

An Adaptive Bias in the Perception of Looming Auditory Motion

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Rising acoustic intensity can indicate movement of a sound source toward a listener. Perceptual overestimation of intensity change could provide a selective advantage by indicating that the source is closer than it actually is, providing a better opportunity for the listener to prepare for the source's arrival. In Experiment 1, listeners heard equivalent rising and falling level sounds and indicated whether one demonstrated a greater change in loudness than the other. In 2 subsequent experiments listeners heard equivalent approaching and receding sounds and indicated perceived starting and stopping points of the auditory motion. Results indicate that rising intensity changed in loudness more than equivalent falling intensity, and approaching sounds were perceived as starting and stopping closer than equidistant receding sounds. Both effects were greater for tones than for noise. Evidence is presented that suggests that an asymmetry in the neural coding of egocentric auditory motion is an adaptation that provides advanced warning of looming acoustic sources.

From an evolutionary perspective, the problem of anticipating an approaching object is an important task. A listener with a perceptual bias to detect approaching objects might gain a selective advantage by better preparing for the object's arrival. In vision, the topic of looming has been widely studied, with investigations ranging from the study of gannets who time their wing folding to coincide with contact with the water when diving for fish (Lee & Reddish, 1981) to baseball outfielders who arrive at the correct position in the field to catch fly balls (McBeath, Shaffer, & Kaiser, 1995). The problem has also been studied to a lesser extent in the auditory domain.

An approaching sound source is characterized by a dynamic increase in intensity at the point of the listener. The specific pattern of rising intensity change can indicate when the source and listener will meet (Shaw, McGowan, & Turvey, 1991). However, whether listeners actually use this information to accurately predict arrival time is an issue of some debate. When asked to predict arrival time on the basis of auditory cues, listeners often err on the side of safety, expecting contact before the source actually arrives (Rosenblum, Wuestefeld, & Saldaña, 1993; Schiff & Oldak, 1990). Performance is slightly more accurate when listeners use intensity change to guide their own locomotion toward a stationary target (Ashmead, Davis, & Northington, 1995; Rosenblum, Gordon, & Jarquin, 2000). However, the tendency to err on the side of safety is still apparent.

Guski (1992) suggested that perhaps this type of "error" should not be interpreted as such. He proposed that, when an object is approaching, the primary role of the auditory system is that of warning, either to direct the visual system toward the object if time allows, or to initiate appropriate behaviors to avoid the object. In this view, precise auditory judgments about time to contact are not as important as a categorical decision about whether the listener has time to turn to look or must simply jump out of the way. This general idea was echoed by Popper and Fay (1997), who suggested that the primary function of auditory localization may not be to provide exact estimates of source location but rather to provide input to the listener's perceptual model of the environment. Thus, under some circumstances, distortions, errors, or biases in auditory localization may prove to be adaptive.

Recent studies have shown that if listeners are asked to judge the loudness in equivalent rising- and falling-intensity signals, rising-intensity sounds are perceived to be louder and change more in loudness than falling-intensity sounds (Neuhoff, 1998; Stecker & Hafter, 2000). Although there were no moving sounds, the results suggest that a rising-intensity bias might be an adaptive trait that has evolved because it provides a selective advantage in perceiving approaching sound sources. If so, the bias may be at the root of the numerous findings of underestimation of auditory time or distance to contact (Ashmead et al., 1995; Rosenblum et al., 1993; Schiff & Oldak, 1990).

If listeners have evolved to be more sensitive to approaching sounds than receding sounds on the basis of intensity change, then one should be able to make several predictions. First, given equal change in intensity, rising-intensity sounds will be perceived to change in loudness more than falling-intensity sounds will. Similarly, given equal stopping points, approaching sounds should be perceived as being closer than receding sounds. This would provide a margin of safety on approach that could provide a selective advantage. Second, at higher intensity levels, the disparity between rising and falling loudness change will be greater. A bias for rising intensity would be more advantageous for loud (close) sounds than for soft (distant) sounds. Finally, the bias for rising intensity and source approach will be greater for tones than for broadband noise. Tonal sounds are produced by a wide variety of single coherent sound sources. Approaching such a source, or anticipat-

ing such a source's approach, is an important environmental event. However, coherent tonal sounds are almost never produced by simultaneously sounding dispersed sources. Multiple sounding sources in a natural environment often result in the production of broadband noise (Nelken, Rotman, & Yosef, 1999). Thus, tonality can act as a reliable marker for single-source identity and can help listeners parse important signals from background noise (Bregman, 1994; Ciocca, Bregman, & Capreol, 1992; Rogers & Bregman, 1998).

In this study, I investigated further the bias for rising-intensity sounds and specifically tested for a perceptual bias for approaching auditory motion. In Experiment 1, I examined the proportion of times that a rising-intensity sound is judged to change in loudness more than an equivalent falling-intensity sound and the magnitude of the difference in perceived change between the two sounds. In Experiments 2A and 2B, listeners were presented with approaching and receding auditory motion and estimated the beginning and end points of travel of the auditory source.

EXPERIMENT 1

Method

Participants. Sixty-six undergraduates between 18 and 24 years of age served as participants. All received class credit for participation. All reported normal hearing.

Apparatus. Stimuli were generated by a 16-bit sound card in a Pentium PC and fed directly to Sony MDR-v600 headphones. The frequency response of the headphones was 5 Hz to 30 kHz. All intensity measurements were made with a flat plate coupler with the sound meter microphone 0.5 in. (1.3 cm) from the center of the speaker element and used the A-weighted scale. Responses were made in a sound-attenuating booth by using a computer mouse to position a cursor on a video monitor that was outside the booth and viewed through a window.

Design and procedure. On each trial, listeners were presented with two sounds, one of rising intensity and one of falling intensity. The task was to indicate whether the amount of loudness change in each sound was the same or whether one sound changed more in loudness than the other. Stimuli were presented in two intensity ranges: 40 to 70 dB and 60 to 90 dB. Thus, on any given trial listeners heard two sounds that either changed from 40 to 70 dB and 70 to 40 dB or from 60 to 90 dB and 90 to 60 dB¹ (see Figure 1). Stimulus duration of each sound was 1.8 sec with an

¹Sounds changed linearly in dB, which specifies an approaching source that is decelerating. Previous work has shown that, in making judgments of source velocity, listeners do not discriminate well between linear and accelerated rates of intensity change (Andreeva & Vartanyan, 1997).

