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Spectral information for detection of acoustic time to arrival

Michael S. Gordon · Frank A. Russo · Ewen MacDonald

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Abstract The exponential increase of intensity for an approaching sound source provides salient information for a listener to make judgments of time to arrival (TTA). Specifically, a listener will experience a greater rate of increasing intensity for higher than for lower frequencies during a sound source's approach. To examine the relative importance of this spectral information, listeners were asked to make judgments about the arrival times of nine 1-octave-band sound sources (the bands were consecutive, nonoverlapping single octaves, ranging from 40–80 Hz to ~10–20 kHz). As is typical in TTA tasks, listeners tended to underestimate the arrival time of the approaching sound source. In naturally occurring and independently manipulated amplification curves, bands with center frequencies between 120 and 250 Hz caused the least underestimation, and bands with center frequencies between 2000 and 7500 Hz caused the most underestimation. This spectral influence appears to be related to the greater perceived urgency of higher-frequency sounds.

Keywords Audition · Motion in depth · Perception and action

Several studies have examined the contributing cues for the detection of acoustic time to arrival (TTA; e.g., Lutfi & Wang, 1999; Neuhoff, 2001; Rosenblum, Carello, & Pastore, 1987). It has been demonstrated that dynamic information, such as the rise in intensity of a sound approaching a listener, can be used to support TTA judgments (Ashmead, Davis, & Northington, 1995; Lee, van der Weel, Hitchcock, Matejowski, & Pettigrew, 1992; Rosenblum et al., 1987; Rosenblum, Gordon, & Jarquin, 2000). In general, as a sound approaches a listener, it will increase in intensity at an exponential rate, with its peak intensity occurring at the position of the listener. This exponential rate of change for a sound source approaching a listener is often referred to as *acoustic tau* (τ) and has been suggested to be one of the principal sources of information supporting judgments of acoustic TTA (Lee et al., 1992; Neuhoff, 2001; Rosenblum, 1993; Shaw, McGowan, & Turvey, 1991). Assuming that a sound source is traveling at a constant velocity on a collision trajectory with a listener, acoustic tau is derived from the equation: $\tau = -2I/(dI/dt)$, where τ specifies the amount of time before a sound source is to reach one's position and I is the time-averaged intensity (Shaw et al., 1991).

Imagine a person standing on a train track with a train fast approaching. The horn has been sounded, resulting in the emission of a broad range of frequencies that may be used to determine the amount of time remaining to escape the impending peril of the oncoming train. Acoustically, all frequency components in the audible spectrum could support the detection of information that may be used in the derivation of TTA. However, one's sensitivity to acoustic tau and the accuracy of its use may be influenced by the fact that lower-frequency components tend to have a more gradual increase in intensity over time than do higher-frequency components. Lower frequencies are less easily attenuated by obstructing surfaces (e.g., trees, cars, or moist air), and consequently may retain more energy over great distances, and thus be more audible than higher frequencies. It is for this reason that acoustic tau, while derived as a uniform constant across all frequency components, does have some variation across the acoustic spectrum. To be clear, the tau value for any frequency component of a sound moving toward a listener provides the same lawful information

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about a sound source's TTA. However, while the net tau value derived from all frequency components is constant with regard to TTA, the rate of change specifying TTA will vary dramatically across the audible spectrum.

Research in TTA has not previously tested how spectrum might affect judgments. However, we know from localization studies that spectrum and the reverberant energy within an environment can influence both the perceived distance and the azimuth of stationary sound objects (see Hofman & Van Opstal, 1998; Little, Mershon, & Cox, 1992; Zahorik, Brungart, & Bronkhorst, 2005; and see Middlebrooks & Green, 1991, for an excellent review of localization). From these static distance judgments, it may be predicted that lower-frequency components (more audible for distant sounds) may bias listeners to make later TTA judgments, and higher-frequency components (less audible for distant sounds) may bias listeners to make earlier TTA judgments.

Another factor that might contribute to this expected pattern of more underestimation (i.e., earlier judgments) in response to higher-frequency components is the association of higher frequencies with greater urgency (Edworthy, Loxley, & Dennis, 1991; Hellier, Edworthy, & Dennis, 1993; Russo & Jones, 2007; Russo, Lantz, English, & Cuddy, 2003). To clarify how urgency might affect judgments, it is important to consider the typical responses to TTA stimuli. Even under ideal conditions, perceivers tend toward slightly underestimating the moment that an approaching object is to reach their position. This bias to respond prior to the occurrence of a collision has been termed the *margin of safety* and is widely observed in TTA studies (see Gibson, 1966; Gordon, 2002; Hancock & Manser, 1998; Rosenblum, 1993; for reviews of TTA). The principle of this margin of safety is that it is better to err on the side of safety in judging the time of a collision (i.e., to respond prior to a collision) than it would be to fail to respond in time. In as much as TTA judgments are related to subjective evaluations of safety, there may be an influence resulting from the perceived urgency of sounds; if stimuli are perceived as being more urgent (and potentially threatening), perceivers should be biased to increase their margin of safety. As would be tested in the following experiments, we hypothesized that the higher-frequency acoustic components, which are associated with greater urgency, contribute to an increased bias for underestimation. To examine this possibility, we first examined whether TTA stimuli with high- and with low-frequency components are associated with more and with less urgency, respectively. After examining this relationship in Experiments 1 and 2, in Experiments 3 and 4 we assessed how TTA judgments are biased by spectrum (and by putative urgency) across the audible range.

Experiment 1: Judgments of perceived urgency for TTA stimuli

In this first experiment, perceived urgency was examined for 1-octave-band TTA stimuli taken from across the audible spectrum. While previous evidence has suggested that higher frequencies are associated with greater urgency, the relationship between these variables has not yet been tested with TTA stimuli. To examine this issue, participants were asked to listen to a 2-s stimulus that simulated the approach of a narrow-band noise moving on a linear and midsagittal path toward the position of the listener. In their responses, participants judged the urgency of the stimuli on a fixed-modulus magnitude estimation task (see, e.g., Hellier, Edworthy, & Dennis, 1995).

Method

Participants A total of ten participants were recruited for this experiment from the University of Toronto at Mississauga, with an average age of 21 years ($SD = 3.1$). The participants received a nominal payment in exchange for participation, and all reported having normal hearing.

Materials and apparatus Acoustic stimuli were calibrated and presented using an Apple G4 Power Mac computer running custom-designed software and presented over Sennheiser HD280 Pro Headphones in a sound-attenuated chamber. Responses were recorded directly onto the computer via the keyboard.

