

Humans detect gaps in broadband noise according to effective gap duration without additional cues from abrupt envelope changes

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Previous studies of behavior and IC single units in the mouse support theoretical expectations that gaps with ramped trailing markers have reduced detectability compared to equivalent gaps with ramped leading markers. In experiment 1, detection probability and response speeds of humans listening for gaps in broadband noise were investigated by independently varying either leading marker fall-time (FT) or trailing marker rise-time (RT). Gaps with silent duration of 1, 4, or 12 ms were presented 2 s into a 3-s noise burst, with either abrupt marker onsets and offsets or linearly ramped RT/FT of 2, 4, or 8 ms durations. Addition of a nonzero RT or FT to the gap silent period increased detectability and also increased reaction speed on trials with “Yes” response, but there was no difference in detectability or response speeds between RT and FT conditions. Experiment 2 extended this finding to gaps having two, one, or no abrupt marker edges. These findings suggest that human listeners do not make use of abrupt onset or offset information to enhance gap detection, but seem to rely on the effective sound level reduction associated with the gap for detection.

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I. INTRODUCTION

The detection of gaps in broadband noise has been studied using a variety of physiological and psychophysical techniques, which have provided similar measures of temporal acuity. These studies range from single unit recordings of auditory nerve fibers in the chinchilla (Zhang *et al.*, 1990), inferior colliculus (IC) neurons in the mouse (Walton *et al.*, 1997; Barsz *et al.*, 1998), and primary auditory cortex neurons in the cat (Eggermont, 2000), to behavioral techniques such as prepulse inhibition in the rat (Ison, 1982; Leitner *et al.*, 1993) and the mouse (Ison *et al.*, 1998; Ison *et al.*, 2002) as well as psychophysical perceptual measures in humans (e.g., Plomp, 1964; Green, 1985; Green and Forrest, 1989; Snell, 1997; He *et al.*, 1999; Florentine *et al.*, 1999). In addition to these applications, gap detection has also assumed significance owing to the importance of temporal acuity for human speech perception (Tyler *et al.*, 1982, 1989; Gordon-Salant and Fitzgibbons, 1993; Busby and Clark, 1999; Phillips *et al.*, 2000; Snell and Frisina, 2000).

Plomp (1964) established much of the theoretical framework that underpins research on auditory temporal acuity. He found that the threshold for gap detection depends on the sound levels of pre- and postgap noise burst markers and suggested that below some minimum gap threshold (MGT) a finite rate of decay of auditory sensation masks the presence of gaps that occur within this decay envelope. This masking also determines the magnitude of the onset response to the trailing noise burst marker. The MGT for simple rectangular gaps in broadband noise is typically between 2 and 3 ms (Plomp, 1964; Irwin and Purdy, 1982; Forrest and Green,

1987; Green and Forrest, 1989; He *et al.*, 1999) and the psychometric function for gap detection is very steep, with a range of approximately 2 ms between 0% and 100% detectability (Green and Forrest, 1989; Moore *et al.*, 1992; He *et al.*, 1999). Computational models of gap detection have generally assumed that detection occurs on the basis of short-term fluctuations within single-channel detectors (Buunen and van Valkenberg, 1979; Buus and Florentine, 1985; Forrest and Green, 1987) or within multiple-channel detectors (Heinz *et al.*, 1996). Florentine *et al.* (1999) have recently suggested that discrepancies between their empirical data and a loudness detector model might arise from additional detection cues being provided by the onset response to the trailing marker of the gap. If so, then altering the onset information of the trailing marker should affect gap detection.

Previous studies in the mouse suggest that ramped marker onsets and offsets do impair gap detection. Barsz and colleagues (1998) covaried the leading marker fall-time (FT) and trailing marker rise-time (RT) of gap envelopes and examined the effect of this manipulation on the encoding of gaps by mouse IC single units. They found that symmetric gaps (RT=FT) with RT/FT greater than 4 ms showed increased detection thresholds, requiring longer gap durations to produce a significant difference in firing rate from the no-gap control. Increasing RT produced longer first spike latencies for phasic units, and slowed the rate of recovery of their asymptotic firing rate response. In contrast, increasing FT reduced the decay of excitation during the gap for tonic units. Ison and colleagues (2002) found, using prepulse inhibition in the mouse, that adding RT and FT to small gaps increased their detectability owing to increased effective gap duration, consistent with energy detector models. They found additionally that the salience of longer gaps was reduced for

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RT ramps compared with FT ramps, supporting the importance of onset information for gap detection.

