Auditory looming perception: Influences on anticipatory judgments

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Abstract. Several studies in the auditory-perception literature hint that listeners may be able to anticipate the time of arrival of an approaching sound source. Two experiments are reported in which listeners judged the time of arrival of an approaching car on the basis of various portions of its auditory signal. Subjects pressed a computer key to indicate when the car would have just passed them, assuming that the car maintained a constant approach velocity. A number of variables were tested including (a) the time between the offset of the signal and the virtual time of passage, (b) duration of the signal, and (c) feedback concerning judgment accuracy. Results indicate that increasing the time between signal offset and virtual time of passage decreases judgment accuracy whereas the actual duration of the signal had no significant effect. Feedback significantly improved performance overall.

1 Introduction
While a good amount of research has been conducted on the topic of visual looming perception (eg McLeod and Ross 1983; Schiff and Detwiler 1979), significantly less has been designed to test issues in auditory looming. It is known that blind individuals can interact successfully with approaching sound sources, in judging when it is safe to cross a busy intersection (eg Winer 1980). The extent of this ability is illustrated by blind athletes who can catch sound-emitting football, basketballs, and softballs, which allows them to participate actively in these sports (M Rosenblum, personal communication). Yet little empirical research has been conducted to determine how listeners determine when a sound source will reach them.

Of the few studies that have explored auditory looming, two have tested listeners’ accuracy in judging the moment of passage of a simulated sound source (Rosenblum et al 1987; Warlick 1978). Rosenblum and his colleagues (1987) asked subjects to press a key at the moment they heard a simulated sound source just passing them. One outcome of this study was the suggestion that subjects were able to anticipate the moment of passage on the basis of the available acoustic information before the time of passage actually occurred. Rosenblum et al (1987) speculated that there might be prospective information in the earlier portions of a signal to specify the later time of passage.

This intuition has recently been given some support by Schiff and Oldak (1990). In one condition, Schiff and Oldak tested whether subjects could make anticipatory judgments of sound-source passage based on information from earlier portions of a looming trajectory. They edited a number of different recorded looming events so that the time between the offset of the stimulus and time of passage varied between 1.5 and 6.5 s. Subjects were asked to press a key when they thought that the sound source would have reached them, assuming a constant velocity. The results indicated that subjects could perform this task with some accuracy although most judgments were underestimated (ie subjects judged time of passage as being sooner than actual time of passage). In addition, as has been found with visual looming judgments (McLeod and Ross 1983; Schiff and Detwiler 1979), accuracy generally declined as the time between stimulus offset and (ostensive) time of passage increased. Finally, while Schiff and Oldak (1990) found that sighted subjects were generally better at
visual than auditory looming judgements, congenitally blind subjects were as accurate in their auditory judgments as sighted subjects were with visual stimuli. This last finding suggests that experience might benefit auditory looming perception.

The fact that listeners can make anticipatory judgments of an auditory looming event suggests that there may be prospective time-to-arrival information in the acoustic signal similar to that thought to exist for visual looming. There is evidence that many anticipatory behaviors such as avoiding and catching looming objects are controlled by visual time-to-contact information (Lee 1976; Lee et al. 1983; Savelsbergh et al. 1991; Schiff 1965; Schiff and Detwiler 1979). This time to contact ($\tau_c$) is thought to be specified in the inverse of the relative rate of optical dilation of a looming surface (Lee 1976, 1980) and is thus available during earlier portions of a looming event. The efficacy of the $\tau_c$ variable has been demonstrated in behaviors as diverse as the diving gannet timing its wing folding (Lee and Reddish 1981), the timing control of a runner traversing a cluttered terrain (Warren et al. 1986), and the timing of a baseball batter’s swing (DeLucia and Cochran 1985).

In a particularly thorough examination of visual $\tau_c$-based behavior, Whiting and his colleagues (Whiting and Sharp 1974; Whiting et al. 1970) tested the minimum visual information needed for catching a looming ball. Using various techniques, Whiting and his colleagues manipulated the duration and period during which the ball’s trajectory was illuminated. They found that the ability to catch the ball successfully is directly related to the amount of visible trajectory (Whiting et al. 1970). However, some subjects are still quite good when shown only the first half of the flight trajectory; this attests to the prospective nature of $\tau_c$ information. In another series of experiments, Whiting and Sharp (1974) asked whether the critical variable was the overall amount of visible trajectory or the time between cessation of illumination and initiation of ball-capture behavior—the occluded period (Whiting and Sharp 1974). To test this issue, Whiting and Sharp varied the occluded period between 0 and 320 ms while maintaining a constant period of illumination (80 ms). They found that successful ball catching increased as the occluded period decreased from 320 to 160 ms but then decreased as the occluded period varied from 160 to 0 ms. This suggests that more than just the amount of visible trajectory is important in $\tau_c$ judgments.

It has also been shown that similar visual information exists for perceiving the time at which a looming object will bypass an observer along near-miss paths (Young, as cited in von Hofsten and Lee 1985). Thus, it could be that time to contact ($\tau_c$) is better construed as a more general time to arrival ($\tau_a$) (Schiff and Oldak 1990).