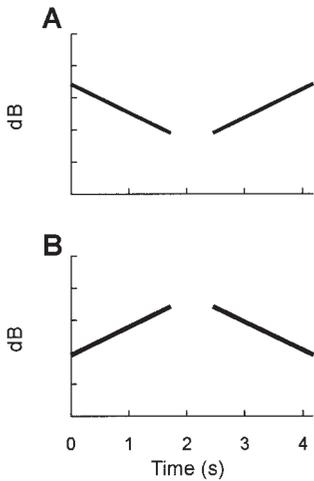


FIGURE 1 Pattern of intensity change in Experiment 1. On half of the trials, intensity fell and then rose (Panel A). On the other half, intensity rose and then fell (Panel B). Each stimulus changed 30 dB, half in the range 40 to 70 dB and half in the range 60 to 90 dB. The duration of each stimulus was 1.8 sec, with a silent interstimulus interval of 0.5 sec. Trials were presented in random order.

interstimulus interval of 0.5 sec. After presentation of a stimulus pair, an unmarked visual analogue scale appeared on the screen with a movable cursor in the center and a button labeled *OK* below. The left end of the scale was labeled *SOUND 1*, and the right end was labeled *SOUND 2*. Listeners were instructed to move the cursor toward the sound that changed the most in loudness and then click *OK*. If both sounds changed the same amount, they were to leave the cursor in the center and click *OK* (see Figure 2). Listeners were instructed that the distance that they moved the cursor should represent how much more one sound changed than the other. For example, if Sound 1 changed only slightly more than Sound 2, then the listener was to move the cursor only slightly to the left. If Sound 2 changed much more than Sound 1, then the listener was to move the cursor far to the right. Each listener heard 40 stimulus pairs at each intensity level for a total of 80 trials in random order. On half of the trials, a rising-intensity sound was presented first; on the other half, a falling-intensity sound was presented first. For half of the participants, the stimuli consisted of white noise (sample rate = 44.1 kHz), and for the other half, the stimulus was the synthetic vowel sound /ə/ that approximated the unstressed syllable in “about” (sample rate = 8 kHz). The vowel sound was produced with a Klatt synthesizer (Klatt, 1980) and had a fundamental frequency of 100 Hz and formants at 450 Hz, 1450 Hz, and 2450 Hz.

Results

Responses were categorized as either *rising* (rising intensity changed in loudness more than falling), *falling* (falling intensity changed in loudness more than rising), or *same* (loudness change was the same for the two sounds). Proportional response

rates for each participant were calculated by dividing the total number of each type of response by the total number of trials at each intensity level. The mean proportion of responses for all participants is shown in Figure 3. Across all conditions the proportion of rising responses was greater than the falling or same responses. Because the data are proportional, an analysis of all the response categories would violate the independence assumptions of the analysis of variance (ANOVA). Thus, the analysis was performed on the proportion of rising responses in a 2×2 ANOVA with the within-subject factor of level (40 to 70 dB and 60 to 90 dB) and the between-subject factor of spectral content (white noise or vowel tone). There was a main effect of level, indicating significantly more rising responses in the 60 to 90 dB

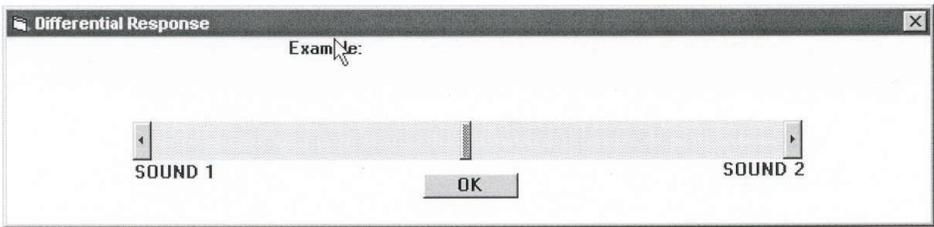


FIGURE 2 Response mechanism that appeared after each trial in Experiment 1. Listeners used a mouse to move the cursor toward the sound that changed the most in loudness and then clicked OK. If both sounds changed the same amount they were to leave the cursor in the center and click OK. Scale distance represented how much more one sound changed than the other.

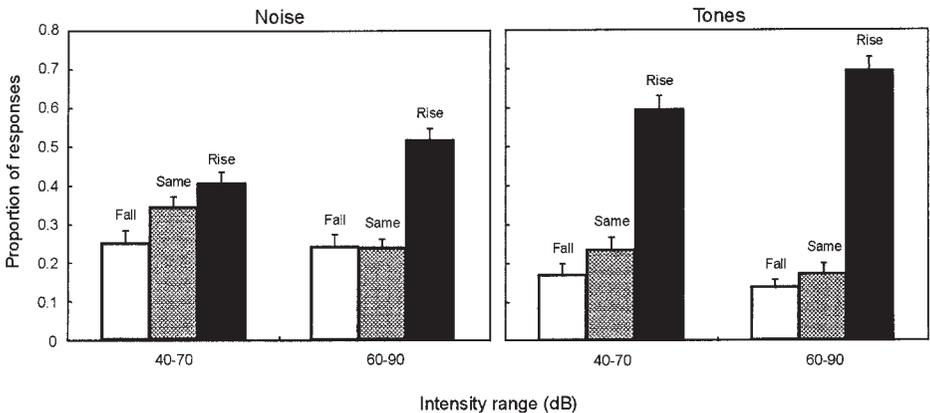


FIGURE 3 Proportion of trials in Experiment 1 on which rising and falling intensity appeared to change more in loudness and on which the two sounds appeared to change the same amount. For all trials, the change in rising and falling level was always the same (30 dB). Error bars represent 1 SE.

condition than in the 40 to 70 dB condition, $F(1, 64) = 24.80, p < .001$. There was also a main effect of spectral content, indicating significantly more rising responses for vowel sounds than for white noise, $F(1, 64) = 19.17, p < .001$.