These mouse studies indicate that onset information is important for gap detection, and that ramped gap envelopes may have reduced psychophysical salience compared with gaps having abrupt marker offsets and onsets. Accordingly, the object of this investigation was to test in humans the effect on gap detectability of ramped marker edges.

II. GENERAL METHODS

Two experiments were conducted to test the effect of ramped marker edges on gap detection. In experiment 1, the effects on detectability and response speeds were investigated of varying the ramp duration at one gap edge (either the leading or trailing marker) while keeping the other edge abrupt. In experiment 2, the effects of having a single abrupt edge versus two or no abrupt edges on gap detection were investigated.

A. Subjects

Fourteen volunteers (nine men and five women) aged between 19 and 65, with a median age of 21 years, participated in this study. All had normal audiograms for their age. The University of Rochester Research Subject Review Board approved the experimental procedure and participants were reimbursed for their participation.

B. Stimuli

The carrier for the gaps consisted of 3 s of broadband noise (16 Hz to 20 kHz, 60 dB A) generated and controlled via a digital signal processing platform (Tucker-Davis AP2) and custom software on a 486 personal computer. The noise bursts were created with a flat frequency spectrum using a sampling rate of 50 kHz. They were presented binaurally using Beyer headphones (DT 48). The noise bursts were separated by a silent postresponse intertrial interval of 2 s. Various shaped gaps (described for the two experiments below) were located 2 s into the noise burst.

C. Procedures

Throughout the experiment, participants were seated in a sound-attenuating chamber and asked to listen for the presence or absence of a gap in the noise bursts. A “Yes”/“No” single-interval procedure was used. Participants were instructed to respond as quickly and accurately as possible on hearing a gap by pressing the right-hand button on a response box, and if no gap was detected to press the left-hand button.

The latency between the 2-s point of the stimuli, where gaps were presented except on control trials, and the subject’s response was collected. For “Yes” responses, if the response latency was greater than 170 ms, but less than 2500 ms, this latency was converted to a reaction speed ($\text{speed} = 1/\text{latency}$) in order to reduce the skewing effects of occasional long reaction time latencies, and mean response speeds for each gap were calculated. Subjects used various response strategies for trials during which they did not hear a gap. The most common strategy was to respond “No” after the cessa-

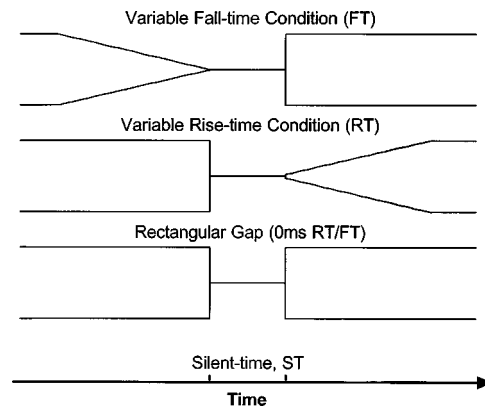


FIG. 1. Schematic representation of temporal gap stimuli used in experiment 1.

tion of the 3-s noise burst, at considerably longer latency than for trials during which they responded “Yes”. In experiment 1 asymptotic values for reaction speed were determined using a 12-ms gap with abrupt edges.

III. EXPERIMENT 1: EFFECT ON GAP DETECTION OF A SINGLE RAMPED EDGE

A. Methods

There were seven participants in experiment 1 (four men and three women) aged between 19 and 65, with a median age of 22 years. Participants were tested over two days, and on each day were presented with six blocks of trials. Within a single block, participants were presented with either variable-RT or variable-FT trials (described below), and each block contained eight presentations of each of the eight stimulus types and a no-gap control trial, so that each condition was presented 48 times. On each day three variable-FT and three variable-RT blocks were randomly presented. Each trial block lasted approximately 7 min and participants were given the opportunity to take a short rest between blocks.