To return to auditory looming, although the Schiff and Oldak study was an admirable first attempt at testing auditory $\tau_c$, many questions are still unanswered. For example, it is unclear how much of an auditory looming trajectory listeners need to hear in order to perform accurate $\tau_c$ judgments. Furthermore, it has not been determined whether actually hearing the moment of passage helps in judgment accuracy. Finally, Schiff and Oldak’s findings with blind individuals suggest that experience might help in this ability. However, no research has been conducted on whether short-term experience or judgment feedback can improve accuracy. In a series of two experiments, we examine these issues of auditory looming perception by implementing a methodology similar to that of Schiff and Oldak (1990) and that of Whiting and his colleagues (Whiting and Sharp 1974; Whiting et al. 1970).

To generate our auditory looming stimuli, we edited two recordings of a looming car so various amounts and segments of the signals were available to listeners. As in the Schiff and Oldak (1990) study, subjects were asked to press a key when they thought the car would be passing them, given constant velocity. In the first experiment, three questions concerning auditory looming information were explored. Specifically, we were interested in the influence on judgment accuracy of
(1) the occluded-period duration, (2) the audible signal duration, and (3) hearing the actual moment of passage.

The second experiment was designed to test the effect of feedback on listeners' judgment accuracy. We were interested in feedback for two reasons. First, as stated, Schiff and Oldak (1990) found that the experience of blind individuals enabled them to be significantly more accurate than sighted subjects at auditory τs judgments. It can be assumed that at least one way in which blind individuals fine-tune their skill is through feedback. Clearly, self-obtained feedback would be far too dangerous a basis for calibrating looming judgments of an oncoming vehicle. However, blind individuals might improve this skill through the verbal feedback provided by mobility trainers or by transferring experience from less threatening contexts in which obtaining (haptic) feedback would be feasible. Secondly, many successful visual τs judgments would seem to involve some form of feedback. Thus, the ball catching of Whiting's experiments, as well as the batting and running tasks mentioned earlier, are likely fine-tuned through haptic and visual feedback.

2 General recording and editing of stimuli

Recordings of an approaching car were made in the free field with a single unidirectional microphone (Sennheiser) and a high-quality monaural cassette recorder (Marantz #PMD221). (The events were recorded monaurally because of constraints on the computer-editing system described below.) The recordings were made from the edge of the road so that the car passed about 3 feet (0.9 m) from the microphone. The microphone was angled so that it was nearly parallel with the road, facing the oncoming car. More precisely, the angle formed by the microphone's direction and road was about 6° so that it pointed at a location about 30 feet from where the car actually passed the microphone. Recordings were made at both 15 and 25 mph and the driver monitored that this velocity stayed constant during the approach. When the car traveled at 15 mph it traversed approximately 140 feet and when the car traveled at 25 mph it traversed approximately 200 feet. Twenty recordings were made and the two best recordings for each speed were chosen based on overall quality. Each of these two recordings was then sampled by a Compaq 386 computer at a sampling rate of 10 kHz. These recordings were low-pass filtered at 5 kHz.

The sound spectrograms of both signals are shown in figure 1. Each signal included the entire trajectory. The signal did not stop at the point where the car reached the microphone, but included a portion of the signal that came after passing the microphone. Including a signal portion after the time of passage ensured that, when hearing a trial which included the moment of passage, subjects' button-press judgments would not be based simply on hearing the signal end. The 15 mph signal was 6328 ms long while the 25 mph signal was 5578 ms long. In order to test anticipatory judgments, each of the recordings was divided into three temporally equal parts (all cut at zero crossings). This allowed us to easily deliver different signal portions and different combinations of these signals to subjects. This strategy of dividing the signal into thirds has been used successfully to determine the salient portions of a ball's visual trajectory in a baseball-batting task (DeLucia and Cochran 1985). Dividing the signal into thirds resulted in three stimulus portions of about 2109 ms each for the 15 mph recording and 1859 ms for the 25 mph recording.

The point at which the car reached the microphone (time of passage) was determined by the peak intensity of the signal and was checked against measurements of elapsed time performed during event recording. The time of passage for both signals is indicated on the spectrograms in figure 1. For the 15 mph signal the time of

\(^{(1)}\) 1 mile h\(^{-1}\) (mph) = 1.6 km h\(^{-1}\).
passage was 714 ms from the onset of the third portion, and for the 25 mph signal it was 709 ms from the onset of its third portion. These edited stimuli acted as the basic building blocks for the stimulus presentations.

Dividing the signals into thirds enabled us to present seven different event types (per speed condition) to subjects (see Figure 2). Types 1, 2, and 3 each contained only the first, second, and third portion (respectively) of the entire signal. Types 4, 5, and 6 each contained two thirds of the entire signal. Type 4 involved the first two thirds, Type 5 involved the last two thirds, and Type 6 involved the first and last third with the middle portion replaced by silence. Lastly, Type 7 was the entire signal.

The stimuli were presented diotically to subjects directly from the computer over high-quality headphones. The decision to present the stimuli over headphones rather than through a loudspeaker was based on a number of considerations. First, informal pilot work suggested that listeners found it somewhat easier to concentrate on the stimuli and task if headphone presentations were used. Second, although Schiff and Oldak (1990) used free-field, loudspeaker presentations for their experiment,
Rosenblum et al (1987) used headphone presentations and obtained systematic looming-judgment data. Third, presenting stimuli through a speaker would mean that, before reaching the subject's ear, the acoustic signal would be structured by the experiment room in addition to the environment under which the stimuli were recorded. It has been found that one way in which listeners determine sound-source (and, potentially, changing sound-source) distance is through the relative reflectances provided by a normal echoic environment (Mershon and Bowers 1979). Given that the echoic environment of our experiment room would modify the signal, using headphone presentations ensured that listeners heard a signal structured mainly by the acoustic environment present during stimulus recording.