The responses were also analyzed for the amount difference in change between rising and falling intensity. Final cursor placement was assigned a number between -50 (full left placement) and $+50$ (full right placement). Cursor placement for same responses was assigned a value of 0 and not included in this analysis. The data were recoded so that negative scores represented trials on which falling intensity was judged to change more than rising, and positive scores represented trials on which rising intensity was judged to change more than falling. The mean magnitude of change difference is shown in Figure 4. All of the means were positive, indicating that the difference in loudness change was greater when rising sounds were judged to change more. A 2×2 (Intensity Level \times Spectral Content) ANOVA showed that the difference in change increased with increasing intensity level, $F(1, 64) = 13.77, p < .001$. There was also a main effect of spectral content, indicating that the difference in change was greater for harmonic tones than for white noise, $F(1, 64) = 25.21, p < .001$.

Discussion

Why should rising intensity change in loudness more than falling intensity? There is ample evidence that listeners are more sensitive to discrete increments in intensity

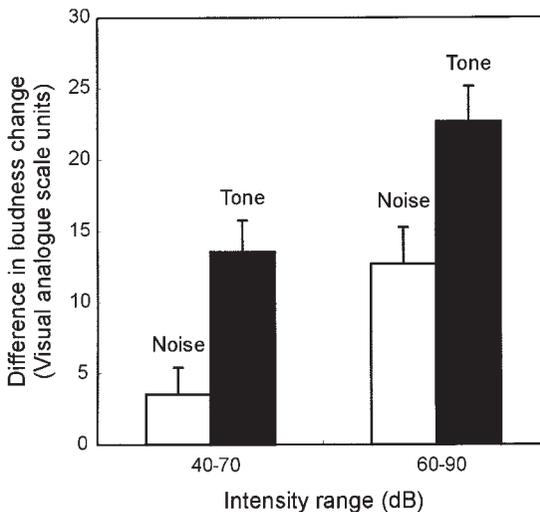


FIGURE 4 Magnitude of difference in loudness change (visual analogue scale units) in each experimental condition in Experiment 1. The positive values indicate that rising intensity changed in loudness more than equivalent falling intensity. Error bars represent 1 SE.

than equivalent decrements (Ellermeier, 1996; Grose & Hall, 1997; Heinz & Formby, 1999; Moore & Peters, 1997; Moore, Peters, & Glasberg, 1999; Oxenham, 1997; Sinnott, Owren, & Petersen, 1987). Similarly, listeners are generally more sensitive to signal onset than offset (Emmerich, Pitchford, & Becker, 1976; Zera & Green, 1993). Although most of the work investigating these effects used discrete intensity change (often at very brief durations), there may be similar mechanisms involved in processing dynamic intensity change at the longer durations used in this experiment. If the auditory system is to provide advance warning of looming auditory motion, then a bias for rising intensity would serve this purpose well. Thus, these results may support Guski's (1992) suggestion that as the distance between a source and an observer decreases, the auditory system provides advance notice of the impending collision to allow for appropriate motor behaviors. This interpretation is consistent with the prevalent underestimation of arrival times and under-shooting of source locations found in previous work (Ashmead et al., 1995; Rosenblum et al., 1993; Schiff & Oldak, 1990).

As the intensity range of a dynamic loudness sweep increased, the disparity between rising and falling loudness change also increased. Listeners were more likely to say that a rising-intensity sound changed more in loudness at high intensity levels, a finding consistent with Stevens's (1956) power law. In a natural environment, this effect would appear to be important because it would be more critical to detect the approach of a close source than a distant one. The closer the source, the less time the listener has to prepare for contact. Thus, the greater bias for rising intensity found at higher levels is consistent with the greater relative importance of nearby sounds (Graziano, Reiss, & Gross, 1999; Rosenblum, Wuestefeld, & Anderson, 1996).

Finally, the results show that the bias for rising intensity is greater for tones than for broadband noise. Single-cell recordings in the cochlear nucleus have shown that a complex interaction between units in the dorsal and ventral auditory pathways is instrumental in the differential processing of tones and broadband noise (Davis & Voigt, 1997; Nelken & Young, 1994; Palmer, Jiang, & Marshall, 1996). The dissociation of the dorsal and ventral pathways (in both audition and vision) is widely thought to represent separate processing of object identification and localization processes and has been referred to as a division between the "what" and "where" perceptual systems (Deutsch & Roll, 1976; Kaas & Hackett, 1999; Mishkin, Ungerleider, & Macko, 1983; Romanski et al., 1999; Shiffrar, 1994; Shiffrar & Freyd, 1993). Spectral differences such as those used in Experiment 1 can be used to parse and identify a sound source, and intensity change can indicate source motion. Thus, auditory processing of source identity may constrain the perception of intensity change and, in turn, the perception of source motion. Such an interaction of identification and localization has already been demonstrated in auditory behavioral studies (Bregman & Steiger, 1980; Mondor, Breau, & Milliken, 1998) as well as in vision (Shiffrar, 1994; Shiffrar & Freyd, 1993).

The results of Experiment 1 are consistent with the idea that listeners exhibit a bias for rising intensity that might provide a selective advantage in processing

sound sources that approach. However, there are important differences between the sounds used in this experiment and those produced by approaching sources. First, the intensity change produced by an approaching source follows the inverse-square law, whereby changes in intensity occur at a faster and faster rate as the source draws closer to the listener. The rate of intensity change in Experiment 1 was linear, thus specifying decelerating approaching sources and accelerating receding sources. Second, the sounds in Experiment 1 were heard through headphones, but the inferences made concerned free-field auditory motion. There have been consistent differences shown between both loudness and localization estimates with sounds heard in headphones and those heard in a free-field setting (e.g., Hartley & Carpenter, 1974; Killion, 1978; Sivian & White, 1933; Stream & Dirks, 1974; Wightman & Kistler, 1989). Finally, in Experiment 1, listeners were asked simply to make estimates of loudness change. Although it is true that monaural loudness change is a primary cue that listeners use to judge auditory source approach (Rosenblum, Carello, & Pastore, 1987), it is possible that the estimates of loudness change made in Experiment 1 do not correspond well to estimates of distance change in a natural listening environment (however, see Warren, 1958). Experiment 1 clearly confirms a bias for rising intensity. However, given these limitations, more data are required before firm conclusions regarding the perception of auditory approach and recession can be drawn. Thus, Experiments 2A and 2B were conducted in an open field and designed to test directly for differences in the perception of approaching and receding auditory motion.