The gap stimuli in this experiment are shown schematized in Fig. 1, and were chosen to correspond directly with those used in a prepulse inhibition study of mice by Ison *et al.* (2002). The nominal gap duration is the silent time of the gap, to which ramped marker onsets and offsets are added. On each trial, except for control trials on which there was no gap in the noise, a gap with a silent-time, ST, of 1-, 4-, or 12-ms duration was presented 2 s after the onset of the noise burst. Gaps with 1- and 4-ms ST were either preceded by a 0, 2, 4, or 8 ms fall-time of the leading marker and followed by an abrupt onset of the trailing marker (Variable-FT Condition), or had an abrupt leading marker offset and a rise-time of the trailing marker of 0, 2, 4, or 8 ms (Variable-RT Condition). The 12-ms ST gap had abrupt marker edges.

The detection probability and response speed data were each subjected to a three-way within-subject repeated measures factorial analysis of variance (ANOVA). The data entered into the ANOVA were the mean values across blocks of trials for each subject for each condition. The three factors were (1) gap silent time, here using only the 1- and 4-ms durations, (2) rising versus falling ramps, and (3) ramp du-

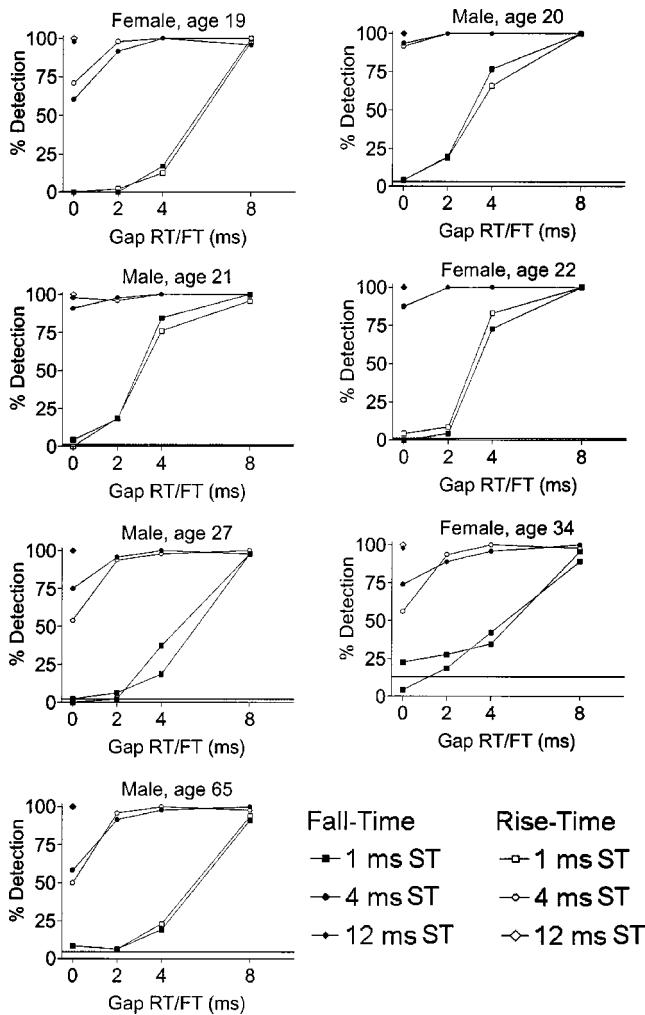


FIG. 2. Percent detection functions for individual subjects. Increasing gap fall- and rise-time (FT and RT) conditions are plotted together, illustrating that there is little difference between them. The data are presented in age order, demonstrating also that there is no systematic age effect.

ration. The number of levels in each factor were, respectively, 2, 2, and 3. The interpretation of the statistical significance of the resulting F -values used the Huynh–Feldt correction (Huynh and Feldt, 1976) for violations of compound symmetry in repeated measures designs.