To create the acoustic TTA stimuli, nine 1-octave noise bands (10-s duration) were generated in MATLAB 6.5 (MathWorks, 2000), ranging from 40 to 80 Hz, 80 to 160 Hz, 160 to 315 Hz, 315 to 630 Hz, 630 to 1250 Hz, 1.25 to 2.5 kHz, 2.5 to 5 kHz, 5 to 10 kHz, and 10 to 20 kHz. To each of these 1-octave bands, we applied three envelopes of an exponential increase in intensity that caused the sound to rise over the 10-s duration of the stimuli and to peak at 0 s (the simulated position of a listener). The slopes of the three envelopes were derived by averaging the natural exponential for the change over time $vb(f)$ of the central spectral bands (100–5000 Hz), were they to travel at slow (35 km/h), moderate (70 km/h), or fast (140 km/h) speeds toward a listener. From this calculation, three exponent slopes were determined, for a *flat*, a *medium*, and a *steep* slope. These acoustic stimuli were edited to begin 3 s before arrival (removing the initial 7 s of the stimuli) and to end 1 s before arrival, using the Cool Edit 2000 software (Syntrillium, 2000). As a final step, the root-mean square (RMS) values of all 27 stimuli were equated, thus eliminating any differences in acoustic energy between the stimuli.

Procedure Participants were instructed to judge the urgency of each stimulus on a scale ranging from 1 to 100, where 1 represented sounds with *very low urgency* and 100 represented sounds with *very high urgency*. Participants were asked to make judgments relative to the test set (rather than to sounds that they had encountered in the real world). The experiment began with a set of five practice trials without feedback. Following practice, the participants provided judgments for two blocks of 27 test trials. The presentation order of the trials in each block was independently randomized for each participant.

Results and discussion

As can be seen in Fig. 1, judgments of perceived urgency were strongly influenced by the central frequency of the spectral bands. Spectral bands with higher central frequencies tended to be judged as being more urgent than those with lower central frequencies. In particular, the bands 40–80 Hz and 80–160 Hz were judged as being the least urgent, relative to all of the other bands. Figure 1 also shows that this trend is stronger with the medium and steep exponential slopes than with the flat slope. Hence, an interaction seems to take place between the magnitude of the intensity change over time (i.e., steeper exponent slopes) and the central frequency of the spectral band that determines the level of perceived urgency.

These observations were confirmed with an analysis of variance (ANOVA) comparing the nine spectral bands for the three exponent slopes. Spectral band was found to have a large main effect, $F(8, 72) = 8.08$, $p < .001$, $d = 0.67$, and we also found a main effect of exponent slope, $F(2, 18) = 3.77$, $p < .05$, $d = 0.44$. Finally, an interaction was apparent between spectral band and exponent slope, $F(16, 144) = 2.67$, $p < .001$, $d = 0.27$. These statistical data support the notion that frequency can influence the perceived urgency of TTA stimuli.

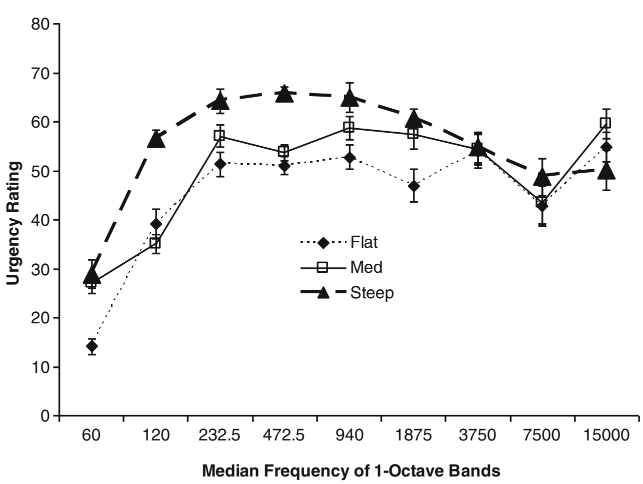


Fig. 1 Mean ratings of urgency (1 = *minimum*, 100 = *maximum*) are shown with respect to the nine frequency bands in Experiment 1, which had been normalized to equal power and intensity. Results are given with standard error bars

It is important to reiterate that the stimulus presentation levels were identical across conditions, and that the presentation times (seconds to reach the listener) were also identical. Within these constraints, higher frequencies were found to instill a greater sense of urgency than were lower frequencies. However, it is possible that differences in loudness sensitivity between the spectral bands may underlie the observed differences in perceived urgency. As has long been established, the historical Fletcher–Munson and current ISO 226:2003 equal-loudness contours have demonstrated the phenomena of greater spectral sensitivity in the central portion of the audible range and of diminished sensitivity for both very high and very low frequencies (Fletcher & Munson, 1937; International Organization for Standards, 2003). Certainly, the data in Experiment 1 seem to support at least some speculation that it may be loudness, rather than frequency itself, that influences urgency judgments. It also remains to be determined whether this perceived urgency affects TTA judgments, or how it might influence the use of predictive informational sources, like acoustic tau.

Experiment 2: Judgments of perceived urgency for equal-loudness TTA stimuli

To account for the variance in perceived urgency that might be attributed to a spectral band's loudness, Experiment 2 replicated Experiment 1 using stimuli that were equated for loudness. In Experiment 2, the spectral bands were normed for loudness against a standard stimulus prior to evaluation. After the norming was completed, the stimuli were presented in a perceived-urgency task similar to that of Experiment 1.

Method

Participants A total of 13 participants (nine women, four men) were recruited from the William Paterson University community for this experiment, with an average age of 24 years (SD = 6.1). The majority of the participants received course credit for participation, while the remainder consisted of volunteers who received no compensation. All of the participants reported normal hearing without correction and were naïve as to the purposes of the experiment.

Materials and apparatus Acoustic stimuli were calibrated and presented using custom software and OpenSesame version 0.26 (Mathôt, Schreij, & Theeuwes, 2012).

To standardize the loudness of the nine spectral bands and three exponent slopes, we first completed a norming task. Each of the 27 stimuli were evaluated in comparison to a standard stimulus and iteratively adjusted until they were judged to be equal in loudness. This task was completed on two separate occasions by a set of five listeners (i.e., ten comparisons per spectral band). The standard was a 2.5-s, steady-state Gaussian noise band with energy from 0 to 22 kHz and presented at 75 dBA (RMS value of −33 dB with respect to the gain on our amplifier). The normed loudness values were averaged and applied to the 27 stimuli in Experiment 2, thus eliminating any direct effects of loudness on the judgments. The averaged judged loudnesses of the stimuli can be found in Table 1.

Auditory stimuli were presented from a Dell Optiplex 790 computer with an Asus XonarDX soundcard to Sennheiser HD280 Pro headphones. Calibration was completed using an Extech HD600 sound-level meter just prior to and after completion of the experiment to confirm the level of the standard.