EXPERIMENT 2A

Listeners in Experiments 2A and 2B were blindfolded, presented with approaching and receding sound sources in an open field, and asked to estimate the starting and ending points of travel. Listeners in Experiment 2A made estimates verbally, and those in Experiment 2B made estimates by blind walking.

Method

Participants. Fourteen undergraduates between 18 and 22 years of age served as participants. All received class credit for participation. All reported normal hearing. None had participated in Experiment 1.

Apparatus. A 16-bit sound module in an IBM Pentium notebook computer generated the stimuli. The signal was fed from the computer to an amplifier (Model TC 1490, Micro Multimedia Labs, Reisterstown, MD) and then to a 4-in. (10.2-cm) single-element speaker (Oaktron 4D45). The speaker was held in a bracket that was suspended from a vinyl-coated cable that stretched horizontally between two

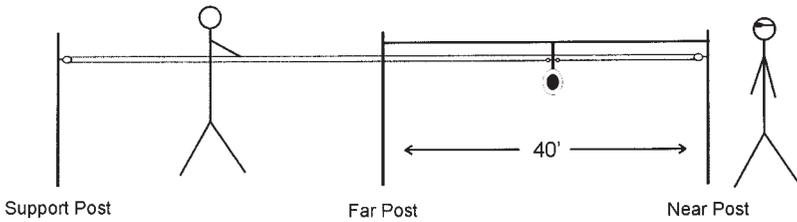


FIGURE 5 Apparatus used to move the speaker in Experiments 2A and 2B.

posts that were 40 ft (12.2 m) apart. The speaker was suspended 48 in. (122 cm) above the ground and was free to travel the entire 40-ft (12.2 m) length of the cable. The listener stood at the near post, and the speaker was moved forward and backward along the cable by two strings (see Figure 5). The first string was attached to the back of the speaker bracket and was pulled by an assistant who was beyond the far post. The second string was attached to the front of the speaker bracket and passed through an eyehook on the post nearest the listener, through another eyehook on the far post, and was pulled by the assistant. Pulling on the first string caused the speaker to move away from the listener. Pulling on the second caused the speaker to move toward the listener. Forty-six feet (14 m) beyond the far post was a support post with another eyehook. Both of the strings passed through this eyehook and were joined, creating a type of pulley system with which the speaker was moved. Between the support post and the far post, hash marks were painted in the grass every 2 ft (0.6 m) for the 40 ft (12 m) that corresponded to the speaker's travel distance between the first two posts. The assistant responsible for moving the speaker carried a Walkman-type tape recorder and wore open-air headphones. A metronome was recorded on the tape at 140 beats/min. To move the speaker at a constant velocity, the assistant held a string and walked such that one foot touched a hash mark on every other beat of the metronome. Thus, the speaker velocity was 2.33 ft. (0.71 m)/sec or approximately 1.58 mph. The experiment was conducted in an open grassy field with the nearest building approximately 250 ft (76 m) away.

Stimuli. Stimuli consisted of either a triangle waveform with a fundamental frequency of 400 Hz or white noise. Both the triangle wave and the noise were band-pass filtered with cutoff frequencies of 400 Hz and 1200 Hz. The sampling rate for all sounds was 44.1 kHz. All sounds were presented at 88 dB-A measured 6 in. (15.2 cm) directly in front of the center of the speaker.

Design and procedure. Each listener stood 1 ft (0.3 m) behind the near post, facing the speaker, and was blindfolded such that no part of the blindfold touched any part of the outer ear. Listeners were told that the speaker would begin to move as soon as it made a sound and would stop sounding once it came to a stop. The listener's task was to verbally estimate the starting and ending positions of the speaker

in relation to him- or herself, in any units of measure that he or she deemed appropriate. All distances were to be estimated from the listener to the speaker position in question. Listeners were told that the speaker could start or stop at any position along the length of the cable. In actuality, there were only three starting and ending positions. On each trial, the speaker moved half the length of the cable (20 ft, or 6 m). On trials in which the speaker moved away from the listener, the speaker either started at the near post and moved to the midpoint of the cable or started at the at the midpoint of the cable and moved to the far post. On trials in which the speaker moved toward the listener, the speaker either started at the far post and moved to the midpoint or started at the midpoint and moved to the near post. Each listener heard the two types of approaching trials and the two types of receding trials with a tone and also with broadband noise, for a total of eight randomly ordered trials. At the end of each trial, listeners verbally estimated the starting and ending points of travel with respect to distance from their observation point. Half of the listeners reported starting positions first, and the other half reported ending positions first. No feedback was provided.²

Results

Separate analyses were performed on the estimated starting and ending speaker positions. In each case, the analyses were conducted only on equal starting and ending positions, respectively. Thus, to examine differences in perceived starting position of approaching and receding sounds, only the four types of trials—2 (spectrum) \times 2 (direction)—that started at the midpoint and moved either toward or away from the listener were examined. Similarly, in examining differences in perceived stopping location, only the remaining four approaching and receding trials with the same stopping location (the midpoint) were compared. Thus, to summarize, starting position trials started at the midpoint and moved toward or away from the listener, and ending position trials started either at the far post and moved toward the listener or started at the near post and moved away from the listener, in both cases stopping at the midpoint.

The mean perceived starting position in each condition is shown in Figure 6. Across all conditions, the mean estimates of starting position were less than 50% of the actual distance. A repeated measures ANOVA failed to show a significant effect of direction of travel, $F(1, 13) = 2.06, p = .174$, or of spectrum, $F(1, 13) = 0.22, p = .644$, on perceived starting location. There was a significant interaction between direction of travel and spectrum, $F(1, 13) = 9.86, p = .008$. However, given that the closest mean estimate in any condition was only 43% of the actual starting distance, the practical significance of the interaction is difficult to determine.