The peak stimulus intensity at the headphones was 75 dB SPL for the 25 mph stimuli and 74 dB SPL for the 15 mph stimuli.

3 Experiment 1
The first experiment was designed to test listener ra accuracy without the benefit of feedback. To determine the salient aspects of the signal, three issues were tested: (1) does the duration of the occluded period (time between signal offset and ostensive time of passage) influence accuracy; (2) does hearing the actual time of passage improve judgment accuracy; and (3) does the duration of the audible looming signal influence accuracy?

3.1 Method
3.1.1 Subjects. Twelve undergraduate students participated in this study as partial fulfillment of a class requirement. All subjects reported having good hearing.

3.1.2 Procedure. Subjects were seated at a table in front of a Macintosh computer. They were told that they would be listening to recordings of a car coming towards them and that their task was to indicate at what point the car would have reached them. The experimenter then demonstrated with a small model car how they could imagine themselves standing by the side of the road facing an approaching car. Subjects were told that some of the recordings they would hear would be full recordings, whereas others would be partial recordings. Subjects were asked to respond in the same manner to both types of recordings and simply indicate at what point the car would have reached them, assuming a constant speed. Subjects started each presentation by pressing a key on the computer, and then indicated their judgment by pressing the key a second time. (This second key press did not stop the stimulus.) The computer was programmed to perform millisecond timing between key presses. After the judgment was made, there was a short delay in which the computer recorded the time between key presses. The subject was then able to initiate the next presentation. No feedback concerning accuracy was given during any part of this experiment.

The stimuli were delivered to subjects in blocks—each containing all seven signal types of a given approach velocity (15 or 25 mph). Blocking the trials in this way was based on memory constraints of the computer system. Within each block, each signal type was presented five times, yielding 35 trials which were randomized within the block. Two blocks were generated for each of the 15 and 25 mph stimulus series. There was counterbalancing for block-presentation ordering such that half of the subjects heard a block of 15 mph stimuli first (15, 25, 15, 25), and the other half received a 25 mph stimulus block first (25, 15, 25, 15). In all, subjects received 10 trials of each of the 14 conditions producing a total of 140 trials (7 signal types × 2 velocities × 10 trials each). Subjects received 6 practice trials before beginning in order to get used to the stimuli and the task. The 6 practice trials consisted of condition types 7, 4, and 6 from both the 15 and the 25 mph looming events. Subject participation lasted for about one hour.
3.2 Results and discussion

In some recent papers in which time-of-passage judgments were reported, data have been converted into a proportional measure defined relative to actual time of passage (see for example McLeod and Ross 1983; Schiff and Oldak 1990; Schiff et al 1992). This measure is the judged time-of-passage value (calculated as the time elapsed between stimulus onset and when the subject indicated time of passage) divided by the actual time of passage (elapsed time between stimulus onset and when the car would have actually passed the observer), multiplied by one hundred to yield a proportion of actual time of passage. This measure is useful for testing accuracy across a number of different looming events which all involve an occluded time of passage. In the present experiment, many of our conditions did not include an occluded time of passage (i.e., condition types 3, 5, 6, and 7). In fact, our experiments were designed so that comparisons could be performed across conditions that did and did not involve an occluded time of passage. For these reasons, we chose not to implement this proportional measure. Instead, we chose to evaluate the mean deviation scores of the judged time of passage relative to the actual time of passage. Thus, for each trial, a difference was calculated by subtracting the actual time of passage from the judged time of passage. Means were then calculated across trials for each condition and then across all subjects.

The deviation scores can be used to determine how often subjects made overestimates and underestimates. Overall, subjects' scores were underestimates 84% of the time. Subjects tended to overestimate more on the condition type 3 trials (48%) and the condition type 2 trials (29%) than on the other trial types. More overestimates were made for the 15 mph signals (22%) than the 25 mph signals (10%). Figure 3 (top) shows the mean deviation values for the seven critical conditions in experiment 1 (pooled over presentation ordering and speed conditions).

Given that the tendency for overestimates was dependent on token type and individual subject, a different measure was used to test judgment accuracy statistically. Unlike in Schiff and Oldak's experiment (1990), our subjects did give quite a few late responses. Accordingly, when averaged over subjects, our signed deviation scores could be potentially misleading as some levels of type could collapse to indicate, erroneously, near-perfect accuracy. Thus, for our statistical tests, the absolute deviation from a perfect score was calculated by taking the absolute difference between the judged and actual time of passage of each trial. As before, these scores were averaged over trials for each condition and then across all subjects. Figure 3 (bottom) depicts the mean absolute deviation scores (pooled over presentation ordering and speed conditions).

![Figure 3](image-url)
An ANOVA was performed on these absolute deviation values to test the factors of block-presentation ordering, condition type, and speed (2 × 7 × 2). A test of homogeneity of variance revealed that this data set did not fulfill this requirement. Accordingly, all tests of significance implemented the Geisser–Greenhouse correction for positive bias (Keppel 1982). The only significant effect was for condition type \( F_{1,22} = 5.54, p < 0.01 \) (with the Geisser–Greenhouse correction). All other effects and interactions were not significant. This finding suggests that the speed of approach (15 or 25 mph) had little bearing on the absolute accuracy of subjects. However, this does not preclude the possibility that signals generated from other, more extreme looming speeds could influence judgment accuracy.