Procedure Participants were instructed to judge the urgency of each stimulus on a scale ranging from 1 to 10, where 1 represented sounds with *very low urgency* and 10 represented sounds with *very high urgency*. Participants were asked to make judgments relative to the test set. The experiment began with a set of five practice trials without feedback. Following practice, participants provided judgments for three blocks of the 27 test trials. The presentation order of the trials in each block was independently randomized for each participant.

To be explicit, there were two important differences between Experiments 1 and 2. In Experiment 2, the stimuli were equalized in loudness but not power, to determine how this variable might influence urgency. In addition, evaluations were made on a 1–10 instead of a 1–100 scale, as per the constraints of the software. The experiment duration was approximately 30 min per participant.

Results and discussion

The results were analyzed in a 9 × 3 repeated measures ANOVA, with spectral band and slope of intensity as the respective variables. As can be seen in Fig. 2, judgments of perceived urgency were found to vary across the spectral bands. In general, participants rated the higher-frequency stimuli as having greater urgency than the lower-frequency stimuli. This observation was confirmed by the main effect of spectral band: $F(8, 96) = 40.30$, $p < .001$, $d = 1.30$.

The ANOVA revealed no reliable differences between the judgments of perceived urgency of the three slopes, $F(2, 24) = 1.35$, $p > .4$, $d = 0.24$. We also found no interaction of slope and spectral band, $F(16, 192) = 1.37$, $p > .1$, $d = 0.17$, and no other reliable statistical differences.

The judgments from Experiment 2 represent a trend similar, albeit more subtle, to that in the judgments from Experiment 1. In general, participants found higher-frequency stimuli to be a little more urgent than lower-frequency stimuli. However, as opposed to Experiment 1, no difference in the urgency ratings emerged between the exponent slopes of intensity change over time. While this is speculative, the latter finding suggests that the tau-like changes over time in intensity have an influence over perceived loudness. By equating loudness across these changing stimuli, differences in urgency attributable to the rate of intensity change over time may have dissipated.

The results of Experiment 1 and 2 are consistent with previous studies concerning perceived urgency, revealing a powerful influence for loudness as well as for frequency. In the subsequent experiments, we investigated how these variables might relate to TTA estimation.

Experiment 3: Judgments of TTA for 1-octave band noises with naturally occurring rates of intensity change

An ideal strategy for making accurate TTA judgments would be to rely solely on acoustic tau and to ignore all other influencing variables. Because acoustic tau is able to provide unambiguous information about a sound source's TTA, it will be accurate across all spectral bands, speeds, and listening conditions. However, while previous research has demonstrated the sensitivity of human listeners to acoustic tau (e.g., Ashmead et al., 1995; Rosenblum et al. 2000), other evidence has suggested that acoustic TTA judgments are biased by speed, truncation, and other factors (e.g., Lutfi & Wang, 1999; Gordon & Rosenblum, 2005; Rosenblum et

Table 1 Average loudness estimation differences (in dB) between participants in Experiment 2

Exponent Slope	60 Hz	120 Hz	232.5 Hz	472.5 Hz	940 Hz	1875 Hz	3750 Hz	7500 Hz	15 kHz
1	5.66	7.82	9.82	9.11	5.95	6.17	5.08	10.18	9.52
2	4.27	6.74	10.74	11.21	7.50	9.77	10.51	10.28	11.37
3	10.22	13.71	8.95	11.86	8.06	7.46	7.21	11.94	10.80

Table shows the average variance between participants for each loudness-equated time-to-arrival stimulus relative to the loudness of the Gaussian standard

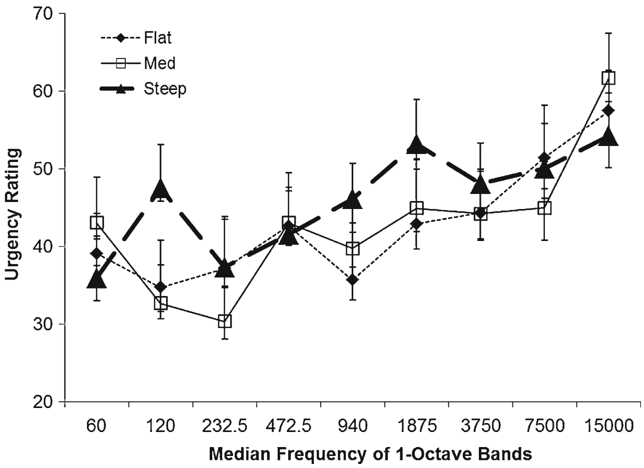


Fig. 2 Mean ratings of urgency (1 = *minimum*, 100 = *maximum*) are shown with respect to the nine frequency bands in Experiment 2, which had been normalized to equal loudness. Results are given with standard error bars

al., 2000). An interesting question is how spectrum might affect TTA judgments. Experiments 1 and 2 provided evidence that spectrum can influence the perceived urgency of TTA stimuli. If more-urgent stimuli imply that safety might be jeopardized, then the frequency components should have a strong impact on TTA judgments, and higher frequencies should bias earlier TTA judgments.

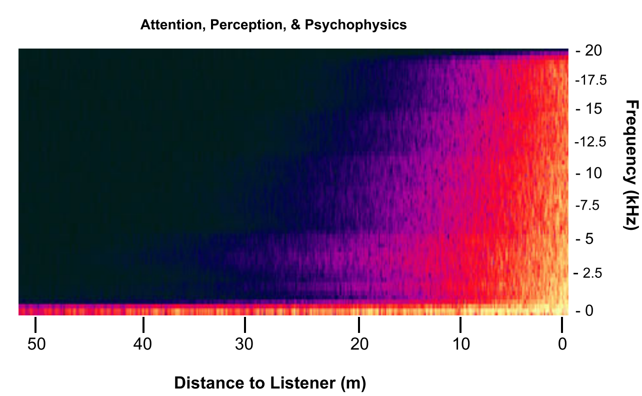
Method

Participants A group of 12 participants were recruited for this experiment from the University of Toronto at Mississauga, with an average age of 21.4 years (SD = 3.3). All of the participants received payment for participation, and none had participated in Experiment 1. Prior to testing, the participants were subjected to pure-tone audiometric screening, spanning standard test frequencies between 250 and 5000 Hz. On the basis of this screening, all participants were found to have normal hearing (i.e., <25 dB HL).

Materials and apparatus Acoustic stimuli were calibrated and presented using a Tucker-Davis System II and presented over Sennheiser headphones (Precision HD 580) in a sound-attenuated chamber. A button box with light-emitting diodes (LEDs) located above each of three buttons was used to take responses and to provide feedback, when appropriate. The button box fed the responses into the Tucker-Davis system.

