°/s rotation condition, the proportion of trials in which front-back errors occurred was 29% for listeners who encountered the condition without prior experience of another one, but only 9% for listeners who encountered the condition after first completing the 50°/s rotation condition. This difference is substantial and was close to being statistically significant (p=.0526). With the 50°/s signal, order of conditions did not produce a significant effect.

There were also signs that with more exposure to a particular condition, front-back confusion diminished. This is most evident for listeners encountering the 50°/s rotation condition for the first time. Front-back error rates were about 23% during the first 20 trials but fell significantly to 1% (p=.04) in the second 20 trials and remained almost significantly reduced at 3% in the third 20 trials (p=.06).

A similar pattern of events, that was close to reaching statistical significance, occurred with listeners who encountered the 50°/s rotation condition after completing the 25°/s rotation condition. For these listeners, substantially more front-back errors occurred during the first 20 trials of the 50°/s rotation condition (shown in Figure 23, part d) than in either of the remaining stages (p=.0679 in both cases). Front-back error rates occurring during the later stages of the 100°/s, 25/°s and the 0/°s conditions were not at significantly different levels from those occurring in the initial stage. As with the overall analysis, Figure 23 shows that front-back errors occurring with rotation appear to be more prevalent with signals of shorter duration than with those of longer duration. Although such an outcome is fairly consistent across the various stages, the differences could not be statistically confirmed.

Although instructed and rehearsed in advance, listeners did not perform the guided rotation task with consistent accuracy, and there are departures of actual from targeted velocities in the results. Figure 24 shows the head-tracker records of six typical listeners. These illustrate rotational performance in the 25°/s, 50°/s and 100°/s rotation conditions. The actual velocities and extents of rotation for each data point in Figure 23 are provided in Table 10. 'Actual velocity', refers to the mean velocity of head rotation occurring over the duration of the signal. Duration, velocity and extent of rotation are intimately related. The simple

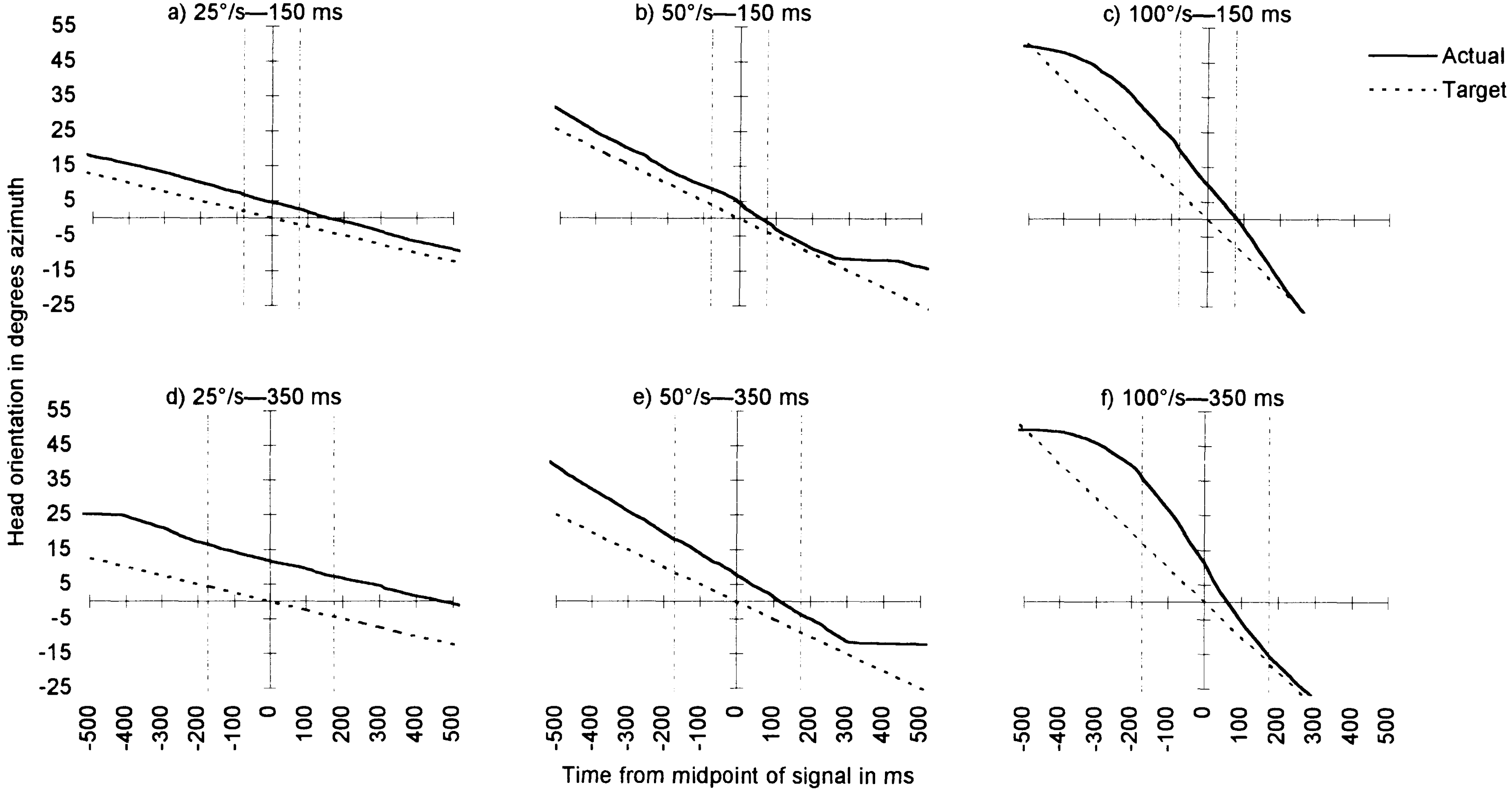

Figure 24. Head-tracker records of rotational movement, for typical listeners in the three guided rotation velocities, with 150-ms and 350-ms signals. The straight dotted diagonal lines represent the targeted performance, while the solid irregular lines represent actual performance.

Table 10. Actual velocities and extents of rotation for each data point in Figure 23 (standard deviations in brackets)

a) trials 1-20

		150 ms	200 ms	250 ms	300 ms	350 ms
0°/s	Velocity °/s	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Extent °	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
25°/s	Velocity °/s	23 (4)	23 (3)	25 (2)	26 (5)	25 (5)
	Extent °	3 (1)	5 (1)	6 (1)	8 (1)	9 (2)
50°/s	Velocity °/s	56 (3)	58 (7)	60 (7)	57 (9)	61 (7)
	Extent °	8 (0)	12 (1)	15 (2)	17 (3)	21 (3)
100°/s	Velocity °/s	119 (30)	120 (47)	119 (45)	129 (56)	121 (43)
	Extent °	18 (5)	24 (9)	30 (11)	39 (17)	42 (15)

b) trials 21-40

		150 ms	200 ms	250 ms	300 ms	350 ms
0°/s	Velocity °/s	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Extent °	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
25°/s	Velocity °/s	26 (2)	25 (3)	26 (2)	25 (3)	27 (2)
	Extent °	4 (0)	5 (1)	7 (1)	8 (1)	9 (1)
50°/s	Velocity °/s	54 (8)	55 (6)	55 (6)	60 (6)	59 (10)
	Extent °	8 (1)	11 (2)	14 (2)	18 (2)	21 (3)
100°/s	Velocity °/s	119 (29)	137 (32)	133 (36)	147 (51)	136 (45)
	Extent °	18 (4)	27 (6)	33 (9)	44 (15)	48 (16)

c) trials 41-60

		150 ms	200 ms	250 ms	300 ms	350 ms
0°/s	Velocity °/s	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Extent °	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
25°/s	Velocity °/s	26 (5)	26 (3)	26 (2)	27 (5)	26 (5)
	Extent °	4 (1)	5 (1)	6 (1)	8 (1)	9 (2)
50°/s	Velocity °/s	56 (8)	54 (8)	54 (11)	61 (9)	59 (10)
	Extent °	8 (1)	11 (2)	14 (3)	18 (3)	21 (3)
100°/s	Velocity °/s	104 (28)	129 (29)	105 (23)	114 (29)	110 (23)
	Extent °	16 (4)	26 (6)	26 (6)	34 (9)	38 (8)