Based on the significant effect of condition type, a number of contrast tests were conducted, each motivated by an attempt to determine the salient aspects of the looming signal. As mentioned above, three signal characteristics were tested for influences on judgment accuracy: (1) occluded-period duration; (2) hearing the actual time of passage; and (3) duration of the audible looming signal. Given that no other variables or interactions with other variables were found to be significant, these contrasts were calculated by pooling over speed and presentation-ordering conditions. Since many contrasts were used to look at specific conceptual issues, a modified Bonferroni test (Keppel 1982) was utilized to keep the familywise error rate at the 0.05 level. All contrast tests were performed with this correction; therefore, the probability value indicated refers to the probability of the familywise error rate.

3.2.1 The effects of occluded period on judgment accuracy. The first issue tested concerned whether the length of the occluded period influences judgment accuracy. Schiff and Oldak (1990) found that with their auditory looming stimuli, the greater the occluded period, the more the listeners underestimated the time of passage (pressing the key before actual time of passage). This patterning of results has also been found for visual judgments once the occluded period exceeds a few seconds (Carel 1961; Schiff and Detwiler 1979). Furthermore, Whiting and Sharp (1974) found that the occluded period, in addition to viewing duration, had an important influence over judgment accuracy for trajectories lasting under 600 ms.

In order to determine whether increasing occluded period produces less accuracy, for our stimuli, the most straightforward comparison is between condition type 1 (first portion) and condition type 2 (middle portion). While both condition types involved the same amount of signal, condition type 1 involved an occluded period of over 2.5 s (2.8 s for the 15 mph condition and 2.6 s for the 25 mph condition), while condition type 2 involved an occluded period of less than 0.72 s (714 ms for the 15 mph condition and 709 ms for the 25 mph condition). If, as observed previously, judgment accuracy decreases with increasing occluded period, then accuracy with condition type 2 should be significantly greater than accuracy for type 1. The mean absolute deviation scores support this prediction, as did a contrast test \( F_{1,22} = 11.47, p < 0.01 \). Thus, our auditory looming results are in accord with previous findings that judgment accuracy declines with increasing occluded period.

3.2.2 Influence of hearing the time of passage. Next we tested whether hearing the signal portion which included the time of passage (last third) produced greater judgment accuracy. It should be noted that the last third of the event also includes about 700 ms of the signal before the exact point of passage.

Surveying the mean absolute deviation values (figure 3) reveals that listeners were most accurate when presented the last third of the signal (condition type 3) and were relatively accurate when presented the entire signal (condition type 7). This could be interpreted to mean that listeners are most accurate when the time of passage is
present in the signal. It should be noted, however, that other condition types which also involved the time of passage (types 5 and 6) did not necessarily produce more-accurate judgments. A number of tests can be conducted in order to determine whether hearing the time of passage significantly helps judgment accuracy.

First, condition type 3—which included the time of passage in its signal—was compared with condition types 1 and 2, both of which did not involve the time of passage. All three of these signals had the same duration. Simple contrast tests were conducted which revealed that only the comparison between types 3 and 1 was significant at the 0.05 level ($F_{1,22} = 21.84, p < 0.01$). However, the fact that no significant difference exists between judgment accuracy for condition types 2 and 3 suggests that hearing the time of passage might not be crucial for judgment accuracy. It further suggests that the relatively lower accuracy found for condition type 1 might not be solely due to it not involving the time of passage. It is the case that condition type 1 included a relatively large occluded period which, as tested above, does influence judgment accuracy. Given this potential confounding influence, other tests were implemented to explore this question.

A second means of testing this issue was a comparison of condition types that involved two thirds of the looming event (types 4, 5, and 6). This comparison revealed that subjects are not significantly more accurate when the two thirds included the time of passage relative to when it did not. Thus, condition type 4 (first and middle third) did not produce judgments which were significantly less accurate than either judgments of condition type 5 (middle and last third) or judgments of condition type 6 (first and last third).

A final test was conducted to determine whether hearing the moment of passage improved judgment accuracy. This test involved pooling across all conditions which included the time of passage (condition types 3, 5, 6, and 7) and comparing these scores with judgments of condition types that did not involve the time of passage (condition types 1, 2, and 4). Pooling across each group of condition types produced a mean of 884.5 ms for the condition types involving the time of passage and a mean of 1063 ms for the condition types not involving the time of passage. A contrast test revealed that judgment accuracy for these two types of condition group was not significantly different at the 0.05 level.

Based on the above comparisons, it seems that subjects are not significantly more accurate at judging passage time when they actually hear the time of passage. This finding could attest to the strength of auditory $\tau_p$ information in our signals. In other words, there might be sufficient prospective information in the earlier parts of the signal for anticipatory accuracy to be comparable to accuracy when the actual time of passage is present.

3.2.3 Effects of signal duration. As mentioned, Whiting et al (1970) initially found an increase in catching success rate as the amount of viewing time of a looming ball increased. The same question was explored with our auditory looming-car signal. The test most closely analogous to that of Whiting et al would be a comparison between condition type 1 (first third), condition type 4 (first and middle third), and condition type 7 (full signal). However, Whiting and Sharp (1974) point out that this type of test involves the potentially confounding variable of the amount of occluded period. Accordingly, two other comparisons were implemented to address this question.