In order to generate ecologically valid stimuli, recordings were made of broadband Gaussian noise (40–20,000 Hz) on a large, grassy football field—thus retaining all of the natural constraints on sound transference over distance for a sound source. The broadband noise was played via a Califone (San Fernando, CA) Presentation Pro PA-300 loudspeaker (loudspeaker height 1.3 m) to a seated listener (ear height 1.4 m) wearing Brüel & Kjær Binaural Microphones (type 4101; Nærum, Denmark) and captured using a Marantz (Mahwah, NJ) CDR-300 Digital Recording Device. A series of 10-s recordings were made while the stimulus was stationary in one of 60 possible positions located at 0° azimuth in front of the listener. The first position was 0.91 m (1 yard), and the farthest was 54.86 m (60 yards) from the listener, with recordings taken at 0.91 m (1 yard) intervals over that distance. In the closest position, the stimulus was measured to project at 94.8 dB SPL. During the recordings, the temperature averaged 22.8 °C, an anemometer registered negligible wind speeds, and the barometric pressure was steady at 101.2 kPa. This collection of noise recordings was then analyzed to determine attenuation functions for each frequency. The recorded sound levels from these recordings are represented in Fig. 3, which shows the relative signal strengths across frequencies at the distances 0.91 to 54.86 m.

These sixty 10-s recordings were analyzed in MATLAB 6.5 (MathWorks, 2000) to determine the sound pressure level as a function of distance. To complete this analysis, the broadband noise was divided into 1/3-octave bands, for which RMS values were measured for each recording position. From these values, the RMS level was determined as a function of distance for each frequency band. An exponential curve was fitted to each function: $\mathrm{RMS}(f) = A(f)e^{b(f)x}$. Since the only variable of interest was the rate of intensity change as a function of frequency, $b(f)$, the $A(f)$ scaling term from the $\mathrm{RMS}(f)$ function was removed after fitting. Removing this term simplified the RMS function to the following: $\mathrm{RMS}(f, x) = e^{b(f)x}$. While this function differs somewhat from acoustic tau (i.e., Shaw et al., 1991), it uses an intensity slope that very closely



Intensity	Color Code	Intensity	Color Code
0-15 dB		61-75 dB	
16-30 dB		76-90 dB	
31-45 dB		91-105 dB	
46-60 dB		106-120 dB	

Fig. 3 Energy recorded from a broadband noise source presented at 94 dB SPL between the distances of 0.91 and 54.86 m. Lighter colors represent greater energy

approximates the acoustic functions that we found in our field recordings. Hence, these simulations captured the changes in intensity associated with a specific spectral band in the natural environment. In each case, the spectra were held constant as the intensity rose over the duration of the simulated approach. With respect to the loudness of a stimulus, each was allowed to vary naturally, as might occur for a given change in intensity over time with respect to a spectral centroid. Hence, as a first attempt to examine the specific influence of spectrum on judgments of TTA, these simulations allowed loudness to vary, while maintaining specific changes in intensity over time and constant bands of frequencies to approximate ecologically valid conditions. Approach velocities were simulated by determining the amount of time to transverse 60 yards (the distance covered by the original recordings) when traveling at a constant speed v. Three velocities were simulated: 35.25 km/h (slow), 70.5 km/h (moderate), and 140 km/h (fast). These velocities were taken from the range of velocities typically tested in TTA research (e.g., Gordon & Rosenblum, 2005; Hancock & Manser, 1997; Schiff & Detwiler, 1979). The exponential function of RMS(f) level over distance was converted to a function of time by replacing x with vt: $\mathrm{RMS}(f) = e^{b(f)vt}$.

Once these RMS functions had been determined, they were applied as envelopes to 1/3-octave Gaussian noise samples. Trios of three consecutive 1/3-octave noise samples were summed to generate each 1-octave band. This process produced nine 1-octave-band stimuli: 40–80 Hz, 80–160 Hz, 160–315 Hz, 315–630 Hz, 630–1250 Hz, 1.25–2.5 kHz, 2.5–5 kHz, 5–10 kHz, and 10–20 kHz. Because our emphasis was on the approach of a stimulus (without passage), our method did not incorporate any simulation of Döppler shifts.

These acoustic stimuli were edited to the three stimulus onsets using Cool Edit 2000 software (Syntrillium Software Corp., 2000). *Approach onset* refers to the amount of time that the sound was presented prior to its reaching the position of the listener. Editing the stimuli for this variable produced noise presentations that varied from 3 to 5 s in duration and that commenced 4, 5, or 6 s before the TTA of the sound at the listener. As can be seen in Fig. 4, two of the bands (0.63–1.25 and 10–20 kHz) were not tested at the fast velocity, because the attenuation function was so steep that there was insufficient sound to enable a judgment.

Procedure After hearing the instructions, participants completed a set of practice trials with feedback and a set of critical trials without feedback. Each of these portions of the experiment will be discussed in more detail.

The instructions informed participants that they would hear the sound of an approaching object, something akin to a wave coming toward them at the beach. In response, participants were to press a key the moment that the noise reached their position. If the noise disappeared before actually reaching their position, the participants were instructed to press the key the moment that the noise would have arrived, had it continued on the same trajectory and at the same velocity. While participants were warned of the difficulty of doing this task, they were instructed to respond to all trials even if they were unsure about their accuracy.

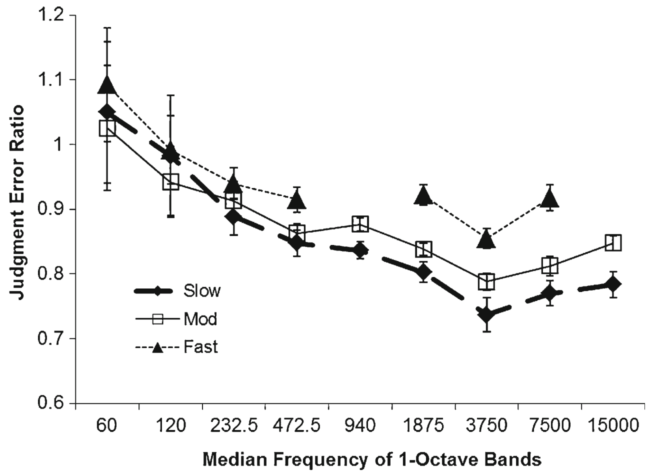


Fig. 4 Judgment error ratio (JER) values for the Spectral Band × Speed interaction (slow = 35.5 km/h, mod = 70 km/h, fast = 141 km/h) in Experiment 3. A JER value less than 1.0 indicates a response before the sound's arrival, and a value greater than 1.0 indicates a response after the sound's arrival. Note that at the fastest speed, the spectral bands centered at 940 and 15000 Hz could not be represented. Results are given with standard error bars

The experiment began with a set of 20 practice trials with feedback. Participants triggered the onset of each trial using the button box. The trials consisted of the presentation of an approaching noise, to which the participant was to respond by pressing a button at the moment of TTA. Feedback was provided by the lighting of one or two of the LEDs to indicate the relative accuracy of the judgment to the actual TTA of the noise. Early judgments made more than 50 ms prior the noise's actual arrival caused the leftmost LED to light; late judgments made more than 50 ms after the noise's arrival caused the rightmost LED to light; on-time judgments (a buttonpress within 50 ms of the arrival of the sound) caused both LEDs to light.