d) trials 61-80

		150 ms	200 ms	250 ms	300 ms	350 ms
0°/s	Velocity °/s	1 (1)	0 (0)	0 (0)	0 (0)	1 (2)
	Extent °	0 (0)	0 (0)	0 (0)	0 (0)	0 (1)
25°/s	Velocity °/s	24 (5)	25 (4)	25 (4)	28 (4)	24 (4)
	Extent °	4 (1)	5 (1)	6 (1)	8 (1)	8 (1)
50°/s	Velocity °/s	56 (6)	59 (5)	55 (6)	59 (9)	60 (7)
	Extent °	8 (1)	12 (1)	14 (2)	18 (3)	21 (2)
100°/s	Velocity °/s	170 (32)	184 (42)	195 (39)	196 (41)	183 (40)
	Extent °	25 (5)	39 (8)	49 (10)	59 (12)	64 (14)

e) trials 81-100

		150 ms	200 ms	250 ms	300 ms	350 ms
0°/s	Velocity °/s	0 (0)	0 (1)	0 (0)	0 (0)	0 (0)
	Extent °	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
25°/s	Velocity °/s	23 (4)	26 (4)	26 (4)	27 (5)	26 (3)
	Extent °	3 (1)	5 (1)	6 (1)	8 (1)	9 (1)
50°/s	Velocity °/s	58 (7)	58 (6)	62 (8)	62 (8)	62 (8)
	Extent °	9 (1)	12 (1)	15 (2)	19 (2)	22 (3)
100°/s	Velocity °/s	166 (27)	170 (30)	186 (52)	196 (40)	177 (43)
	Extent °	25 (4)	34 (6)	46 (13)	59 (12)	62 (15)

f) trials 101-120

		150 ms	200 ms	250 ms	300 ms	350 ms
0°/s	Velocity °/s	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Extent °	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
25°/s	Velocity °/s	25 (5)	26 (3)	26 (2)	25 (5)	26 (5)
	Extent °	4 (1)	5 (1)	6 (1)	7 (1)	9 (2)
50°/s	Velocity °/s	63 (8)	57 (8)	62 (11)	59 (9)	59 (10)
	Extent °	9 (1)	11 (2)	15 (3)	18 (3)	21 (3)
100°/s	Velocity °/s	165 (28)	177 (29)	183 (23)	191 (29)	187 (23)
	Extent °	25 (4)	35 (6)	46 (6)	57 (9)	65 (8)

Less than 10% front-back errors | Elimination of front-back errors formula: *velocity multiplied by duration equals extent of rotation*, describes this relationship mathematically. The relationship is such that doubling the velocity of rotation produces a doubling of the extent of rotation if signal duration is held constant, and doubling the signal duration produces a doubling of the extent of rotation if head velocity is held constant.

Using Table 10, it can be seen that in the initial stage of the experiment, front-back errors were eliminated only when a mean actual extent of rotation of at least 39° occurred. This was achieved in the 100°/s condition with an actual mean velocity of 129°/s for the 300-ms signal and 121°/s for the 350-ms signal. Reduction of front-back error rates to less than 10% occurred if the mean actual velocity of rotation was 119°/s or greater and for signals of all durations. At that velocity, the actual mean extent of rotation was 18° during the time of activation of the 150-ms signal.

Performance in the final stage of the experiment showed substantial improvement over performance at the outset. Front-back errors were eliminated in both the 50°/s and the 100°/s rotation conditions, with all signal durations. With the 150-ms signal in the 50°/s rotation condition, the mean actual extent of rotation was 9° and the mean actual velocity of rotation was 63°/s. Front-back error rates remained below 10% with the 25°/s condition as long as the signal duration was

200 ms or greater. With the 200-ms signal, the mean actual velocity of rotation was 26°/s and the mean extent of rotation was just 5°.

The design of the experiment meant that comparisons of the proportion of front-back errors arising with approximately equal extents of rotation could be made. For example, in the first stage, an extent of 8° was achieved in the 25°/s condition with a 300 ms signal as well as in the 50°/s condition with a 150-ms signal. In these cases the proportion of front-back errors was exactly the same (29%). Also in the first stage, an extent of 17° was achieved in the 50°/s condition with a 300 ms signal and associated with a front-back error rate of 17% while an extent of 18° was achieved in the 100°/s condition with a 150-ms signal and is associated with an error rate of 4%. Although clearly different, this and other similar differences were not found statistically significant.

5.1.3. Discussion

The results show that the faster the head is rotated during activation of a sound, the greater the reduction in front-back confusion. With faster rotation, the angular displacement of the head is greater within a given time. Therefore greater velocity *per se* may not be the crucial factor, but rather, the extent of the rotation.

Although it is not clear whether velocity of head rotation *per se* affects front-back discrimination, in practical terms, it seems that rotating the head at higher velocities assists front-back discrimination more than rotating the head at lower velocities, since to rotate the head at a lower velocity means the angular extent of rotation is also reduced over equivalent times.

Within the range of durations used, no significant differences in the number of front-back confusions were found, although there were some signs that with increasing duration, front-back confusion was slightly diminished. Lack of a significant effect for duration suggests that duration *per se* is not an important factor; this may not be the case for signals shorter than 150 ms or in cases involving durations longer than 350 ms

The results do show that head movement can eliminate front-back confusion with durations of as little as 150 ms, provided the velocity of rotation is within the vicinity of about 63°/s or greater, and provided listeners have had a fair degree of experience. Even without much experience, rotation at velocities in the vicinity of 120°/s or faster produced front-back error rates below 10%. These results suggest that the minimum time required for resolving front-back ambiguity is 150 ms or less, although head rotation must be fairly rapid. Examination of head rotation occurring in Experiment 6, when listeners oscillated between left and right at their own pace, showed that the mean peak velocity of head rotation was approximately 110°/s. This suggests that rotation velocities allowing front-back discrimination of signals as brief as 150 ms need not be unusual.

In the motionless condition, when encountered as the first block, listeners gained no advantage in distinguishing the front source from the rear with increased experience. Front-back discrimination remained at chance responding across the 60 trials. However, motionless listening produced significantly more accurate front-back discrimination for those listeners who had previously experienced the 100°/s rotation condition. The information for (limited) front-back discrimination in the motionless condition is presumably derived from a weak torso-induced spectral cue. A similar outcome occurred with the 25°/s rotation condition, with listeners who encountered that condition after obtaining prior experience with the 50°/s rotation condition responding substantially more accurately than those without the prior experience. This suggests that listeners entering a novel acoustical environment are unable to gain front-back information unless they move sufficiently while sounds occur, which is of course, almost inevitable, as people transfer between places in their surroundings. With substantial movement, listeners cannot help gaining familiarity with the acoustics of the environment, thus allowing them to judge the direction of sound sources more adequately.

Wightman and Kistler (1997) have argued that in order for listeners to make use of pinna-induced spectral cues for sound localization, the listener must first know the spectrum of the source. Such an argument could also be applied to the case of weak spectral cues arising when low-frequency acoustic energy interacts with the torso. Although the spectrum of the signal used in the present experiment was constant across all trials, listeners without prior knowledge of the signal's spectrum would not be able to judge its direction, based on the spectra impinging on their eardrums. For example, if the original spectrum produced by the source is adjusted by artificial means, the spectra occurring at a listener's eardrums could be kept constant while the direction of the source is varied. Therefore, if the original spectrum of the source is unknown, source direction based purely on spectral information would be impossible.

One way in which a listener might obtain information about the actual spectrum of the signal is precisely through engaging in substantial head movements and through a process of averaging the incoming spectra over time. Within a short space of time, substantial changes in head orientation would create a wide range of different spectra. Averaging over these different spectra would be expected to provide the listener with a more accurate estimation of the actual spectrum of the signal than could be obtained from the spectral information arising if the head remained at the same or nearly the same orientation throughout the time of signal activation.

Normally, a person is free to move their head, and will do so when carrying out everyday tasks. It is as likely as not that people will be moving when sounds of short duration occur. The results of the present experiment suggest that rotational movements assist listeners in localizing sources of short duration sounds, and that the faster they are moving the better.

5.2. EXPERIMENT 9

The two main components of Wallach's theory address front-back resolution and elevation detection. As Experiment 8 considered limits on the operation of a front-back cue, the final experiment is aimed at examining such limits on elevation detection. The experiment was designed to allow an exploration of the functional limits of the head rotation cue for localization of sources arrayed throughout the MVP.

5.2.1. Method

Sixteen listeners (8 females, 8 males) participated in the experiment. All reported normal hearing and all but two had no previous experience in localization experiments. The two with previous experience participated in Experiment 4.