First, a test was conducted to determine whether stimuli with different signal durations but the same occluded period induced different accuracy. For this test, condition type 2 (middle portion) was compared with condition type 4 (first and middle portion), both of which had the same occluded period. Condition type 2 had a mean absolute deviation of 732 ms while condition type 4 had a mean of 923 ms.
A contrast test revealed that the difference between these groups was not significantly different at the 0.05 level.

The second test contrasted condition types with one-third, two-thirds, and full portions of the event against each other. The pooled mean absolute deviation for the one-third group (involving condition types 1, 2, and 3) was 898 ms, the mean for the two-thirds group (involving types 4, 5, and 6) was 1096.8 ms, and the mean for the full signal (condition type 7) was 744 ms. A series of contrasts were conducted and revealed no significant differences between any of these three groups at the 0.05 level. Both of these tests suggest that increased signal duration does not significantly improve judgment accuracy.

The overall conclusion from these tests is that lengthening the signal—once occluded period is factored out—generally did not improve judgment accuracy. Why this observation is different from that of Whiting et al (1970) will be discussed in section 4.

3.3 Conclusions from experiment 1

Overall, the results suggest our listeners could make anticipatory judgments of the looming car signals. Two aspects of the results support this conclusion. First, our results suggest that hearing the actual time of passage did not significantly improve judgment accuracy relative to trials which involved an occluded period. This would suggest that for our listeners, prospective tₐ information was as useful as hearing the actual time of passage.

Second, although subjects did tend to underestimate under most condition types, their accuracy would seem to be well within a margin of safety, if the stimulus and task are considered. In a real-world context, the action most likely performed upon hearing an approaching automobile would be to move out of its path before the moment of contact. In fact, Guski (1992) has recently argued that if tₐ information is to be considered truly behaviorally relevant, then it might best be reconceptualized as offering 'time-to-turn' or 'time-to-jump' information. Regardless, our data generally reflect a safe anticipatory tendency such that appropriate avoidance behavior could occur. A predominance of underestimates to looming sound sources has also been observed by Schiff and Oldak (1990) and Rosenblum et al (1987). Underestimates are also often observed for visual looming stimuli (e.g., McLeod and Ross 1983). Schiff and Oldak (1990) suggest that, in fact, less-skilled observers might display a greater margin of safety in their tₐ judgments. The issue of experience and its effect on tₐ judgment accuracy will be addressed in experiment 2.

Finally, it is concluded from experiment 1 that while occluded-period duration did influence judgment accuracy, there was no influence of either total signal duration or hearing the moment of passage. These potential influences will be investigated again in experiment 2 to determine whether they influence judgments when feedback is provided.

4 Experiment 2

As mentioned above, there is some indication that experience might improve auditory looming judgment accuracy. Schiff and Oldak (1990) reported that blind subjects were significantly better at judging auditory tₐ than were sighted subjects. Clearly, blind listeners' dependence on auditory tₐ for guiding various activities necessitates a higher degree of accuracy. As mentioned, one way of improving this skill is through various forms of feedback information—provided either explicitly (e.g., by a mobility trainer) or implicitly (through haptic experience).

In experiment 2 we examine the role of explicit feedback in improving auditory tₐ judgment accuracy. In experiment 1, no explicit feedback was given to subjects. However, it is acknowledged that for condition types which involved an audible
moment of passage, hearing the passage point before or after pressing the computer key could potentially act as feedback. Still, for the condition types of most interest—those that involved an occluded time of passage—no feedback was present in experiment 1.

In experiment 2, subjects were provided explicit feedback for each trial. They were informed whether each of their judgments was early, late, or perfect, as well as the extent to which their judgment differed from the actual time of passage. The decision to use feedback on amount as well as direction of discrepancy was based partly on a review of methodologies used in other occluded-trajectory contexts. For example, in the baseball-batting experiment of DeLucia and Cochran (1985), batters were visually aware of the trajectory of the batted ball. The trajectory of a hit ball is largely dependent on swing timing and could inform subjects about the degree to which subsequent swings need to be modified. Secondly, Whiting et al. (1970) report that, in their ball-catching study, subjects did improve their catching accuracy across the experiment. They noted that on many trials subjects would manage to touch the ball while failing to grasp it. It could be that subjects' improvement in accuracy is partly due to this haptic feedback provided when they made any contact with the ball.

Regarding auditory situations, it is feasible that most feedback used to fine-tune auditory-based judgments by the blind involves information concerning amount as well as direction of discrepancy. Thus, the haptic feedback available after an individual approaches a sound source (e.g., a ringing telephone) would certainly provide information about direction and amount of position discrepancy. It can also be assumed that when a trainer provides verbal feedback to a blind individual judging automobile looming, she or he likely specifies both the direction and the amount of the discrepancy of a judgment.

Given these considerations, experiment 2 was designed to test the influence of feedback that included information on direction and degree of discrepancy. Although Schiff and Oldak (1990) found that long-term experience with auditory judgments (i.e., that of blind subjects) did influence judgment accuracy, it is unclear whether short-term experience (within a single experiment) would have the same influence. Experiment 2 was also designed to determine whether experience (through feedback) differentially influenced the effects of occluded period duration, hearing the moment of passage, and signal duration.

4.1 Method
4.1.1 Subjects. Twelve undergraduate students participated in this study as partial fulfillment of a class requirement. Subjects reported normal hearing. None of these subjects participated in experiment 1.