Participants were informed about the difficulty of getting an on-time response and were asked to use the practice trials to hone their ability to judge these stimuli. The 20 stimuli used in the practice set were a random sample of the possible stimuli tested in the critical test set. Following this practice session, participants had a short break to allow for additional questions prior to commencing the critical test set.

The critical test set contained the nine noises presented at the three possible speeds and three approach onsets. All of the sounds terminated 1 s prior to their arrival at the listener. At this distance, and with the natural attenuation functions used in this experiment, the bands 0.63–1.25 and 10–20 kHz did not contain sufficient acoustic energy to allow for a judgment at the fastest speed (140 km/h). These bands both have very steep attenuation functions, and thus contained no audible energy beyond 1 s, and so could not be simulated in this experiment.

To reduce the likelihood that participants could depend on the 1-s termination prior to the sound's arrival as a cue for judgments, a set of stimuli that arrived and passed the listener were also included. Previous research that has combined presentations of passage and approach trajectories has been successful in generating TTA values that were not a function of the approach offset (e.g., Gordon & Rosenblum, 2005; Rosenblum et al., 1987). Passage trials were not analyzed, because of their physical impossibility of occurring in natural environments. (These sounds traveled through the head of the listener and out the other side, without accounting for variables such as the width of a listener's head.)

Three iterations of each trial type were presented together in a fully randomized, within-subjects design. Participants completed a total of 81 critical trials, interspersed with 27 distractor trials/full passages, which yielded 108 trials. Including all directions and the 20 practice trials, the experiment lasted approximately 90 min per participant.

Results and discussion

The three independent variables (spectral band, velocity, and arrival time) were tested in this experiment and analyzed to determine the judgment error ratio (JER) and the judgment variability (JV) performance. JER is the average proportion of over/underestimation relative to the actual arrival time in response to each condition (e.g., JER = 1.0 when the response time matched the arrival time); JV is the standard deviation of the judgments across the three iterations of each trial for each participant, then averaged together for the group. As can be seen in Fig. 4, spectral band influenced the TTA judgments. Spectral bands centered at higher frequencies tended to produce more underestimation than did spectral bands centered at lower frequencies. The error bars in Fig. 4 also show that, while performance was fairly consistent across the central range of the spectral bands, this was not the case with the bands centered at 40–80 and 80–160 Hz. It seems that the much more gradual rise in intensity at this lowest spectral band was insufficient to support TTA judgments, and participants appeared to be generally unable to anticipate the TTA of the sound in this frequency range. Performance with stimuli from these lowest spectral bands was inconsistent and produced the unusual finding of slight overestimation. Taken together, these data suggest that participants were unable to support TTA judgments in this frequency range.

Statistical analyses confirmed this description of the spectral bands. To compensate for the two missing conditions (the bands 0.63–1.25 and 10–20 kHz at the fastest speed), two separate ANOVAs were completed to allow each to have a balanced design. A band-limited analysis included seven of the nine spectral bands (the bands that were fully represented across the three velocities), the three velocities, and the approach onsets. A speed-limited analysis tested the two slower velocities (and not the fast velocity), with all of the nine spectral bands and each of the possible approach onsets. For both the band-limited and speed-limited analyses, we found a main effect of spectral bands in the JER data, $F(6, 66) = 5.42$, $p < .001$, $d = 0.57$, and $F(8, 88) = 5.21$, $p < .001$, $d = 0.49$, respectively. As was stated previously, performance was much less consistent at the lower than at the higher spectral bands. A main effect of spectral band was also found in the JV analyses of the band-limited and speed-limited data sets, $F(6, 66) = 4.65$, $p < .001$, $d = 0.53$, and $F(8, 88) = 6.02$, $p < .001$, $d = 0.52$, respectively. This main effect demonstrates the inconsistency of participants with the lower-frequency spectral bands. As can be seen in Fig. 5, the bands 40–80 and 80–160 Hz had higher JV scores (i.e., less consistency between judgments) than the other bands. Paired-comparison least significant difference (LSD) testing confirmed that each of these bands differed from the other spectral bands at the .05 level in both the band-limited and speed-limited analyses. These two lowest bands were not found to differ statistically from each other in their JV values.

Figure 4, depicting the JER data, also shows that participants tended to underestimate the arrival time of slower-

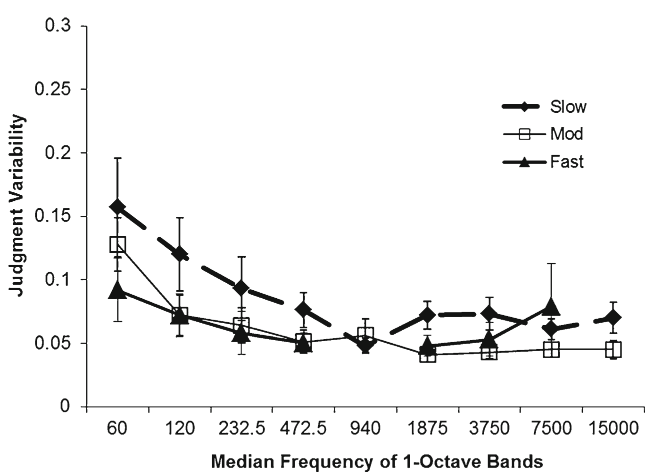


Fig. 5 Judgment variability (JV) values for the Spectral Band × Speed interaction (slow = 35.5 km/h, mod = 70 km/h, fast = 141 km/h) in Experiment 3. JV is the standard deviation of the judgments across the three iterations of each trial per participant, then averaged together for the group. Results are given with standard error bars

moving sounds more than of the faster-moving sounds. This finding replicates the typical pattern of TTA results with regard to velocity (see Hancock & Manser, 1998, for a review). Statistical analyses of both the band-limited and speed-limited data sets showed main effects of velocity, $F(2, 22) = 21.588$, $p < .001$, $d = 1.98$, and $F(1, 11) = 5.573$, $p = .038$, $d = 1.01$, respectively. As might be expected, the speed-limited analysis, which did not include the fastest velocity, also produced a smaller effect than did the analysis that included all three of the velocities. Testing of variable error also showed differences in consistency across the three velocities. Participants tended to be more consistent in judgments at the faster than at the slower velocities. We found a main effect of velocity in both the band-limited and speed-limited analyses, $F(2, 22) = 12.294$, $p < .001$, $d = 1.49$, and $F(1, 11) = 19.953$, $p < .001$, $d = 1.91$, respectively. Potentially, the more abrupt rate of intensity change for the faster-moving objects may have made it easier for participants to be consistent in their judgments of TTA.