²There is evidence that listeners can improve their estimates of auditory approach when provided with feedback (see Rosenblum et al., 1993). However, no feedback was provided here because of the emphasis on investigating an auditory warning mechanism.

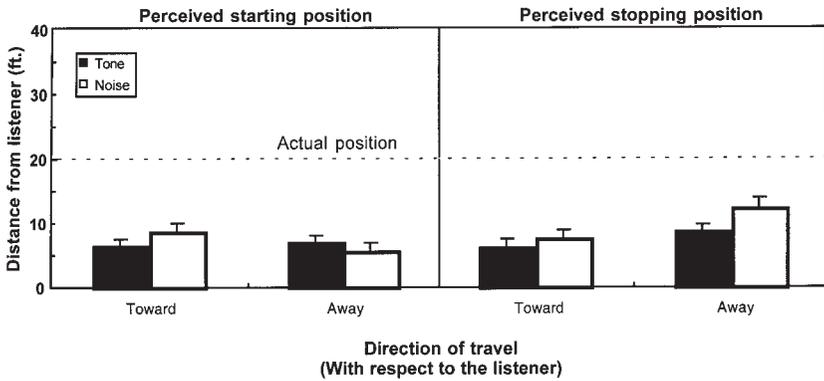


FIGURE 6 Perceived starting and stopping points of approaching (toward) and receding (away) speaker travel in Experiment 2A. Distance estimates were made verbally. Error bars represent 1 SE.

The mean perceived stopping position in each condition is also shown in Figure 6. Once again the mean estimates of position were all well under the actual stopping position. However, unlike the starting positions, there was a significant effect of travel direction on perceived stopping location, $F(1, 13) = 22.72, p < .001$. Approaching sounds were perceived to stop closer to the listener than receding sounds despite equal stopping points in each case. There was also a significant effect of spectrum on perceived stopping location, $F(1, 13) = 5.62, p = .034$. Tones were perceived to stop more closely to the listener than noise. These results are discussed further later, in conjunction with the results of Experiment 2B.

EXPERIMENT 2B

Method

Participants. Ten undergraduates between 18 and 22 years of age served as participants. All received class credit for participation. All reported normal hearing. One had participated in Experiment 2A.

Design and procedure. The apparatus, stimuli, and procedure in Experiment 2B were identical to those in Experiment 2A, with the exception of the participant's method of response. After the speaker had come to a stop, it was removed. Listeners then guided themselves by the cable and walked blindfolded to the point on the track where they heard the speaker start and stop. On trials where the speaker approached the listener, participants walked to the perceived stopping point, and their position was recorded. They then continued on to the perceived

starting point. On trials where the speaker traveled away from the listener, the perceived starting point was recorded first. The blindfold was removed after recording both responses, and the listener returned to the observation point. No feedback was provided.

Results

The analysis of perceived starting and stopping position, using trials with equal starting and ending points, respectively, was conducted in the same manner as Experiment 2A. The mean starting and stopping positions are shown in Figure 7. The estimates made by the blind walking technique generally show a greater degree of accuracy than those made verbally. A repeated measures ANOVA failed to show a significant effect of direction of travel on perceived starting position, $F(1, 9) = 0.33$, $p = .581$. However, tones were perceived to originate significantly closer to the listener than noise was, $F(1, 9) = 13.12$, $p = .006$. There was also a small but significant interaction between spectrum and direction of travel, $F(1, 9) = 5.52$, $p = .043$. The analysis of perceived stopping position showed that approaching sounds were perceived to stop closer to the listener than receding sounds, $F(1, 9) = 8.87$, $p = .015$, and tones were perceived to stop closer to the listener than noise, $F(1, 9) = 25.42$, $p = .001$.

Discussion

The results of Experiments 2A and 2B demonstrate a perceptual bias to perceive approaching auditory motion as closer than it actually is. The bias was due primarily to a tendency to perceive the stopping position as closer to the observer than it actu-

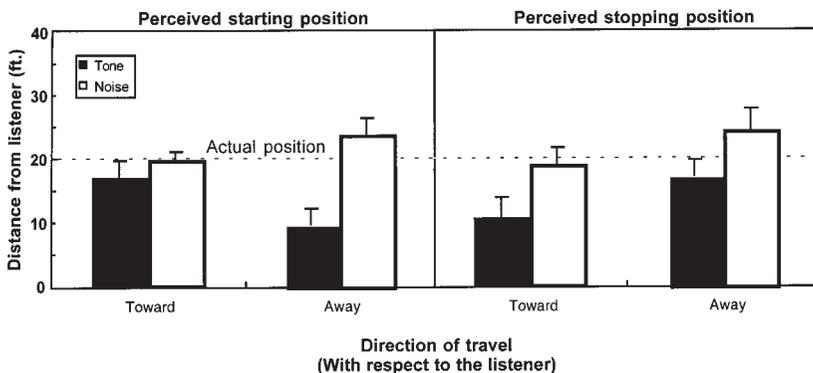


FIGURE 7 Perceived starting and stopping points of approaching (toward) and receding (away) speaker travel in Experiment 2B. Distance estimates were made by blind walking. Error bars represent 1 SE.

ally was. The effect was more pronounced for tonal stimuli than for broadband noise. Listeners were generally more accurate with estimates made by blind walking than with those made verbally, although the distance from the sound source to the listener was consistently underestimated in both conditions.

These findings confirm the predictions about approaching and receding auditory motion that were made with the rising- and falling-intensity stimuli presented in headphones in Experiment 1. They are also consistent with studies that have shown consistent underestimation when listeners are asked to estimate time to contact with an approaching auditory source (Ashmead et al., 1995; Rosenblum et al., 1993; Schiff & Oldak, 1990). In an earlier work (Neuhoff, 1998), I suggested that such a bias may have evolved because it provides a selective advantage. Perceiving an approaching source as closer than it actually is would allow more time to prepare for the arrival of the source. However, in the earlier work (Neuhoff, 1998) it was unclear whether rising intensity was perceived as greater than, or falling intensity was perceived as less than, the actual intensity change that would be created by motion between a source and the observer. It was also questionable whether judgments of intensity change in headphones were indicative of approaching and receding auditory motion estimates. The results of this study clearly demonstrate a bias for approaching auditory motion that is consistent with the adaptive hypothesis I proposed (Neuhoff, 1998).