Listeners were presented with low-pass noise bursts from 12 loudspeakers, spaced at 30° intervals throughout the MVP. As in the previous experiments, the loudspeakers were mounted on a framework constructed from PVC and steel tubing so that each loudspeaker faced the centre of the listener's head at a distance of 1.25 m. The loudspeakers were hidden from view by the complete spherical screen.

The signals used were 2-kHz low-pass filtered white noise of 200 ms, 400 ms, 800 ms, and 3000 ms duration including 20-ms rise and fall times. The signals were digitally generated in the manner described in Experiment 4, except that the pink noise filtering procedure was omitted.

There were six conditions; four involved the guided head rotation procedure employed in the previous experiment. These conditions were: 1) rotation at 100°/s with a 200-ms signal, 2) rotation at 100°/s with a 400-ms signal, 3) rotation at 50°/s with a 400-ms signal and 4) rotation at 50°/s with an 800-ms signal. The specific rotation velocities and signal durations were chosen because they would theoretically produce 20° of rotation in conditions 1 and 3, and 40° for conditions 2 and 4. Signal durations were generally greater than those used in the previous experiment because the results of Experiment 4 suggested that less movement was required for front-back discrimination than for elevation judgement. Two other conditions were also included: 5) Motionless listening with a 3-s signal and 6) free rotation with a 3-s signal, similar to that used in Experiments 6 and 7, but with 100° head oscillations, rotating between approximately +50° and -50° azimuth. The free rotation condition was included to gauge individual listeners' optimal performance. In pilot testing involving the guided head rotation procedure, listeners' elevation judgements appeared to be far less accurate than observed with the free rotation procedures used in Experiments 6 and 7. All listeners began the experiment with the free rotation condition, then proceeded to the guided rotation conditions, which were counterbalanced across listeners, and ended with the motionless condition. Testing was conducted in blocks of 12 trials with each loudspeaker activated once in a random sequence in each block. In the free rotation and the motionless conditions there were two blocks of trials, while in each of the guided rotation conditions there was one block of trials. There were thus 8 blocks of trials per listener.

Counterbalancing of guided rotation conditions was such that half of the listeners encountered two blocks of 100°/s rotation followed by two blocks of 50°/s rotation. This order was reversed for the other listeners. Within each velocity of rotation condition, half the listeners assigned to a particular order-of-velocity encountered the shorter signal in the first block and the longer signal in the second. This order was reversed for the other listeners.

Before the experimental trials of a particular type of rotation began, the procedures involved were demonstrated by the experimenter. Then the listener underwent practice trials until the experimenter was satisfied they were able to perform the required movements satisfactorily. All practice trials involved the loudspeakers positioned directly in front, directly behind and directly left of the listener. No feedback on accuracy of responses was given during practice or the experiment. Polhemus Isotrak II head tracking and closed circuit TV monitoring were again used as in experiment 4.

5.2.2. Results

Apparent elevation. Figure 25 shows the apparent elevation for each source and each condition (broken lines are for sources below the HP). Response patterns for the motionless and free rotation conditions were very similar to those occurring for MVP sources in Experiment 7. With upper hemisphere sources, the free rotation condition produced considerably more accurate elevation judgement than any other condition. Apparent elevation does not differ between guided rotation conditions, and is only marginally more accurate than in the motionless

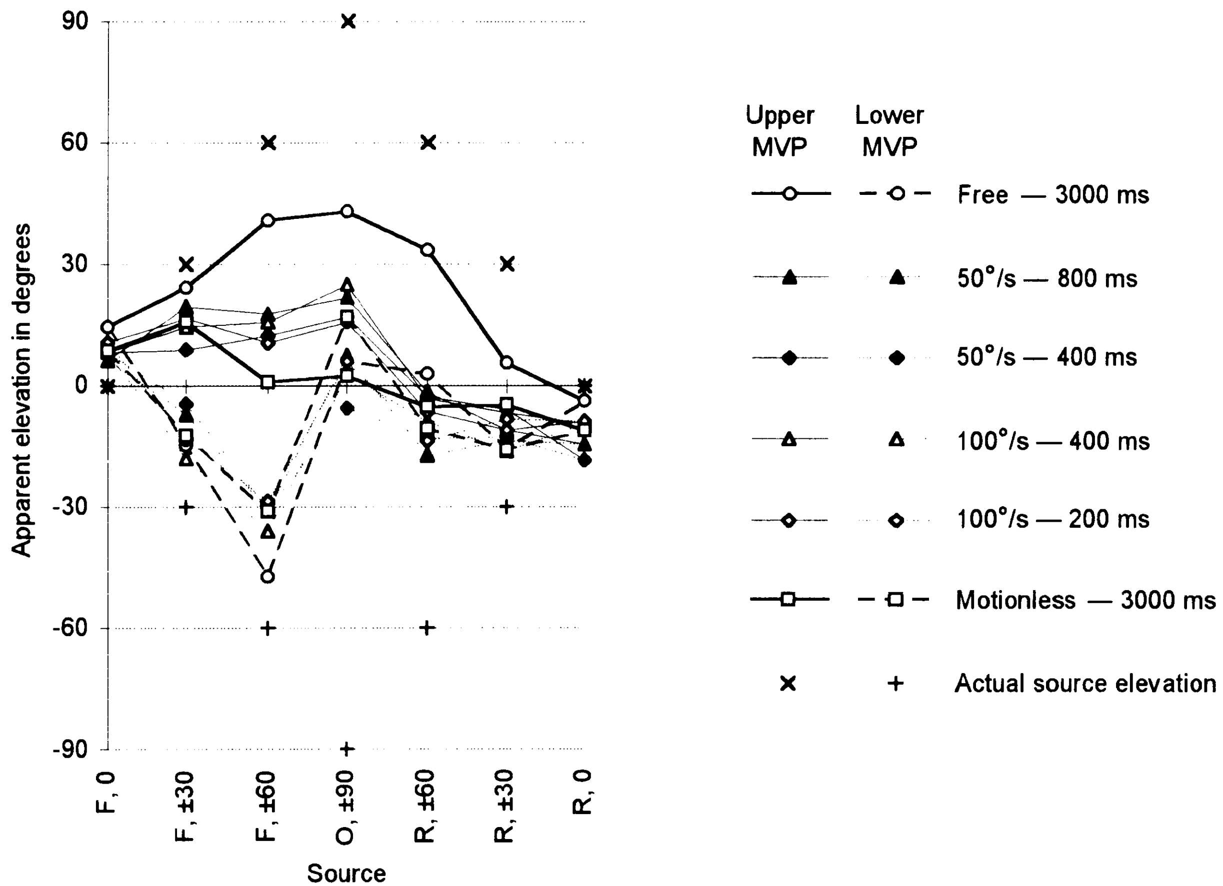

Figure 25. Apparent elevation under rotation and motionless conditions in Experiment 9. Actual source positions are at 0°, ±30°, ±60° elevation, forward (F, 0, etc.); overhead and below (O, ±90), and ±60°, ±30°, 0° elevation, rearward (R, ±60, etc.). The symbol "×" indicates the actual elevation of sources above the HP; the symbol "+" indicates sources below. Error bars indicate standard error of the mean.

condition, for sources at 60° and 90° elevation. In the lower MVP, apparent elevation is about the same across all conditions. As observed in Experiment 7, there are signs that listeners are able to judge, to some extent, the elevation of front MVP sources that lie below the HP.

Absolute elevation error. The accuracy of elevation judgement across all six conditions (motionless, free rotation, and four guided rotation conditions) was assessed statistically using a one-factor repeated measures ANOVA with absolute elevation error averaged across all loudspeakers acting as the dependent variable. This showed significant differences occurring between conditions. Post-hoc testing using Tukey's HSD multiple comparisons revealed that all four guided rotation conditions produced significantly less absolute elevation error than did the motionless condition ($p<.05$ in each case). Guided rotation conditions were not significantly different from one another. The free rotation condition produced significantly less absolute elevation error than any of the guided rotation conditions ($p<.05$ in each case). The free rotation condition also produced less absolute elevation error than the motionless condition ($p<.01$).