As an additional test of the effect of urgency on the TTA, we correlated the mean ratings for each frequency tested in Experiments 1 and 2 with the JER data collected in Experiment 3. Overall, the correlations were very high: $r(7) = -.77$, $p < .05$, for JER relative to the Experiment 1 urgency ratings, and $r(7) = -.93$, $p < .01$, for JER relative to the Experiment 2 urgency ratings. These correlations provide an additional indication that higher urgency ratings tend to correlate with early TTA estimates.

As would be expected on the basis of the previous literature, approach onset was not found to influence the judgments of TTA (e.g., Gordon & Rosenblum, 2005; Harris & Giachritsis, 2000; Schiff & Detwiler, 1979). Approach onset is principally used to generate some variety in the judgments and to diminish the possibility for participants to rely on a counting strategy (i.e., disallowing the strategy of simply pressing the key at the same interval relative to the onset of a stimulus). In that we found no effects of approach onset, this manipulation appears to have been successful in causing participants not to rely on a counting strategy. Statistically, no main effect of approach onset was found for either the band-limited or the speed-limited analyses with the JER data, $F(2, 22) = 1.416$, $p > .1$, $d = 0.51$, and $F(2, 22) = 0.208$, $p > .1$, $d = 0.19$, respectively. Approach onset was also found to have no influence on the JV of judgments in either the band-limited or the speed-limited analyses, $F(2, 22) = 1.883$, $p > .1$, $d = 0.59$, and $F(2, 22) = 1.679$, $p > .1$, $d = 0.55$, respectively.

Two factors principally influenced the judgments of TTA: the spectral bands of the presentation and the speed of the approaching object. The greatest level of underestimation was associated with the highest spectral bands and with the lowest speeds. This influence of spectral band is consistent with speculation about the role of urgency for TTA judgments. Higher frequencies were found to instill greater urgency in Experiments 1 and 2, and in this third experiment, higher frequencies were found to bias participants to respond earlier, as might be necessary in order to take precautions for approaches of greater urgency.

The simulations also were designed to allow loudness to vary freely with the differences in spectral band and the changes in intensity. As previously described, this was important in order to maintain the ecological validity of the simulations, even as loudness might be speculated to influence the conclusions. Certainly the results of Experiment 2 suggested that differences in the rate at which intensity might change over time and in the overall sensitivity to the distribution of spectra would be expected to vary in relation to loudness. Experiment 3 suggested how naturally occurring changes in loudness with respect to spectra might influence TTA judgments overall.

However, to more directly investigate the change in intensity over time and its relationship to TTA estimates, the velocity of an approaching sound must also be considered. As we have stated, in previous studies velocity has been found to bias earlier TTA judgments for slower-moving objects (Gordon & Rosenblum, 2005; Hancock & Manser, 1997). It has been speculated that the faster rates of change in a sound source may be easier to anticipate. Hence, in evaluating the effects of velocity, it should be considered that both the rate of intensity change and the direct effects of velocity itself are influenced by a third variable: the slope of the rate of exponent change. While it was necessary to allow the exponent change to vary freely in this experiment, in order to simulate ecologically valid acoustic parameters, in doing so the influence of this variable could not be directly assessed. In a fourth experiment, we examined the influence of exponent slope more directly. We predicted that faster rates of change might be easier to anticipate, and thus might reduce underestimation.

Experiment 4: Influence of exponent slope on judgments of TTA for 1-octave band noises

As stated above, both the spectral band and speed of approach influence the rate of change of intensity. Higher spectral bands tend to have more rapid rates of change, and increasing the velocity of an approaching sound will also increase the rate of change. In order to assess the influence of rate of change, this variable was independently manipulated in this final experiment. When we implemented this manipulation, spectral bands were no longer associated with their naturally occurring rates of change. Varying the rate of change produces some very unusual and unlikely simulated patterns for the highest- and lowest-frequency spectral bands. For example, the highest spectral bands simulate an object moving very slowly (e.g., 1 m/s) over a distance of just a few meters, and the lowest spectral bands simulate a sound moving at unnaturally high velocities (e.g., 400+ km/h) over wide distances. However, aside from these spectral bands at the extremes of the audible range of the spectral distribution, the midrange spectral bands (between 200 and 5000 Hz) were simulated to move within the velocity conditions simulated in Experiment 3.

The other consequence of this rate-of-change manipulation was that velocity could no longer be independently controlled. Velocity is a direct function of the rate of change, so artificially setting the rate of change determined this value. It can generally be expected that steeper slopes of change represent higher velocities, and shallower slopes, lower velocities. It may be predicted that if listeners principally rely on tau information to determine TTA, then each of the tested spectral bands should support relatively analogous performance. However, if listeners attend to some other heuristic based on urgency, then it might be predicted that spectral band would continue to influence judgments.

Method

Participants A group of 12 participants were recruited from the University of Toronto at Mississauga for this experiment, with an average age of 20.8 years (SD = 4.1). None of the participants had participated in Experiment 1 or 2, and all received payment for participation. Prior to testing, the participants were subjected to pure-tone audiometric screening. On the basis of this screening, all were found to have normal hearing (i.e., <25 dB HL).

Materials and apparatus All of the materials from Experiment 3 were used in Experiment 4, with the following modifications to allow for the independent testing of the exponent slopes. The exponent slopes $vb(f)$ of the central spectral bands (100–5000 Hz) were averaged at the slow, moderate, and fast speeds. From this calculation, three exponent slopes were determined for a *flat*, a *medium*, and a *steep* exponent change that were the same as those used in Experiment 1. Each of the nine spectral bands was generated with the three possible exponent slopes and edited to fit the three approach onsets used in Experiment 3.

Procedure The procedure was identical to that of Experiment 3. Participants were first trained with a subset of 20 trials with feedback, followed by a test block with three iterations of each stimulus and an equal number of catch trials. Testing took approximately 1 h.