4.1.2 Stimuli. The same stimuli, conditions, and presentation setup used in experiment 1 were used for this experiment.

4.1.3 Procedure. The same general procedure was used in this experiment as in experiment 1, except that feedback was given to subjects on each trial. After each time-of-passage judgment, a long horizontal bar was displayed on the computer monitor and the subject's accuracy was represented by a vertical hash drawn on this bar. The bar was labeled 'Early' on the left end and 'Late' on the right end, and had a short vertical line drawn in the middle to represent an exactly correct response. Subjects were told that the position of the hash mark depicted the degree to which their judgment was early or late relative to the actual time of passage. Subjects were told to take the time to examine this feedback for every trial. This feedback display stayed on until the subject pressed a key to continue with the next trial.
The decision to use this graphical form of feedback rather than numerical time of judgment discrepancy (e.g., seconds) was based on two considerations. First, it was assumed that in most real-world contexts, feedback generally takes a form which is not defined as an actual numerical time. Certainly this is the case for activities such as catching, batting and stepping over looming obstacles. It is also clearly the case for a blind individual calibrating an approach to a sound source through haptic feedback. The second reason for using the graphical rather than numerical time form of feedback is based on an attempt to avoid a "postperceptual" basis for subjects' judgments. In receiving explicit time feedback, subjects could be led to counting (to themselves) in order to improve judgment accuracy. Although improving a \( \tau_a \) skill can be a somewhat conscious task, it could be that feedback provides a means by which the subject learns to better attend to the appropriate invariant information in the looming signal (Gibson 1979). Clearly, counting to oneself would distract from this attunement. In fact, in pilot experiments which did involve explicit numerical feedback (in seconds), a number of subjects reported counting to themselves in order to improve their judgment accuracy. For these reasons, the graphical form of feedback was used for this experiment.

The same six practice trials used for experiment 1 were used for this experiment. Subjects were provided graphical feedback on each practice trial and the experimenter made sure each subject understood how to interpret this feedback. Subject participation lasted for about one hour.

4.2 Results and discussion

Mean deviations from actual time of passage were again calculated in the manner discussed above. This revealed that subjects overestimated an average of 35% of the events. There were more overestimates for the condition type 2 (56%) and condition type 3 (63%) tokens than for all other types. Again, there were more overestimates for the 15 mph signal (42%) than for the 25 mph signal (27%). Figure 3 contains the mean signed deviation and absolute deviation scores averaged over subjects, presentation ordering, and approach speeds. Again, an absolute deviation from a perfect response was calculated for each trial. A test of homogeneity of variance revealed that, like the data of experiment 1, this data set did not fulfill the homogeneity requirement. Thus, the Geisser-Greenhouse correction was implemented again (Keppel 1982).

First, in order to determine the influence of feedback, comparisons were conducted between the absolute deviation scores from experiments 1 and 2. Comparison of functions in figure 3 suggests that all scores for all fourteen conditions were lower for experiment 2 than for experiment 1. An ANOVA testing mean absolute deviation scores across the two experiments revealed that subjects were significantly more accurate in experiment 2 than in experiment 1 \((F_{1,21} = 16.96, p < 0.01)\). There were no interactions between experiment, condition type, speed, and presentation ordering. This suggests that accuracy improved significantly when graphical feedback was provided for subjects relative to when no feedback was present.

An ANOVA was performed on the mean absolute deviation values for experiment 2. This yielded an order \( \times \) type \( \times \) speed design \((2 \times 7 \times 2)\). The ANOVA indicated that, as in experiment 1, there was a significant effect for condition type \((F_{5,60} = 15.18, p < 0.01)\). For experiment 2, there was also a significant effect for order \((F_{1,10} = 6.15, p < 0.05)\). The six subjects who received the blocks in the order 15 mph, 25 mph, 15 mph, 25 mph performed significantly better than the six subjects who judged the blocks in the order 25, 15, 25, 15 mph. All other effects and interactions were not significant. It is unclear why an order effect would occur for this experiment. One possibility is that subjects learned to make use of the feedback more quickly when
judging the slower 15 mph events. If so, subjects who were presented first with a block of 15 mph trials would benefit from feedback sooner than subjects who received a 25 mph block first.

Given the significant improvement of accuracy in experiment 2, the three issues addressed in experiment 1 were readdressed with data from this experiment. Reexamining these issues with trained subjects might reveal more about the salient information for the auditory looming event. Again, the modified Bonferroni test (Keppel 1982) was utilized to keep the familywise error rate at the 0.05 level.

4.2.1 The influence of occluded-period duration on judgment accuracy. As in experiment 1, the effects of occluded-period duration on judgment accuracy were tested in experiment 2. Again, condition types 1 and 2 were compared, since both signal types included the same signal duration but quite different occluded periods. This test revealed that subjects were significantly more accurate with type 2 than with type 1 ($F_{1,22} = 11.33$, $p < 0.01$), suggesting that increasing occluded period decreases judgment accuracy. Thus, as with untrained subjects, trained subjects show the effects of occluded period most recently demonstrated by Schiff and Oldak (1990).

4.2.2 Influence of hearing the time of passage. As in experiment 1, subjects in experiment 2 were quite accurate when presented with the last portion of the signal (condition type 3). Again, tests were employed in order to determine whether hearing the signal portion that included the actual time of passage induced greater judgment accuracy. Judgments for condition type 3 were tested against those for condition types 1 and 2. Contrasts revealed that, in fact, subjects were more accurate in condition type 3 than in type 2 ($F_{1,22} = 12.88$, $p < 0.01$) and type 1 ($F_{1,22} = 13.36$, $p < 0.01$).