Benefit from rotation. To demonstrate how the various rotation conditions affected absolute elevation error across the different loudspeaker positions, Figure 26 presents the benefit obtained from each type of rotation. Benefit from

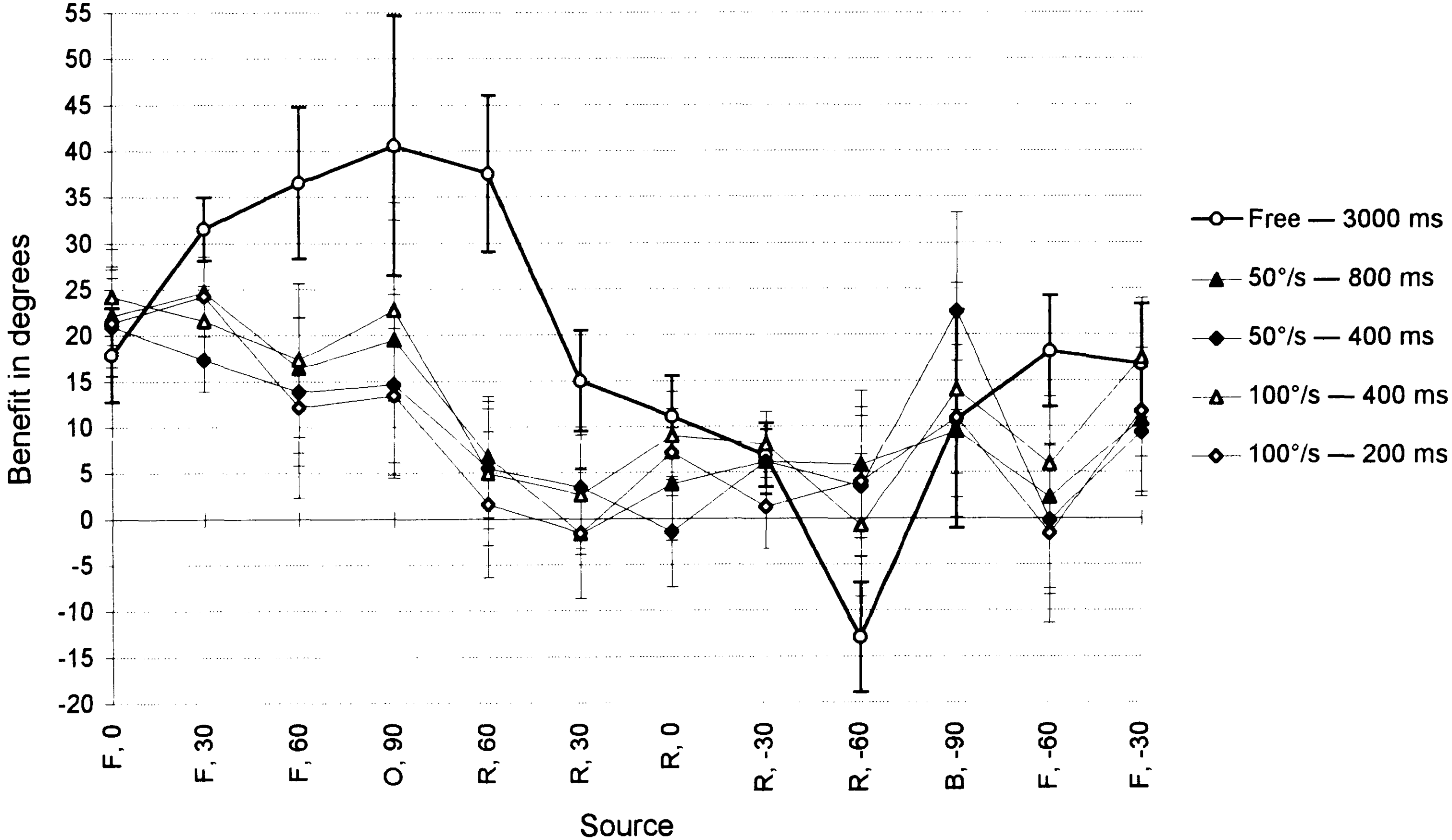

Figure 26. Benefit from rotation for each rotation condition in Experiment 9. Actual source positions are at 0°, 30°, -30°, 60°, -60°, 90°, -90°elevation, "F, 0, 30, -30 etc." indicates sources forward of the listener; "O, 90" the source overhead; "R, 0, 30, -30, etc." sources rearward of the listener; and "B, -90" the source directly below.

rotation was calculated by subtracting the amount of absolute elevation error in each particular rotation condition from that occurring in the motionless condition. Benefit from rotation, therefore, represents the reduction in absolute elevation error delivered by the type of rotation relative to the absolute elevation error occurring without rotation. This way of representing localization performance reveals that all forms of rotation provide considerable benefit in detecting source elevation. The benefit from free rotation is generally greater than for guided rotation, with substantial benefit occurring for sources to the front or above the listener. There are virtually no signs of differences in benefit occurring between the various guided rotation conditions, at any source position. Benefit in these conditions is mainly associated with localization of sources in the front MVP from 90° through to -30° elevation, as well as the source directly below.

Up-down errors. To gauge how well listeners were able to distinguish between sources above and below the HP, listeners' localization performance was appraised in terms of up-down errors. An up-down error was assigned whenever a signal from one hemisphere, above or below the HP, was erroneously attributed to a position in the opposite hemisphere. Sources in the HP are not considered in this analysis. Figure 27 shows the proportions of up-down errors occurring in each condition across pairs of sources, at symmetrically opposite positions with respect to the HP, (e.g., frontal sources at +30° and -30° elevation were paired).

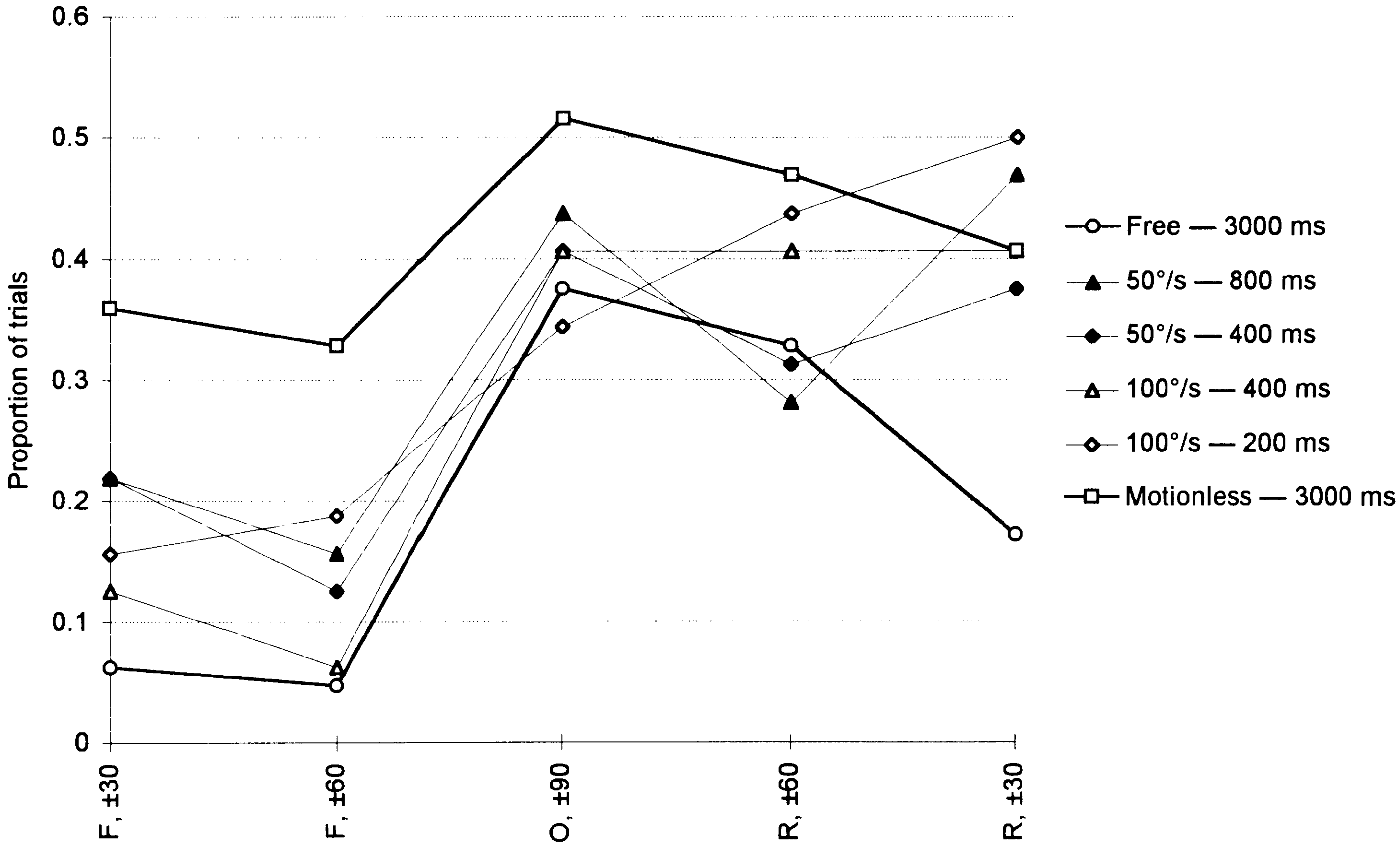

Figure 27. Up-down errors for each condition in Experiment 9. data for sources at symmetrically opposite positions relative to the HP are combined.