Results and discussion

In this experiment, all nine of the spectral bands were represented at each exponent slope and approach onset. JER and JV analyses were completed for the variables *spectral band*, *slope*, and *approach onset*. Figure 6 shows that the higher-frequency spectral bands tended to be more underestimated than the lower-frequency spectral bands. This trend was found across each of the possible slopes of intensity change, wherein even shallow-sloping high frequencies were more likely to be underestimated than steeply sloping low frequencies. The error bars in Fig. 6 show that performance was fairly consistent across the spectral bands, with the exception of the lowest band (40–80 Hz). Hence, it seems that even with the rise in intensity controlled across the possible spectral bands, it was still more difficult to judge the TTA of lower than of higher frequencies. This difficulty could have been caused by some amount of insensitivity among participants discriminating intensity changes at very low frequencies, by a bias in past experience that emphasized attention to more midrange or higher frequencies for TTA, or by the artifact of applying an intensity rise that would simulate motion at incredibly high velocities for these low frequencies (i.e., the exponent slopes that were applied to the stimuli in this experiment produced a much larger modification away from the naturally occurring slopes at the lowest than at other frequencies). While the present data do not allow us to distinguish between these and other possibilities, we can only speculate that using very low frequencies for judgments of TTA may pose great difficulty. At the opposite tail of the distribution, the extremely slow velocities simulated for the highest frequencies did not seem to cause any additional performance inconsistency.

Statistical analysis supported these observations. We found a main effect of spectral band for the JER data, $F(8, 88) = 18.87$, $p < .001$, $d = 0.93$. Post-hoc paired-comparison LSD testing revealed statistical differences at

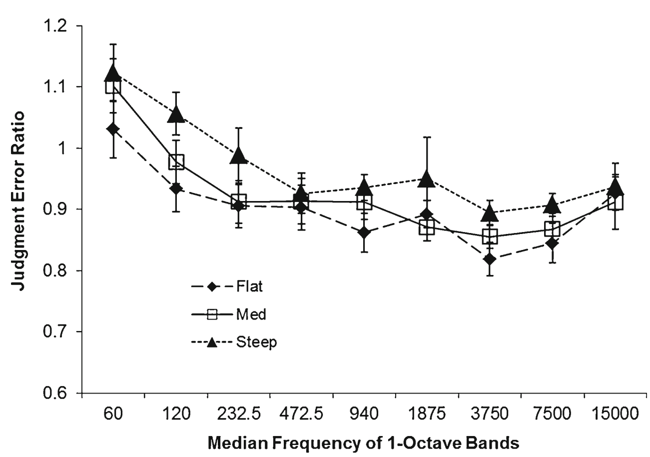


Fig. 6 Judgment error ratio (JER) values for the Spectral Band × Exponent interaction in Experiment 4. A JER value less than 1.0 indicates a response before the sound's arrival, and a value greater than 1.0 indicates a response after the sound's arrival. Results are given with standard error bars

the .05 level for the two lowest spectral bands, 40–80 and 80–160 Hz, which showed less underestimation than did all of the other bands, and for the band 2.5–5 kHz, which tended to cause relatively more underestimation than did all of the other bands. The description of the consistency of judgments across the spectral bands was statistically supported by statistical analysis of the JV data (see Fig. 7). A main effect of spectral band emerged, $F(8, 88) = 7.16$, $p < .001$, $d = 0.57$. Post-hoc paired-comparison LSD testing revealed that the lowest band, 40–80 Hz, reliably differed at the .05 level from all of the other spectral bands. No other differences between spectral bands were found in the JV data.

As can be seen in Fig. 6, participants showed a greater tendency to underestimate shallower exponent slopes than steeper exponent slopes. This pattern is consistent with the previously found velocity data, in that shallower slopes tend to occur at lower velocities and tend to increase the amount of underestimation relative to higher velocities. However, the exponent slopes did not appear to strongly influence the consistency of judgments (i.e., the JV data), as we had found in Experiment 3. As can be seen in the statistical analysis, a main effect of exponent slope was apparent for the JER analysis, $F(2, 22) = 12.36$, $p < .001$, $d = 1.06$, but not for the JV analysis, $F(2, 22) = 2.82$, $p = .08$, $d = 0.50$. Post-hoc LSD paired-comparison testing of the JER data with regard to exponent slope revealed that each of the three levels reliably differed from the others at the .05 level.

We also found a main effect of approach onset in both the JER and JV data. As previously stated, approach onset was varied in order to reduce the ability of participants to employ a simple counting strategy rather than making TTA judgments. A main effect in the JER data of this variable

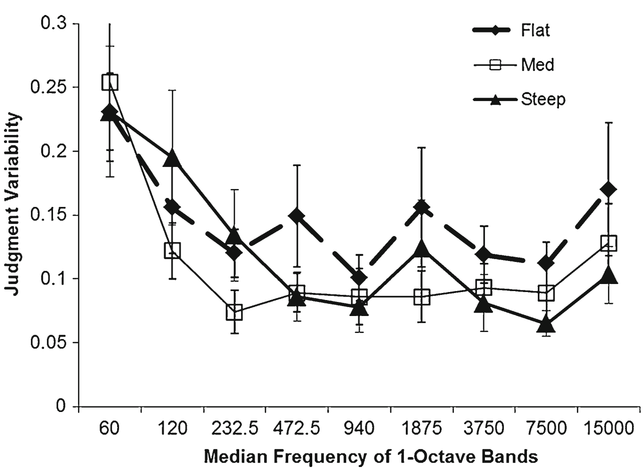


Fig. 7 Judgment variability (JV) values for the Spectral Band × Exponent interaction in Experiment 4. JV is the standard deviation of the judgments across the three iterations of each trial per participant, then averaged together for the group. Results are given with standard error bars

suggests that in some conditions, a counting strategy was used. However, only the lowest band, 40–80 Hz, seemed to show differences between the three approach onsets. This observation further supports the notion that the simulated velocities for the lowest band may have caused it to become extremely difficult to estimate TTA, leading to an increased likelihood of adopting a counting strategy.

The judgments of all of the other spectral bands did not seem to be influenced by approach onset. Statistical analyses support these observations. In the JER data, we found a main effect of approach onset, $F(2, 22) = 5.41$, $p < .05$, $d = 0.70$, and an interaction of spectral band and approach onset, $F(3, 33) = 4.98$, $p < .01$ (Greenhouse–Geisser corrected), $d = 0.67$. Post-hoc LSD paired-comparison testing revealed that the band 40–80 Hz at the 4- and 5-s approach onsets differed from all of the other spectral bands at the .05 level. As can be seen by comparing Figs. 6 and 7, the JER data mirrored the pattern described with the JV data, in that as the participants seemed to rely more on a counting strategy for the lowest spectral band, their judgments were least consistent for the shortest approach onset (4 s) relative to the other two approach onsets. Statistical analysis showed a main effect of approach onset in the JV data, $F(2, 22) = 8.84$, $p < .01$, $d = 0.90$, although no interaction of spectral band and approach onset emerged there, $F(3, 37) = 1.84$, $p < .05$, $d = 0.40$. It is important to note that the other eight spectral bands were judged with relatively the same consistency and accuracy as in Experiment 3, suggesting that TTA judgments were possible for those simulated velocities and spectral bands.

No other main effects or interactions were found for either the JER or the JV data.