Next, a test was conducted to test the influence of time of passage across condition types that involved two thirds of the looming event. These tests reveal that hearing the time of passage does seem to improve judgment accuracy when in condition type 5 ($F_{1,22} = 11.75$, $p < 0.01$), but does quite the opposite when in condition type 6.

Finally, as in experiment 1, a test was conducted to determine whether inclusion of the time of passage in the stimulus significantly improves accuracy across all condition types. Again, this comparison involved pooling across all conditions that involved the time of passage (condition types 3, 5, 6, and 7) and comparing these scores with judgments of condition types that did not involve the time of passage (condition types 1, 2, and 4). The mean for the condition types involving the time of passage was 411.3 ms and the mean for the condition types not involving the time of passage was 635.7 ms. A contrast test revealed that judgment accuracy was significantly better for condition types that involved the moment of passage relative to those that did not ($F_{1,22} = 28.79$, $p < 0.01$).

Taken together, these results indicate that hearing the signal portion that included the time of passage did help the judgment accuracy of trained subjects. This improvement in accuracy was not observed for experiment 1, in which subjects did not receive feedback. It has yet to be determined what aspects of feedback induce greater relative accuracy when hearing the third portion of our signal. One possibility is that when hearing the last third of the signal in experiment 2, subjects simply waited for the time of passage and responded immediately after. Potentially, this 'reaction-time' type of judgment could induce greater absolute accuracy than anticipatory judgments. In other words, it might be that the feedback provided in experiment 2 induced a reaction-time strategy for condition types with the last third present (types 3, 5, 6, and 7), thereby improving absolute accuracy. However, if subjects in experiment 2 were using a reaction-time strategy and responding after the moment of passage, it should be reflected in more positive-signed deviation means for the relevant condition
types for experiment 2 relative to experiment 1. Surveying figure 3 suggests that this is not the case. In fact, for the eight signed means for the relevant condition types (four for 15 mph and four for 25 mph conditions), experiment 1 produced five negative means while experiment 2 produced six negative means. Thus it is probable that a reaction-time response strategy was not the basis for the improvement with hearing the moment of passage in experiment 2.

Another possibility is that the feedback offered in experiment 2 acted to draw the listeners' attention to the information available during the 700 ms immediately prior to the moment of passage (as available in our third signal portions). Future research can be designed to determine whether this short prepassage period is salient for judgment accuracy.

4.2.3 Effects of signal duration. In order to determine whether increasing signal duration would improve judgment accuracy with trained subjects, the same tests implemented in experiment 1 were used for the data of experiment 2. First, condition types 2 (middle third) and 4 (first and middle third) were compared in order to determine whether two stimuli with the same occluded period but different signal durations would induce different accuracy. The means for these two condition types suggest that judgment accuracy does not differ with increasing signal length in this context and a contrast test revealed that the difference between these condition types was not significant at the 0.05 level.

As for experiment 1, the second test contrasted condition types with one-third, two-thirds, and full portions against one another. The one-third group (types 1, 2, and 3) had a mean of 541.67 ms, the two-thirds group (types 4, 5, and 6) had a mean of 523.5 ms, and the full-signal (type 7) had a mean of 356.5 ms. A series of contrasts revealed a significant difference between the one-third and full groups ($F_{1,22} = 8.57, p < 0.05$) and a significant difference between the two-thirds and full groups ($F_{1,22} = 6.97, p < 0.05$). There was no difference found between the one-third and two-third groups at the 0.05 significance level.

Although these latter results could be interpreted to suggest that signal duration does have some influence over judgment accuracy with trained subjects, there is a potential confounding variable in this analysis. Specifically, within each of these groups, the number of conditions that included the time of passage differed. Thus, while all conditions used for the full-signal group included the time of passage, only two of three conditions in the two-thirds group did (condition types 5 and 6), and only one of three conditions in the one-third group included the time of passage (condition type 3). Earlier, it was concluded that for trained subjects, hearing the time of passage did improve judgment accuracy. Accordingly, it could be that the accuracy means for the three ‘duration’ groups were not actually ordered on the basis of signal duration. Rather, the result differences found between each ‘duration’ group could reflect more the percentage of condition types that included time of passage for each group. For this reason, the previous analyses were given more weight in our interpretation of the duration issue.

Thus, once again, the bulk of our evidence suggests that signal duration does not play a significant role in judgment accuracy for our stimuli. Since this was also observed for experiment 1, it would seem that the inclusion of feedback does not change the relative effectiveness of signal length.

The fact that signal duration does not seem to improve judgment accuracy—even with feedback—would seem to be counter to the general observation of Whiting et al. (1970). However, it should be noted that major differences exist between the work of Whiting et al and present studies. Most obviously, while the present study concerns auditory looming judgments, Whiting et al implemented a visual looming paradigm.
Also, Whiting et al used a catching task—a task quite different from the button-press response used in the present sets of experiments. Last, while the total looming-event duration for our stimuli ranged between 5 and 7 seconds, the stimuli used by Whiting et al were always less than 500 milliseconds. Further research can be designed to determine which factors account for the differential influence of signal duration across the two methodologies.