There were substantial proportions of up-down errors in all conditions. All rotation conditions produced substantially fewer up-down errors for sources to the front than did the motionless condition, but for rearward sources and those directly overhead and below, up-down errors were common for all conditions, with the exception of rearward sources at ±30° elevation when free rotation was employed. It is noticeable that even in the motionless condition, up-down errors occurred less often for sources in the front than for other sources.

Corrected apparent elevation. Wallach's theory proposes that rotation alone does not resolve differences between source positions above and below the HP. It is therefore conceivable that the large proportion of up-down errors may have hidden important rotational effects. If listeners accurately judged the angle of vertical displacement of sources but inaccurately judged the direction of that displacement (producing many up-down errors), calculated means for both apparent elevation and absolute elevation error would tend to hide Wallach's rotational effect. For example, if half the listeners were to judge the overhead source as lying at +90 and the others judged it as lying at -90°, the mean apparent elevation would be 0° and the mean absolute elevation error would be 90°. Correcting for up-down errors by making the sign of all individual apparent elevation scores positive when considering data for upper MVP sources and negative when considering data for lower MVP sources would reveal the accuracy of listeners judgements of vertical displacement regardless of up-down confusion. The apparent elevation data were therefore corrected for up-down errors.

Apparent elevation for HP sources was also corrected. The sign of all apparent elevation scores for HP sources was made positive to allow comparison with upper MVP data, and also made negative to allow comparison with lower MVP data. Thus two sets of data for the HP sources were created, being 'mirror-images' of each other. The corrected data are plotted in Figure 28 and do suggest stronger effects for rotation conditions than were depicted by the uncorrected apparent elevation data plotted in Figure 25. As might be expected, there is little sign, if any, that listeners are able to judge the displacement of sources from the HP in the motionless condition. Differences between the guided rotation conditions for the source positioned overhead are now evident.

Using corrected apparent elevation data for the source positioned directly overhead as the dependent variable, the four different guided rotation conditions were statistically compared. A one-factor repeated measures ANOVA revealed that there were significant differences between conditions. Post-hoc tests showed that apparent elevation was significantly greater for the 50°/s-rotation—800-ms-signal condition than for the 100°/s-rotation—400-ms-signal one ($p<.05$)

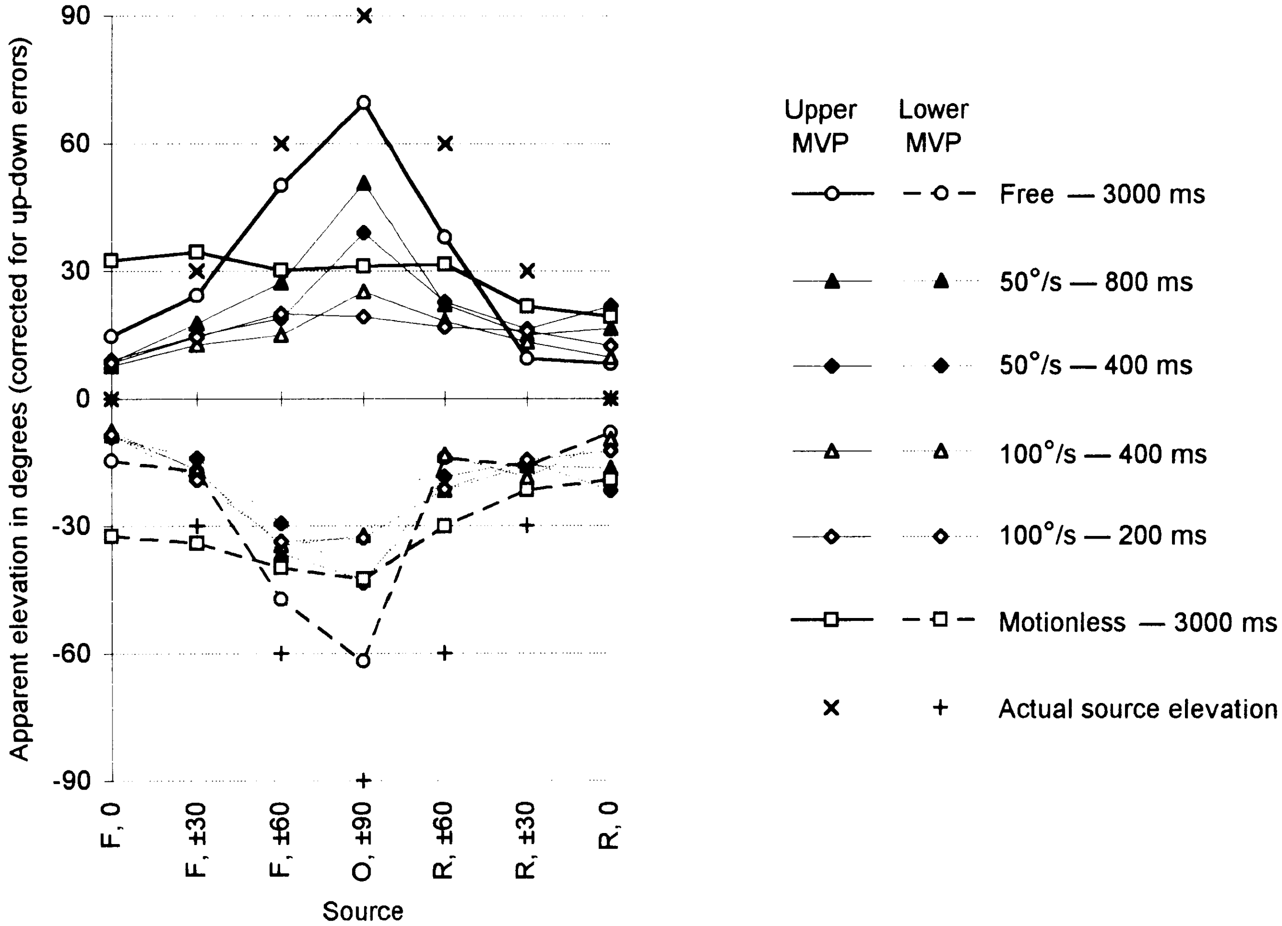

Figure 28. Corrected apparent elevation under rotation and motionless conditions in Experiment 9. Actual source positions are at 0°, ±30°, ±60° elevation, forward (F, 0, etc.); overhead and below (O, ±90), and ±60°, ±30°, 0° elevation, rearward (R, ±60, etc.). The symbol "×" indicates the actual elevation of sources above the HP; the symbol "+" indicates sources below.

and significantly greater for the 50°/s-rotation—400-ms-signal condition than for the 100°/s-rotation—200-ms-signal one (p<.05). The only other significant difference occurred between the 50°/s-rotation—800-ms-signal and the 100°/s rotation—200-ms-signal conditions (p<.01).

Table 11. Actual velocities and extents of rotation for each condition in Experiment 9 (standard deviations in brackets).

Condition	Nominal rotation velocity	Signal duration	Mean actual rotation velocity	Mean actual extent of rotation	Mean apparent elevation
1	100°/s	200 ms	164°/s	33°	21° (25°)
2	100°/s	400 ms	159°/s	64°	30° (21°)
3	50°/s	400 ms	62°/s	25°	40° (22°)
4	50°/s	800 ms	64°/s	51°	52° (28°)

Results presented in Table 11 suggest that the velocity of rotation may be an important factor in elevation judgement for the source overhead. Doubling the duration of the signal, and thereby doubling the angular extent, did not produce significant effects when velocity of rotation remained the same (condition 1 vs. 2, 3 vs. 4). Halving the velocity whilst doubling the duration, thereby keeping the angular extent approximately the same (actually somewhat less), produced significant increase (improvement) in corrected apparent elevation for the overhead source (condition 1 vs. 3, 2 vs. 4). However, rotating at reduced velocity when attempting to judge the angular displacement of a source from the HP may not be very useful in practical terms. If the signal is held constant at 400 ms, rotating at 62°/s did not produce significantly greater corrected apparent elevation than rotating at 159°/s, although the trend is in that direction (condition 2 vs. 3).