Listeners showed greater accuracy when indicating their responses by blind walking than by indicating them verbally. Using stationary auditory targets, Loomis, Klatzky, Philbeck, and Golledge (1998) found that listeners typically underestimated the distance to the source, and there was greater variability in the verbal estimates of distance than walking responses. However, verbal and walking estimates in Loomis et al.'s study were more concordant than those in this study. The discrepancy may be due to the use of stationary sound sources by Loomis et al. and moving sources in this study.

Finally, listeners showed a greater bias for tonal sounds than for broadband noise. This finding is consistent with a pattern of results that is beginning to emerge from other studies. Specifically, listeners appear to be more accurate at estimating time to contact or walking to a sound source when the sound is broadband noise than when the sound is tonal. Ashmead et al. (1995) used noise stimuli and found relatively accurate performance when listeners were asked to blindly walk to the target location. Schiff and Oldak (1990) used more tonal stimuli (e.g., voices) and found that listeners made estimates of arrival time that were often 40% to 60% of actual arrival time. The greater accuracy for noise stimuli might be explained by greater signal bandwidth. Many studies have shown that broadband sounds are generally localized better than narrowband sounds (Butler & Planert, 1976; Chandler & Grantham, 1992; King & Oldfield, 1997; Middlebrooks, 1992; Recanzone, Makhamra, & Guard, 1998; Saberi, Takahashi, Farahbod, & Konishi, 1999; Terhune, 1985). However, the difference in accuracy due to signal bandwidth does not explain why the distance to tonal sounds was systematically underestimated. It

also does not explain why the tonal sounds in Experiment 1 were perceived to change in loudness more than the broadband noise.

It may be that the explanation lies in the relative evolutionary importance of harmonic tones in a natural environment. Naturally occurring harmonic tones typically exhibit a correlation between the intensity changes of their individual spectral components. This correlation can be used by the listener to parse auditory sources and separate them from background noise (Bregman, 1994). Of course, biological organisms produce both noise and harmonic tones. However, broadband noise is less commonly produced by single organisms and is often the result of multiple or dispersed sources (Nelken et al., 1999). In essence, then, a tonal sound can specify an environmentally important individual sound source that can more easily be separated from other sounds than can broadband noise. Thus, for purposes of localizing oncoming auditory motion, the greater evolutionary pressure would seem to be anticipating the approach of the source of a harmonic sound.

GENERAL DISCUSSION

The results of three experiments confirm a perceptual bias for the perception of rising versus falling intensity and an analogous bias in the perception of approaching versus receding auditory motion. Sounds that increased in intensity were perceived to change more in loudness than sounds that decreased, despite an equal amount of intensity change in each case. Sounds that approached listeners were perceived as stopping closer than sounds that departed, despite identical stopping points. A bias for looming auditory motion may provide a selective advantage in preparing for contact with an approaching source, or an increased margin of safety on approach. If the source is perceived as closer than it actually is, then the listener will have longer than expected to prepare for the source's arrival. These findings are consistent with Guski's (1992) suggestion that, in dealing with auditory source approach, the role of the auditory system is to provide advanced warning so that a decision about the appropriate course of action can be made and executed as quickly as possible. The results are also consistent with Popper and Fay's (1997) suggestion that the function of auditory localization is not necessarily to provide exact estimates of source location but rather to provide input into the organism's perceptual model of the environment that increases the likelihood of the organism's survival.

In addition to the disparity between rising and falling intensity and approaching and receding motion, the pronounced effect for tonal sounds over broadband noise also provides support for the adaptive hypothesis. Tones were generally perceived to change more in loudness and stop closer to the observer than equivalent noise was. This finding may indicate environmental priorities in processing auditory motion. Complex tonal sounds are produced by many biological sources and consist of a series of harmonics that undergo correlated changes in acoustic dimensions. These changes can provide cues to source parsing, identification, and localization

(Bregman, 1994; Ciocca et al., 1992; Rogers & Bregman, 1998). A perceptual bias in processing approaching tones might provide a selective advantage by allowing more time to prepare for the approach of biological sound sources. Meaningful broadband noise is less commonly produced by single biological sources, and the uncorrelated changes typical of the components of noise make segregating such auditory sources more difficult (Bregman, Abramson, Doehring, & Darwin, 1985; Bregman, Levitan, & Liao, 1990). This difficulty is compounded by the fact that broadband noise often results from simultaneously sounding multiple sources in a natural environment (Nelken et al., 1999). Although broadband noise can be produced by individual biological organisms, an ordered harmonic series with correlated dynamic changes is rarely produced by dispersed simultaneously sounding multiple sources. Thus, the presence of a dynamic complex harmonic tone usually acts as a marker for a coherent single source. These results suggest that the auditory system treats the motion of these types of sounds with preference.

It has been suggested that lower level psychophysical phenomenon or even hysteresis effects in the perception of loudness change explain differences in the perception of dynamic loudness change, such as those in Experiment 1 and in Neuhoff (1998). Specifically, the terminal portion of a changing-intensity stimulus might be more influential in a listener's judgment of loudness change (B. Scharf, personal communication, March 19, 1999). For example, if one uses the same range of intensity change for rising and falling sounds, then rising-intensity stimuli end at a higher level than falling-intensity stimuli. Thus, the argument has been posed, listeners might be more likely to say that rising-intensity stimuli changed more in loudness, erroneously basing their judgments of loudness change on terminal intensity alone. The results of Experiments 2A and 2B suggest that this is not the case. In both experiments the terminal intensity of approaching and receding sounds at the point of observation was the same. Furthermore, both the overall intensity of the stimulus and the amount of intensity change at the observation point were greater for sounds that moved away from the listener. Clearly these findings are not explained by the traditional psychophysical findings in the perception of loudness change.