As an additional test of urgency on the TTA, we correlated the mean ratings for each frequency tested in Experiments 1 and 2 with the JER data obtained in Experiment 4. Overall, the correlations were very high: $r(7) = -.80$, $p < .01$, for JER relative to the Experiment 1 urgency ratings, and $r(7) = -.88$, $p < .01$, for JER relative to the Experiment 2 urgency ratings. These correlations provide an additional indication that higher urgency ratings tend to correlate with early TTA estimates.

This fourth experiment isolated the relative contribution of the rate of change in intensity from spectral bands and found that each of these variables had an independent contribution to TTA judgments. The results in Experiments 3 and 4 allow for some speculation concerning the role of spectral band to TTA. Generally as the central frequency of the spectral bands increased, the more likely participants were to underestimate judgments; this relative increase in underestimation occurred even after the steepness of the exponent slopes of intensity change were controlled in the fourth experiment. This finding is consistent with the data of Experiments

1 and 2, in which higher frequencies instilled greater perceived urgency.

General discussion

Experiments 1 and 2 demonstrate a relationship between spectral bands and perceived urgency, while Experiments 3 and 4 suggest that spectral bands influence TTA judgments. When these findings are taken together, we can conclude that spectral band has an effect on TTA judgments, and that the effect is likely mediated by perceived urgency. Clearly, the strongest effects of spectral band were at the tails of the spectrum (central frequencies over 5 kHz or under 350 Hz). At these extremes, listeners may have had more difficulty performing the TTA task, and thus relied more heavily on frequency-based cues. However, spectrum was also found to bias judgments in the central range of the audible spectrum, suggesting that perceived urgency may modify one's margin of safety. These data suggest both that TTA may be easier to determine from the central range of the audible spectrum, and that within that range, higher frequencies will tend to bias listeners to determine earlier arrival times for approaching stimuli.

Previous research has consistently found that the perceived urgency of a sound is strongly influenced by its frequency characteristics. In particular, urgency ratings tend to increase relative to increases in fundamental frequency and spectral centroid (Arrabito, Mondor, & Kent, 2004; Edworthy, Loxley, & Dennis, 1991; Haas & Casali, 1995; Hellier et al., 1993; Russo & Jones, 2007; Russo et al., 2003). Behaviorally increasing urgency (by varying frequency and other acoustic variables) has previously been found to reduce the response times to alarms (Haas & Casali, 1995; Russo & Jones, 2007). The extent of underestimation in the present research may be interpreted as a response time bias influenced by the frequency characteristics of the sound source.

Related physiological findings would seem to complement this past behavioral research. In particular, rising tones designed to simulate looming stimuli have been correlated with amygdala and related sympathetic activity in humans (Bach et al., 2008). Converging evidence from comparative research with rhesus monkeys has demonstrated greater sensitivity and response to looming auditory stimuli (i.e., intensity rising) relative to receding stimuli (Maier & Ghazanfar, 2007). The specific sensitivity and alarm-oriented response toward looming stimuli putatively provide a physiological mechanism that could be supporting the behavioral urgency findings. In as much as urgency seemed to be a mediating factor in the present experiments, it would be interesting to determine whether specific looming frequency bands correlate with more powerful amygdalar activation in humans.

The results of the first two experiments also corroborate previous findings concerning the powerful influence of loudness on urgency judgments (Bach et al., 2008; Hellier et al., 1993). The leveling of loudness in Experiment 2 was found to diminish the overall differences between the spectral bands observed in Experiment 1. Moreover, equating loudness was found to remove all influence of the exponent slopes—that is, the influence of intensity rise time—on perceived urgency. Judgments of TTA and the use of acoustic tau are somewhat necessarily predicated on sensitivity to changes in loudness. Hence, it may not be surprising that manipulating changes in intensity over time and direct manipulations of loudness have been found to mediate, respectively, TTA estimates and the perceived urgency across spectral bands. Previous research has found that loudness relates directly to the perceived urgency of acoustic stimuli (e.g., Edworthy et al., 1991; Hellier et al., 1993) and to the perceived distance of sound sources (Zahorik et al., 2002). The present research provides some indication of the role of loudness in a TTA task. Future studies that specifically manipulate loudness relative to intensity across frequencies would allow for more direct observation of this relationship and its application of TTA.

With respect to the roles of loudness, frequency, and intensity, however, it may be interesting to consider the specific question of why higher-frequency components tended to lead to more urgency, and hence to more underestimation of TTA. As stated, higher frequencies are, in general, more easily attenuated over distance than are lower frequencies. Consequently, when listeners are able to detect higher frequencies from a sound source, those frequencies are likely to be fairly close to the listener. Figure 3, depicting our field recordings, shows that even a 95-dB-SPL broadband noise is almost completely inaudible over 3 kHz beyond 30 m in our test environment. As has been found in research with echolocation, bats use different calls and have evolved somewhat different echolocation mechanisms to take advantage of the specific properties of their natural environments (Jones & Teeling, 2006; Lawrence & Simmons, 1982). It is interesting, though speculative, to consider the possibility that human sensitivity to acoustic motion information, like acoustic tau, may be similarly flexible to one's environment and the atmospheric conditions.

In part, TTA judgments might be expected to parallel static auditory distance judgments. Listeners attending to an approaching sound source would be expected to have access to all of the acoustic cues available in a static judgment; namely, the overall loudness, spectrum, and ratio of direct to reflected sound might all influence TTA judgments (see Mershon & Bowers, 1979; Moore & King, 1999; and

Zahorik et al., 2002, for discussions of acoustic distance in stationary listeners). The present study provides some initial data on the specific roles of spectrum and frequency, as they might operate in a dynamic TTA task. Distance judgments made while stationary suggest that listeners are sensitive to changes in spectrum over distance, and the present data provide some indication of how spectrum applies in a dynamic distance task. As we described in the introduction, with attenuation across distance there tends to be a proportional increase in lower- relative to higher-frequency sound. In testing TTA, we were able to manipulate the availability of these spectral components as they occur during the approach of a sound source toward a listener. The other powerful static auditory distance cues of overall loudness and the ratio of direct to reflected sound might be speculated to contribute to TTA, as well.

However complex is the relationship between the environment and the acoustic spectrum, hearing high frequencies may increase judgments of urgency (particularly for moving sources) precisely because when a listener can detect these sounds, they tend to indicate a sound source very close to one's position. If we recall the listener standing on the train tracks (in the introduction), he hears the train horn and must determine how much time remains before the oncoming train reaches his position. Several of the variables that map onto perceived urgency (high frequency, high intensity) will become increasingly present in the sound source as the train approaches his position. Perhaps we, like him, have associated those acoustic qualities of proximity with feelings of a need for quick responsive action. Judgments of TTA may be biased because it is better to respond quickly and safely to urgent sounds than to wait on the tracks for an unambiguous sign of the train's arrival.

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