Front-back errors. Figure 29 shows the proportion of front-back errors occurring in each condition for MVP sources aligned at the same elevation. Sources directly above and below are not included in this analysis. Substantial proportions of front-back errors occurred in the motionless condition, but very few occurred in any of the rotation conditions. No front-back errors occur in any of the rotation conditions for sources in the HP or at -30° elevation. In all conditions including the motionless condition, there were generally more front-back errors associated with sources above the HP than below, with proportions increasing with increasing elevation above the HP.

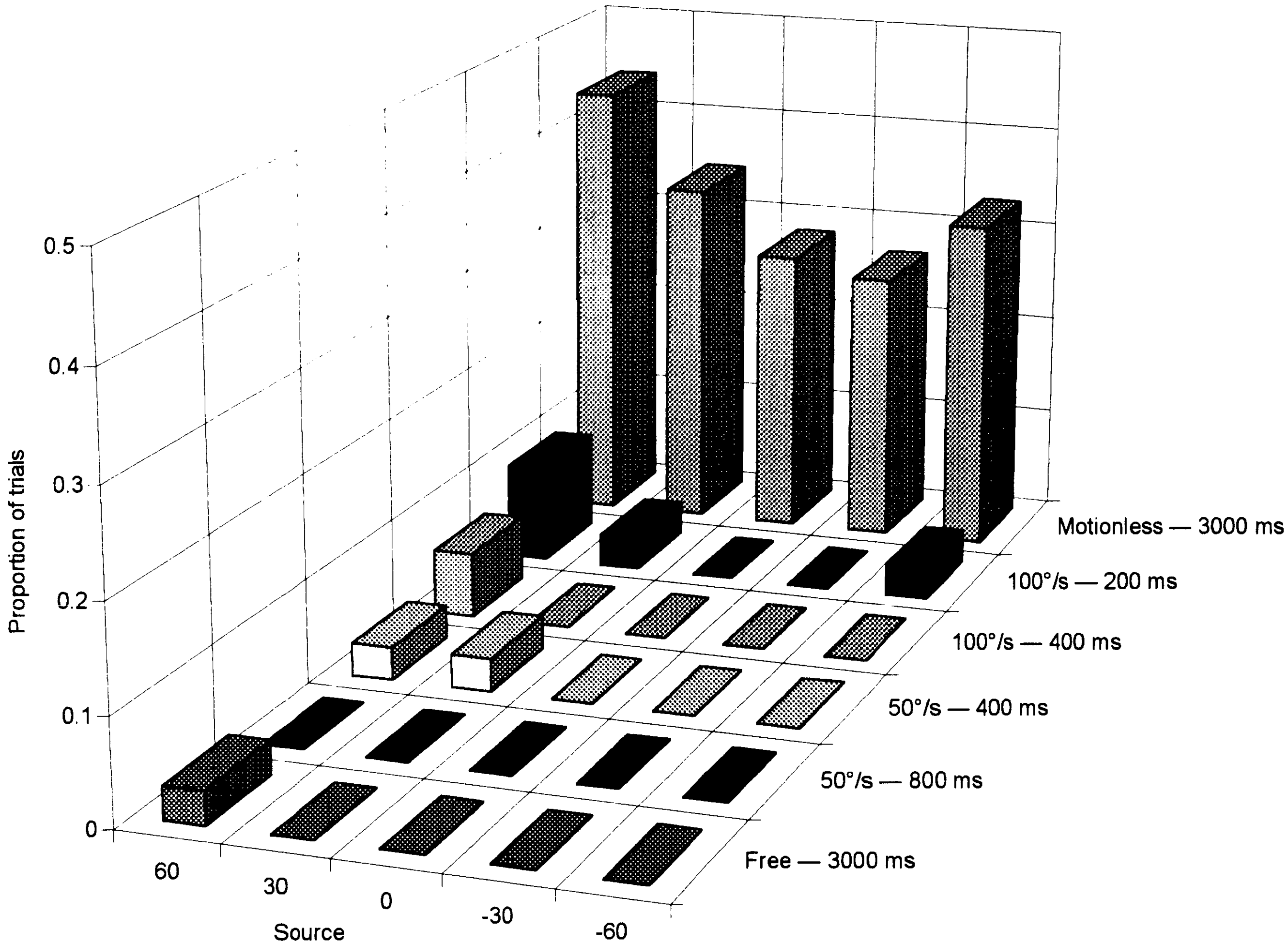

Figure 29. Front back errors for each condition at each elevation in Experiment 9.

5.2.3. Discussion

The results of the present experiment confirm those of Experiment 7 and provide further evidence that repeated oscillations of the head allow listeners to localize sources of 2-kHz low-pass noise in the MVP, with much greater accuracy than they can achieve without movement.

As observed in Experiment 7, the pattern of responding in motionless listening suggests that, to some extent, listeners can judge the elevation of sources in the lower-front quadrant of the MVP, and for forward regions appear somewhat able to distinguish between positions above and below the HP. In the four guided rotation conditions, in which the head was rotated once, in a continuous sweep from right to left throughout signal activation, listeners achieved greater accuracy, in terms of elevation judgement, than they did in the motionless condition, but less accuracy than in the free rotation condition. Guided rotation produced many fewer up-down confusions than motionless listening for sources forward of the listener, but these continued to occur at high rates for sources in other regions.

When apparent elevation data were corrected for up-down errors a greater effect due to rotation was noticeable. This is apparently because of how the Wallach cue to source elevation functions. As theorised by Wallach, rotation of the head would specify the angle by which the source is displaced from the HP, but would not specify the direction of that displacement. Correction for up-down errors allowed differences between the various guided rotation conditions to become discernible. With slower rotation velocities, appreciation of the magnitude of the angular displacement of the overhead source from the HP was significantly more accurate. This finding is somewhat surprising because the previous experiment had shown that front-back discrimination increased in accuracy with increasing rotational velocity, and the outcomes will be discussed further, towards the end of this section. Of theoretical importance is that differences occurring between the guided rotation conditions appear to be solely to do with a cue brought about through head rotation, which informs the listener that the overhead source is somewhat displaced from the HP, but provides no information whether the source is above or below. This is exactly what Wallach's theory suggests. The differences between the guided rotation conditions therefore suggest that the operation of a pure Wallach cue is dependent upon the velocity of the head rotation.

The teasing out of a pure Wallach cue, ambiguous in the way Wallach hypothesized, suggests that any ability to distinguish between above and below must be achieved on the basis of some other cue. Wallach argued that up-down ambiguity would be resolvable if listeners engaged in side to side tilting of the head (pivot movements). In this experiment, listeners were instructed to rotate the head and not to employ any other movements. Analysis of head tracker records revealed that listeners nonetheless could not help making small amounts of pivot movement. The mean extents of pivot movement occurring in each condition are shown in Table 12; they exhibit a range from 2.9° to 6.8° in the guided rotation conditions and 10.4° in the free rotation conditions. Also, as already mentioned, the results show that substantial reductions in up-down confusion occurred in the rotation conditions relative to the motionless condition.