4.3 Conclusions from experiment 2

Overall, experiment 2 has revealed some interesting differences in performance between trained and untrained subjects. First, subjects trained with feedback are significantly more accurate than untrained subjects in making looming judgments. The fact that no interaction was found between experiment (1 and 2) and condition type indicates that feedback training helped for every stimulus condition. Thus, as intimiated by Schiff and Oldak (1990), our trained listeners displayed a smaller margin of safety than our untrained listeners from experiment 1. Interestingly, while Schiff and Oldak found greater accuracy with subjects who, presumably, had a great deal of auditory looming experience (blind subjects), we observed a significant improvement with subjects who had less than one hour of training.

Furthermore, performance by trained subjects improved when the moment of passage was present in the signal. This is contrasted with performance by untrained subjects, for whom hearing the time of passage seemed to make little difference. Possible reasons for this difference across training conditions are discussed above.

In contrast, the influence of both signal duration and occluded period was the same for trained and untrained subjects. Again, the duration of the signal seemed to have little influence over judgment accuracy. On the other hand, occluded period did have a significant bearing on judgment accuracy for both subject groups, replicating results in the literature on both auditory and visual looming.

5 General discussion

Results of these experiments suggest that subjects can make anticipatory judgments of a looming sound source. Given these findings along with those of past research, it is assumed that there is information available in the acoustic signal which specifies the τe of a looming source.

A number of acoustical dimensions which are modulated with changing distance can potentially support anticipatory looming judgments (for a review, see Coleman 1963). For example, as a sound source approaches an observer, there is an increase in the intensity of the signal (at the observer) due to the inverse-square power law. This change would be reflected in the perceived loudness of the signal. Recently, Shaw et al (1991) derived a τi variable based on intensity change and argued that it could provide a basis for looming judgments. A second source of information for auditory looming could be the overall pattern of spectral change. As a sound source approaches an observer, there is selective amplification of high-frequency components (at the observer) due to differential atmospheric absorption. For a listener, this would be noticeable in the changing timbre of the source—the sound would seem 'brighter' as it approaches. In fact, the signal spectrograms in figure 1 reveal that both the intensity and the spectral composition of our signals did change over the course of the approach events. In these figures, intensity is demarcated by the darkness of the spectral patterning. If one surveys figure 1, it is clear that the overall intensity of the signals increases to the time of passage. Furthermore, the higher-frequency portion of the spectrums seems to increase at a disproportionately faster rate. Thus, it would seem that both the intensity and the specific pattern of spectral change of our signals could be informative about time to contact.
Next, the acoustic change of the Doppler shift has been shown to specify changing sound-source distance (eg Rosenblum et al 1987). The Doppler shift induces a compression (shortening) of wavelengths in front of a moving source and an expansion (lengthening) of wavelength behind the source. These changes in wavelength are heard by a stationary observer as a change in sound-source pitch throughout the looming trajectory.

Finally, mention should be made of the importance of sound-source familiarity. Modulation of intensity, spectral composition, and frequency can be induced by changes in either distance or sound-source characteristics. Accordingly, it has been argued that for listeners to determine that an acoustic change corresponds to a distance change, they would need to have some familiarity with the sound-source characteristics (eg von Bekesy 1949; Coleman 1962; Middlebrooks and Green 1991). The sound of an approaching car is certainly familiar to American adults. Thus, it can be assumed that our stimulus provided an appropriate backdrop allowing subjects to use these acoustic dimensions for their looming judgments.

Since our looming car stimuli were recorded in the field with a complex source, all of these acoustic dimensions could potentially provide the basis of judgments for our listeners. Future research will be designed to determine the degree to which each dimension is useful.

Finally, the issue of judgment improvement and the role of feedback deserves further exploration. It is clear from these experiments that feedback can help listeners improve judgment accuracy. This is not surprising given that auditorily guided animals most likely use some form of feedback to improve this skill. However, it is not clear in what way feedback helps fine-tune this skill. It could be that feedback modifies an internal cognitive representation of the trajectory (eg Jagacinski et al 1983). On the other hand, feedback could simply aid the observer in becoming attuned to the salient information provided in the acoustic array (eg Gibson 1979; Michaels and Carello 1981). Future research with an auditory looming paradigm can be conducted to determine which of these two interpretations is more valid.

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References


Coleman P D, 1962 “Failure to localize the source distance of an unfamiliar sound” Journal of the Acoustical Society of America 34 345 - 346

Coleman P D, 1963 “An analysis of cues to auditory depth perception in free space” Psychological Bulletin 60 302 - 315

Delucia P R, Cochran E L, 1985 “Perceptual information for batting can be extracted throughout a ball’s trajectory” Perceptual and Motor Skills 61 143 - 150

Gibson J J, 1979 The Ecological Approach to Visual Perception (Boston, MA: Houghton Mifflin)

Guski R, 1992 “Acoustic tau: an easy analogue to visual tau?” Ecological Psychology 4 189 - 197


Lee D N, 1976 "A theory of visual control of braking based on information about time-to-collision" Perception 5 437–459
Lee D N, 1980 "Visuo-motor coordination in space-time", in Tutorials in Motor Behavior Eds G E Stelmach, J Requin (New York: North-Holland)
Schiff W, Detwiler M L, 1979 “Information used in judging impending collision” Perception 8 647–658
Warlick, ... , 1978 “Ecological acoustics” unpublished honors thesis, Lake Forest College, Lake Forest, IL