Physical (or Perceptual?) Correlate Theory

A possible relation between judgments of loudness change and judgments of auditory distance is addressed in Warren's (1958) physical correlate theory. The theory suggests that changes in the nature of a stimulus are perceived in terms of environmental physical correlates rather than in terms of changes in sensory magnitude per se. Thus, judgments of loudness change can be made in terms of changes in source distance. The theory predicts that estimates of half-loudness of a source should be equivalent to the effect of doubling the distance from the source to the listener. Although there is some experimental support for the theory (Stevens & Guirao, 1962;

Warren, 1958, 1963; Warren, Sersen, & Pores, 1958), the studies that support the theory used only static sounds. The results of this study suggest that under dynamic conditions the relation between judgments of loudness change and distance to an auditory source is somewhat more complex. Specifically, under dynamic conditions, the direction of change can affect both the magnitude of loudness change and estimates of source location. An analogous systematic bias was exhibited in judgments of both dimensions.

The similar pattern of responding in each case suggests a modification of physical correlate theory. Given that listeners tended to err conservatively in both conditions, it may be that changes in loudness are mediated by correlates of perceived location rather than correlates of physical location as suggested by Warren (1958). Under dynamic conditions, judgments of loudness change, such as those made in Experiment 1, are not well accounted for by correlates of physical location. In terms of auditory distance, the rising and falling intensity in Experiment 1 indicated equidistant movement toward and away from the listener, but judgments of intensity change were asymmetrical. However, if listeners perceive approaching sources to be closer than they actually are, as was demonstrated in Experiments 2A and 2B, then the asymmetrical pattern of responding in Experiment 1 is consistent with a correlate of perceived rather than physical source location.

Loudness, Loudness Change, and Loudness Decruitment

These results also underscore the importance of the distinction between judgments of loudness and judgments of loudness change. Previous work on an effect termed *loudness decruitment*³ has shown that if listeners are asked to provide magnitude estimates of the loudness of a tone that steadily decreases in intensity, then the loudness estimate at the end of the tone is less than if the terminal intensity were presented alone as a discrete static tone (Canévet, 1986; Canévet & Scharf, 1990; Schlauch, 1992). The effect does not occur to the same extent for rising-intensity tones. At first glance, this finding may appear to be at odds with the results of Experiment 1 (for a discussion, see Canévet, Scharf, Schlauch, Teghtsoonian, & Teghtsoonian, 1999; Neuhoff, 1999). Falling-intensity tones appear to cover more perceptual space than rising-intensity tones. However, in loudness decruitment experiments, listeners are asked to make snapshot judgments of *loudness*, whereas in Experiment 1 listeners were asked to make judgments of *loudness change*. The distinction is an important one. Absolute loudness at any one point in time provides no information about source approach. Rate of change on the other hand, is a critical variable, because it *can* specify arrival time (Shaw et al., 1991), or at least provide in-

³The term *decruitment* as it applies to loudness has also been used to describe a pathology in which patients with temporal lobe damage are unable to perform alternate binaural loudness balancing and to satisfactorily balance tones of equal intensity (Mencher, Clack, & Rupp, 1973).

formation that facilitates a categorical decision about the appropriate actions to be taken as the source approaches (Guski, 1992). Viewed in this way, loudness decreasement clearly supports the evolutionary position. Decreasing loudness may signal decreasing environmental importance because it can signal the departure of a sound source. The endpoint of a downward sweeping sound (or departing source) would be less important (and less loud) than the endpoint presented alone, which might signal the onset of an important new environmental source.

The Argument for an Adapted Mechanism

There are specific scientific criteria that can be applied in evaluating adaptive hypotheses. These criteria were recently outlined by Buss, Haselton, Shackelford, Bleske, and Wakefield (1998, p. 543). The criteria are listed here, and the hypothesis regarding the evolution of a bias for looming auditory motion is evaluated on each point.

1. *"Is the evolutionary psychological hypothesis formulated in a precise and internally consistent manner?"* Simply put, the adaptive hypothesis states that listeners have evolved to perceive rising intensity as changing more than equivalent falling intensity and approaching auditory motion as closer than equidistant receding auditory motion. The bias for rising intensity and auditory source approach is an adaptation that provides a selective advantage in preparing for source arrival and a margin of safety on approach. The change in intensity and in location of tonal sounds is more significant perceptually than equivalent changes in broadband noise because tonal sounds can act as reliable markers for environmentally important coherent sound sources. The internal consistency and level of precision of the hypothesis allow empirical tests to be conducted that are capable of falsifying the hypothesis.

2. *"Does the hypothesis coordinate with known causal processes in evolutionary biology, much like hypotheses in cosmology must coordinate with known laws of physics?"* The hypothesis suggests an asymmetry in the neural processing of approaching and receding auditory motion. There is evidence that the neural architecture of the auditory system is selective in processing directional motion and that neural firing rates in response to auditory motion can vary asymmetrically on the basis of direction of travel (Doan & Saunders, 1999; Kautz & Wagner, 1998; Rauschecker & Harris, 1989; Wagner & Takahashi, 1992; Wagner, Trinath, & Kautz, 1994; Wilson & O'Neill, 1998). Although the specific neural substrate responsible for the bias has not yet been identified, the hypothesis is consistent with known biological processes.

3. *"Can new specific empirical predictions about behavior or psychology be derived from the hypothesis for which data are currently lacking?"* Several specific predictions can be made. For example, if a bias in perceiving auditory approach has evolved in order to allow greater preparation for the arrival of looming sources, then one might expect to see a greater bias in species that are typically prey than those that

are typically predators. One would also expect that organisms that rely heavily on the auditory system for accurately tracking motion would show little or no such bias, because a bias would specify an incorrect source location. Organisms that use the auditory system as an alert or warning mechanism should show a greater bias, thereby creating a greater margin of safety. However, it is important to note that the hypothesis should not be viewed solely in terms of predator–prey relationships. Perceiving dynamic intensity change and looming auditory motion is important in many other tasks, including spatial navigation (Ashmead et al., 1998; Rosenblum et al., 2000; Russell & Turvey, 1999; Schenkman & Jansson, 1986; Stoffregen & Pittenger, 1995). Finally, one might expect sex differences in the bias similar to those found in the time-to-contact literature (e.g., Schiff & Oldak, 1990).