Table 12. The extent of pivot movement occurring in each rotation condition in Experiment 9

Condition		Extent of pivot
100°/s	200 ms	2.9°
100°/s	400 ms	6.3°
50°/s	400 ms	3.8°
50°/s	800 ms	6.8°
Free	300 ms	10.4°

In spite of evidence that pivot movement did occur during the rotation trials, the present experiment provides little evidence to support the idea that pivot movement contributed in any way to the reduction in up-down confusion. The pattern of up-down confusion does not correspond with what would be expected from changes in interaural cues due to pivoting. Changes in interaural cues would be greatest within the plane of movement and would reduce to zero within the axis of movement. The distribution of front-back errors supports this notion since no errors occurred in the plane of rotation movement but became increasingly prevalent with greater displacement from the HP (see Figure 29). Up-down discrimination, on the other hand, was most inaccurate for sources at ±90° elevation, in the free rotation condition although these sources roughly occupy the plane of pivot movement (see Figure 27). Further evidence against the role of pivot movement is provided by the differences in the proportions of up-down confusion for sources in front compared to those behind. The same changes in pivot-induced interaural time differences would be expected to occur for sources at comparable elevations in the front or in the back, yet up-down discrimination was greatly superior for front sources than for back sources. Finally, substantial reductions in up-down confusion occurred for sources to the front, even when the extent of pivot was on average only 2.88° and 3.78°, as occurred in the 100°/s-rotation—200-ms-signal and 50°/s-rotation—200-ms-signal conditions respectively. No additional advantage occurred when the extent of pivot movement was on average 6.25 and 6.79° as occurred in the 100°/s-rotation—400-ms-signal and 50°/s-rotation—800-ms-signal conditions respectively. Although such arguments do not conclusively demonstrate that pivot movement was not involved in resolution of up-down positions, the evidence strongly suggests that pivot movement, as theorized by Wallach, was not a contributing factor in the reduction of up-down errors occurring in the conditions of this experiment.

Clearly, the reduction of up-down errors associated with rotation conditions needs a different explanation. The pattern of listeners' responses across motionless and rotation conditions suggest that torso-induced low-frequency spectral cues may be what is important. A consistent finding, across this experiment and Experiment 7, has been that listeners gain some appreciation of the elevation of sources positioned in the lower-front quadrant of the MVP, even while motionless (see Figure 25). It is also noticeable that the lower-front quadrant of the MVP is a region associated with increased ability to discriminate between front and back. In both motionless and rotation conditions the lower-front is distinguished from the lower-back more accurately than the upper-front is from the upper-back (see Figure 29). This similar pattern extends to up-down discrimination and again involves the lower-front quadrant of the MVP. The lower-front region is distinguished from the upper-front more accurately than the lower-back is from the upper-back, in both motionless and rotation conditions (see Figure 27). The consistent involvement of the lower-front MVP with more accurate localization, in both motionless and rotation conditions, suggests that relatively strong low-frequency spectral cues are available if the signal is produced from this region. Therefore, evidence from the present experiment suggests up-down discrimination occurring in the rotation conditions operates on the basis of dynamic torso-induced low-frequency spectral cues, rather than on the basis of Wallach-type pivot cues.

According to Wallach's theory a source positioned overhead is heard as displaced 90° above or below the HP if the head is rotated about a vertical axis. Such a movement would result in no change in azimuth angle and therefore no change in interaural information. According to Wallach, a lack of changing interaural information occurring simultaneously with head rotation would specify that the source is either directly overhead or directly below. Sources at all other elevations would be associated with some change in classically defined interaural information; sources at the HP being associated with maximal change. In judging the vertical displacement of a source elevated 90° from the HP, the task for the listener is thus to detect that no change in interaural information has taken place during the head movement. Similarly, detection of change or no change in interaural information is enacted in some MAMA experiments. Employing a movement versus no movement discrimination task, showed listeners' MAMAs increase with increasing velocity of source movement for a 500-Hz pure tone (Perrott & Musicant, 1977) and for narrow- and broadband noise, and pure tones of various frequency, Chandler & Grantham, 1992). Similar velocity effects on MAMAs have been obtained for pure tones of various frequency employing a direction of movement discrimination task (Perrott & Tucker, 1988). These findings suggest that detection of change or no change in interaural information is more accurate at slower velocities of source movement. The results of the present experiment are thus in line with the MAMA findings, showing that increased apparent vertical displacement is associated with decreased velocity of head movement.

The results of the present experiment nonetheless seems to contradict what was found in the previous one (Experiment 8). In that experiment it was found that higher velocities were associated with a decrease in front-back confusion. According to Wallach's theory, the task of front-back discrimination involves the detection of the direction of change in azimuth angle, for example, from +30° to -30° versus from -30° to +30°, occurring as a result of a given head rotation. Such a task being similar to that enacted in the MAMA study of Perrott and Tucker (1977).

Results from the present experiment suggest a solution to this apparent contradiction. As previously noted, even when motionless, some front-back discrimination is possible. Also, fewer front-back errors were associated with sources below the HP than sources above in the motionless condition, and this general pattern of (infrequent) front-back errors was evident across the rotation conditions. Thus, front-back error reduction may be associated with the availability of torso-induced low-frequency spectral information. If this is indeed the case, comparisons between findings of MAMA research and the present experiment may be expected to show different outcomes because it is highly probable that transformations of spectra, as a result of head movement occurring while the torso remains motionless, would be different from spectral changes resulting from a source moving about a listener with both head and torso motionless. The generally similar MAMA results between low-frequency pure tone and broadband noise, presented from in front of the listener (Chandler & Grantham, 1992), suggest that MAMA data relate mainly to changing interaural time differences. It may therefore be useful to assume that front-back discrimination based on head rotation operates along different lines to detection of source movement.

Part of the evidence from the final experiment in the present program suggests that a cue to the displacement of a sound source from the HP operates on the basis of a lack of change in interaural information relative to head motion. Wallach's theory predicts that the (up-down) direction of such displacement would not be resolvable on the basis of the changing interaural information that occurs with rotational head movements, and results associated with the source positioned directly overhead are consistent with this prediction.

Research findings show that MAMA thresholds are lower when velocity of source movement is lower. The same general finding for pure tone signals as well as complex signals suggests that MAMA tasks involve detection of change (or lack of change) in classical interaural information. If cues to vertical displacement, derived from head rotation, like MAMA tasks, are based on detection of change (or lack of change) in interaural information, then judgement of elevation involving head rotation should closely correspond with MAMA research findings. Outcomes from the final experiment reveal such a correspondence. When apparent elevation scores were corrected for up-down errors, decreased velocity of head rotation was seen to be associated with greater apparent displacement of the overhead source from the HP. This is consistent with the outcome of MAMA research, namely that it is easier to detect a change, relative to a lack of change, in interaural information, the lower the rate of that change.

5.3. OVERALL CONCLUSIONS

The outcomes from the guided rotation conditions show clearly that a listener is capable of utilizing purely dynamic information for the purpose of sound localization and that this is more useful than static information. The results of these experiments show that head rotation assists localization with signals of 150 ms and 200 ms duration in terms of front-back discrimination and elevation judgement respectively.

In the eighth experiment it was revealed that increasing velocity of head rotation coupled with increasing extent of rotation was associated with increasing accuracy in front-back discrimination. The results of that experiment also suggest that head rotation allows a listener to gain information about the acoustic environment, and once this information has been obtained, subsequent localization is more accurate, even in motionless conditions.

The ninth experiment provides evidence to support the view that a rotational cue operates along the lines theorized by Wallach (1939; 1940), suggesting that a lack of change in classical interaural information allows an appreciation that a source is displaced from the HP, but not allowing an appreciation of the direction of that displacement. Decreasing velocity of head rotation and increasing signal duration were associated with more accurate judgements of the magnitudes of source displacement from the HP. The pattern of results suggest that pivot movement, working in the way theorized by Wallach does not have any affect on up-down discrimination of low-pass noise. Instead, such discrimination involves the use of dynamic torso-induced low-frequency spectral information.

Chapter six: General discussion and conclusion

The ability to localize sound allows people to orient themselves so that they can see the whereabouts of whatever is producing a particular sound. Much evidence from localization research demonstrates that the acoustic energy impinging on the eardrums of a motionless listener carries important information about the direction of the sound source. This information can be in the form of ITDs, ILDs, pinna-induced high-frequency spectral cues and torso-induced low-frequency spectral cues. However, the characteristics of a particular sound may mean that not all of these forms of information are available, and so a motionless listener will often make localization errors. This is clearly evident when a sound lacks the complex high-frequency acoustic energy necessary for the generation of pinna-induced spectral cues. A low-pass noise test signal, devoid of high-frequency energy, was successfully used in the program of experiments reported here to produce consistently high levels of localization error under motionless listening conditions. When broadband noise, comprising both low- and high-frequency acoustic energy was used as the test signal, motionless listening produced relatively accurate localization, but a substantial proportion of trials continued to result in front-back errors. Thus, even when the signal is optimal, in terms of its potential to provide localization cues, a motionless listener often fails to gain a clear appreciation of the direction of the sound source.