4. “*Can the hypothesis more parsimoniously account for known empirical findings, and overall, is it more evidentially compelling than competing hypotheses?*” One of the most consistent empirical findings in auditory distance perception and auditory time to contact is that listeners often perceive sounds to be closer than they actually are. A secondary finding is that this effect tends to be greater for tones than for noise. The adaptive hypothesis can parsimoniously account for both the consistent underestimation of auditory time to contact as well as the differences between tones and noise in judgments of loudness change and estimates of source distance.

However, there are several alternative hypotheses to the evolution of a bias for rising intensity and approaching auditory motion. First, the bias might simply be a functionless by-product of another naturally selected trait or neural mechanism. The human bellybutton is often used as a classic example of an evolutionary by-product (Buss, 1999; Buss et al., 1998). It does not appear to solve any adaptive problem, and it provides no reproductive or survival advantage. It is simply a by-product of the umbilical cord, a structure that is an adaptation. In this view the bias for looming auditory motion is not a characteristic that solves an adaptive problem. It is simply the coupled by-product of another adaptive mechanism. It is important to note, however, that providing evidence for this alternative hypothesis requires identifying the adaptation with which the bias is coupled and providing evidence that this mechanism is indeed an adaptation itself. Second, the bias might be what Gould (1991; Gould & Vrba, 1982) termed an *exaptation*. Gould has defined exaptations as “features that now enhance fitness, but were not built by natural selection for their current role” (p. 46). In this view, the bias would have evolved as an adaptation to a different problem or as a by-product of another adaptation but has since been co-opted for the task of providing advanced warning of auditory approach. Like the by-product hypothesis, the exaptation hypothesis also requires identifying and providing evidence for the original adaptation that was co-opted. Finally, the bias might be a randomly evolved effect that neither helps nor hinders survival or reproduction. Thus, the trait is passed on so long as it does not interfere with the other adapted and functioning mechanisms of the organism.

At present, the weight of the evidence suggests that the bias for rising intensity and approaching auditory motion is an adapted characteristic that has evolved to

solve the problem of advanced warning of auditory source approach. There is currently no evidence to suggest that the bias is a by-product of some other evolved mechanism. Similarly, it is unlikely that the bias is an exaptation. There is currently no evidence to suggest that the bias evolved initially for another purpose but at some point was co-opted to serve as an early detection system for approaching auditory motion. Finally, the current evidence suggests that it is unlikely that the bias is simply a random effect that serves no purpose. Adaptations are important to an organism's survival and reproduction. As such, to be defined as an adaptation, a characteristic must be typical of most or all members of a species (with certain exceptions, such as sex-linked characteristics; Buss et al. 1998). Random effects are not important to survival and reproduction and, as such, tend to be distributed randomly among the members of a species. Indeed, one of the ways in which adaptations can be discerned from random effects is their prevalence among members of a species. Although the number of participants who took part in the experiments in this study is comparatively small, it should be noted that all of the 24 participants in Experiments 2A and 2B showed a bias for approaching auditory motion.

5. *"Is the proposed psychological mechanism capable of solving the hypothesized problem?"* Implicit in the adaptive hypothesis is Guski's (1992) proposal that the auditory system functions as an advance warning mechanism to either direct the visual system toward the approaching source or to initiate appropriate motor behaviors to avoid the source. Clearly the ability of the auditory system to respond differentially to motion in different directions exists (see Wilson & O'Neill, 1998). A similar type of differential neural response to approaching and receding sources would provide a neural basis for a bias in perceiving looming auditory motion. Such a bias would yield a selective advantage in detecting and preparing for the arrival of approaching acoustic sources as well as providing a margin of safety on approach. Thus, the adaptive hypothesis proposes a psychological mechanism that solves the "advance warning" problem with looming auditory sources.

Converging Evidence

There are several sources of converging behavioral and physiological evidence that support the adaptive hypothesis proposed here. The bias for looming auditory motion suggests an asymmetry in the neural coding of dynamic rising and falling intensity. The neural locus of the effect is as yet unknown; however, recent recordings in the inferior colliculus of the mustached bat have revealed cells that show greater response to moving sound entering a receptive field than exiting it (Wilson & O'Neill, 1998). Sound movement in the experiment was along points on a sphere, all equidistant from the bat. The results of the current study might be explained by a similar asymmetry in neural responding for motion toward the listener. One interesting theory suggests that the inferior colliculus is tuned to biologically important sounds and that an asymmetry in neural timing in the inferior colliculus, from rapid input to

slowed output, mediates motor responses to such sounds (Casseday & Covey, 1996). Thus, the inferior colliculus may be important in mediating a bias for rising intensity and the ensuing motor behaviors suggested by Guski (1992). Furthermore, analogous systematic errors are found in auditory spatial memory and distance-perception experiments. Listeners perceive and remember auditory sources as closer than they actually are (Loomis et al., 1998; Radvansky, Carlson-Radvansky, & Irwin, 1995). In a time-to-contact experiment, Schiff and Oldak (1990) varied the trajectory of an oncoming source and asked listeners to estimate time to contact or time to passage. As would be predicted from the adaptive hypothesis, estimates of time to contact or time to passage showed a greater anticipatory bias when the source approached the listener on a collision course than when on a bypass course. Other evidence shows that listeners tend to hear rising pitch as a source approaches, despite falling frequency due to the Doppler shift (Neuhoff & McBeath, 1996). It has been suggested that the illusory pitch rise functions to aid in processing auditory source approach.

CONCLUSIONS

Clearly more data are required before strong conclusions can be drawn. However, given these findings, the consistent underestimation of time-to-contact estimates (Ashmead et al., 1995; Rosenblum et al., 1993; Schiff & Oldak, 1990), the evidence for asymmetries in neural firing due to auditory motion (Wilson & O'Neill, 1998), and the lack of a currently viable alternative hypotheses, it seems reasonable to suggest that the bias for rising intensity and auditory source approach is an adaptation that has evolved because it provides a selective advantage in preparing for source arrival. Rosenblum (1993; see also Kugler, Turvey, Carello, & Shaw, 1985) underscored the importance of looming sources by suggesting that, from an ecological perspective, "all behavior can be understood as the control of collisions with objects of the environment" (p. 303). Given such importance, perhaps it is not surprising that a perceptual bias has evolved to meet the challenge of auditory source approach.

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