The evidence from the program of experiments reported here demonstrates that rotation of the head during the time a sound is occurring greatly assists listeners in orienting to face the source. As a listener rotates the head, the available directional information undergoes continual change. The outcomes from the present research show that this changing (dynamic) information is richer than the unchanging (static) information available to a listener who is motionless. The dynamic information arising from changing ITDs and torso-induced low-frequency spectra resolves front-back ambiguity and provides an appreciation of the source elevation.

In the everyday world, head rotation is likely to occur in response to hearing a sound if there is a need to localize its source. Thus if the sound is of sufficient duration to allow the person time to react by head rotation, they will be able to make use of dynamic information. If the sound ceases before the person has had time to react then they will have to rely on static auditory information to guide a visual search for the sound source. Some of the present results show that listeners did not react soon enough to make use of dynamic localization cues under a 'natural' listening condition when the signal duration was 500 ms. Nonetheless, when instructed to rotate in response to hearing the onset of the signal, they were able to react soon enough and to make use of the dynamic front-back information thus available. A quick reaction may well be what is provoked in the real world.

Although people may not have enough time to react in response to hearing a short duration signal, head movement is a common feature of ongoing human behaviour, even when not in response to hearing sounds. In the process of everyday living, head rotations occur as people direct their visual attention to various parts of the environment. For example, searching for items on supermarket shelves, following a path while monitoring surroundings, such as crossing the street, or observing the state of the weather, all involve rotational head movements. For whatever reason, head turning during the incidental occurrence of a short sound may be common, therefore allowing people access to dynamic information concerning the whereabouts of the source.

The task of auditory localization within the so-called 'natural' conditions employed in some of the experiments reported here, was fairly unlike that occurring in the everyday world. One major and important difference is that listeners were not given the option to employ a visual search for the source. Listeners were required to localize sound sources without ever gaining visual confirmation of their actual location. Under conditions occurring in the everyday world, localization of a sound source will seldom be achieved on the basis of auditory information alone. Much of the localization task will involve active visual search. For example, if a person hears the song of a bird which sounds like it is emanating from a position directly in front, and yet sees that the bird is obviously not in that position, they will probably engage in a visual search for the bird's position, moving the head in the process. They would then gain dynamic auditory localization cues to help in this visual search. In the laboratory situation, without the option of engaging in visual search, a listener is likely to respond to the position directly in front without engaging in visually driven head movements. This happened in some cases where listeners, though free to move, remained still throughout the period of the sound. The lack of an option to engage in a visual search may even have been responsible for the relatively slow reaction times occurring in the 500-ms natural movement conditions. In everyday conditions in which visual search behaviour is an option, greater use of head movement may conceivably occur. There was no evidence from subsequent experiments to suggest that keeping still allows listeners any advantage over moving.

6.1. EVERYDAY USE OF DYNAMIC LOCALIZATION

This is how dynamic localization might take place in the everyday world, taking into account the knowledge gained from the present program of experiments.

When a person, who happens to be motionless, first hears a sound, they will pick up salient information about the approximate azimuth of the source on the basis of classical interaural cues. They may also gain some information about the elevation and front-back location of the source on the basis of spectral cues. The motionless listener uses all this information to direct their visual search for the source. The range of possible positions that must be searched will mainly depend on the strength of the available spectral cues. Thus, with strong spectral cues available, the person may be able to look directly to the source, requiring minimal visual search. With weak spectral cues, however, the listener will need to search a range of directions consistent with the azimuth of the source. A bias to expect sources to occur in or near the HP may ensure that initial head movement is roughly rotational. The salience of ITDs and ILDs, providing strong left-right information will mean that the person begins their visual search by rotating their head (leftward or rightward) consistent with the azimuth of the source. If the interaural cues suggest the source is in or near the MVP, lack of a visual sighting of a source to the front would suggest its location is rearward, again resulting in head rotation.

If the sound is of short duration, and ceases before the head turning associated with visual search begins, visual search for the source must continue without any further assistance from auditory cues. If, on the other hand, the sound continues or recurs while the person is engaged in visual search, dynamic auditory cues will inform them as to whether the source is forward or rearward. On the basis of this information the listener can narrow down the visual search for the source so that the head will be oriented to bring the sound in line with their front MVP. In this orientation, static localization cues are optimal. If the source still remains unseen, further visual scanning, involving head rotations will provide the listener with salient elevation information.

The current set of experiments mainly involved investigation of rotational movement, but these also included small amounts of pivot movement. Under everyday conditions, it would be expected that people will employ various other types of movement in localizing sounds. For example, it is possible that rotation in conjunction with tipping of the head and leaning back of the torso may provide additional localization cues for resolving up-down confusion.

6.2. LINKS BETWEEN VISION AND HEARING

The abilities of auditory localization and vision seem to operate in partnership. Heffner and Heffner (1992) have provided strong evidence that a major function of auditory localization in mammals is to allow them to direct their field of best vision towards a sound source. They show that across various species of mammal, the narrower the species' horizontal width of field of best vision, the more accurate they are at localizing sound. Heffner and Heffner suggest that mammals with narrow fields of best vision have a greater need to localize sounds accurately than mammals with wide fields of best vision. For example, horses have wide fields of best vision and therefore have less need to be able to localize sounds accurately, whereas humans have narrow fields of best vision and therefore have a strong need to be able to localize sounds accurately. The auditory localization acuity of humans is about 1° compared to 25° in horses.

Perrott, Saberi, Brown and Strybel (1990) have provided direct evidence that the spatial sensitivity of the human auditory system assists humans to search for visual targets. They showed that the time required for a visual search is substantially reduced when a click train is produced from the position of the visual target, yielding a significant effect, even when the visual target lies within 10° of the initial line of sight. Thus it seems clear that a primary role of auditory localization is to regulate visual search. One further important outcome from the study by Perrott et. al. (1990), was the finding that head movements are a significant factor underlying most adjustments of visual gaze during the search for a visual target.

If the human behaviour of localizing a sound source entails directing the field of best vision towards the source, and in the process involves head movement, then the methods employed by a large proportion of auditory localization research may be at risk of overlooking essential elements of how human auditory localization operates in the real world. Many localization experiments are carried out with the listener blindfolded and motionless.

Wallach (1939; 1940) proposed that head movements enable unambiguous auditory localization and provided empirical evidence to support his theory. He also obtained evidence to suggest that the visual system provides information about head movements which contributes to localization accuracy. Until now, little other evidence has suggested that head movements actually assist auditory localization.

Outcomes from the present program of research clearly show that rotations of the head provide a listener with dynamic auditory cues to the whereabouts of sound sources, and that these dynamic cues greatly assist auditory localization. It therefore appears that the process of visual search makes an important contribution to auditory localization in that the head movements it involves allow access to dynamic auditory information. This information, in turn, assists visual search behaviour. Therefore it does seem that visual search and auditory localization operate in close association with each other.

Wallach (1940) suggested that to make use of dynamic auditory information for the judgement of source elevation, the listener must have access to information about the rate of head movement in relation to the change in interaural information. Perrott, Buck, Waugh and Strybel (1979) showed that human listeners are able to detect differences in the velocity of auditory targets and Waugh, Strybel & Perrott (1979) showed that this ability has virtually the same degree of accuracy as detection of differences in the velocity of a visual target. This suggests that velocity judgement involves a central process common to both the visual and auditory modalities. Thus, there is evidence that the visual and auditory systems are closely linked as far as dynamic information is concerned.

6.3. SUMMARY OF MAIN FINDINGS.

The present program shows that head movement is an important factor involved in the localization of sound. Rotation of the head, during the activation of a sound, assists a listener to judge whether the source of the sound is positioned in the front or the rear hemisphere. Rotation of the head during the activation of a sound also assists in judgements about the elevation of the source. Finally, rotation of the head, assists in detecting the horizontal position of the source.

With head rotation, front-back confusion is substantially reduced, even when the signal is as brief as 150 ms. Elevation judgement is substantially more accurate with a signal lasting as little as 200 ms duration. Localization of broadband noise is assisted by head rotation with significantly fewer front-back errors and significantly more accurate elevation judgement than occurs under motionless listening conditions. The region in which greatest benefit from rotation occurs is the front MVP. There is evidence that head rotation cues involve dynamic ITDs and dynamic torso-induced low-frequency cues.

The findings from the present program provide evidence for Wallach's theory, but add complexity to it by suggesting that head rotation combines with dynamic torso-induced low-frequency spectral cues to help allow source positions to be detected more accurately.