B. Results

Individual subject psychometric functions for gap detection are shown in Fig. 2. Gap detectability increased uniformly with the silent duration of the gap, ST, and with both increasing RT and FT, with no systematic difference in detectability apparent between these two types of gaps across subjects. These data also demonstrate the uniformity in psychometric functions across participants, who are presented in age order, showing also that there is no apparent age dependence for the effects of this RT/FT manipulation on gap detection.

Mean gap detection probabilities across participants were calculated and are shown in Fig. 3. Detection of gaps increased with increasing ST and also with increasing gap FT and RT. The ANOVA shows that there was no significant difference in detectability between the FT and RT conditions

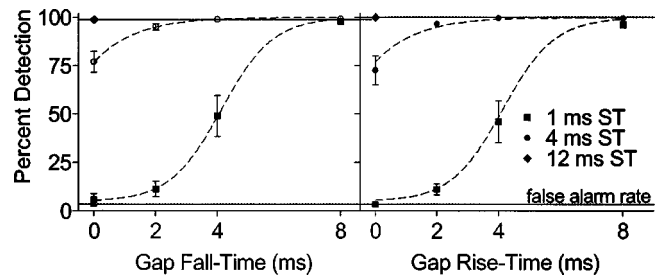


FIG. 3. Group average percent detection functions against gap FT (left panel) and RT (right panel) for three gap silent times. Error bars denote standard errors of the mean, while the within-subject standard error is 3.6% for the RT condition and 3.4% for the FT condition. The false alarm rate (FA) for both experimental conditions was $<5\%$. Both 1-ms silent time data sets are shown with a logistic function described by Eq. (1) obtained by fitting to the FT data.

for equal gap silent time [$F(1,6) = 1.1$, $p > 0.3$]. Gaps with 1-ms silent time and 0-ms RT/FT were infrequently detected. These gaps had a mean detectability and standard error of $4.5(\pm 1.6)\%$. Detectability increased equally with increasing RT and FT, with 50% detectability near 4 ms for both, and approached 100% for the 8-ms RT/FT. The logistic function is commonly used to descriptively model psychometric detection functions (e.g., Green, 1993; Florentine *et al.*, 1999; He *et al.*, 1999) and takes the form

$$\text{Detection}(\%) = \alpha + \frac{100 - \alpha}{1 + e^{-k(t-m)}}, \quad (1)$$

where α is the false alarm rate, m is the midpoint of the psychometric function, and k describes the slope of the function (Green, 1993). The 1-ms FT and RT data of Fig. 3 are shown with a function of this form, calculated by least-squares fitting to the FT data. The function describes these data well, with $R^2 = 0.9997$, and additionally the same function describes the RT data with $R^2 = 0.9963$, further highlighting the similarity of these two data sets.

The detectability of all the 4-ms silent-time gaps was above 50% and their detectability increased rapidly from the 0-ms RT/FT gap, $74.9(\pm 4.5)\%$ detection, with little difference between variable-RT and FT condition, and approached 100% for longer RT/FT. These data cannot be fit reliably with a logistic function because they are clustered at high values of this function, but are shown in Fig. 3 with a logistic function fitted to the FT data to illustrate the similar trends in detectability for the two gap-types.

The 12-ms abrupt-edged gap was almost always detectable (means for RT and FT conditions were 100% and 99.0% detection, respectively). The false alarm rate was $4.0(\pm 2.0)\%$ for the variable-FT condition and $3.1(\pm 1.6)\%$ for the variable-RT condition. The within-subject standard error terms obtained from the ANOVA, which exclude variance arising between subjects (Loftus and Masson, 1994), are 3.6% for the RT condition and 3.4% for the FT condition.

The individual participant data for response speeds are shown in Fig. 4, calculated from the response latencies on trials with “Yes” responses. Across subjects, speeds increased with silent duration and with RT/FT and again showed uniformity between the RT and FT conditions, although response speed appears more variable among subjects

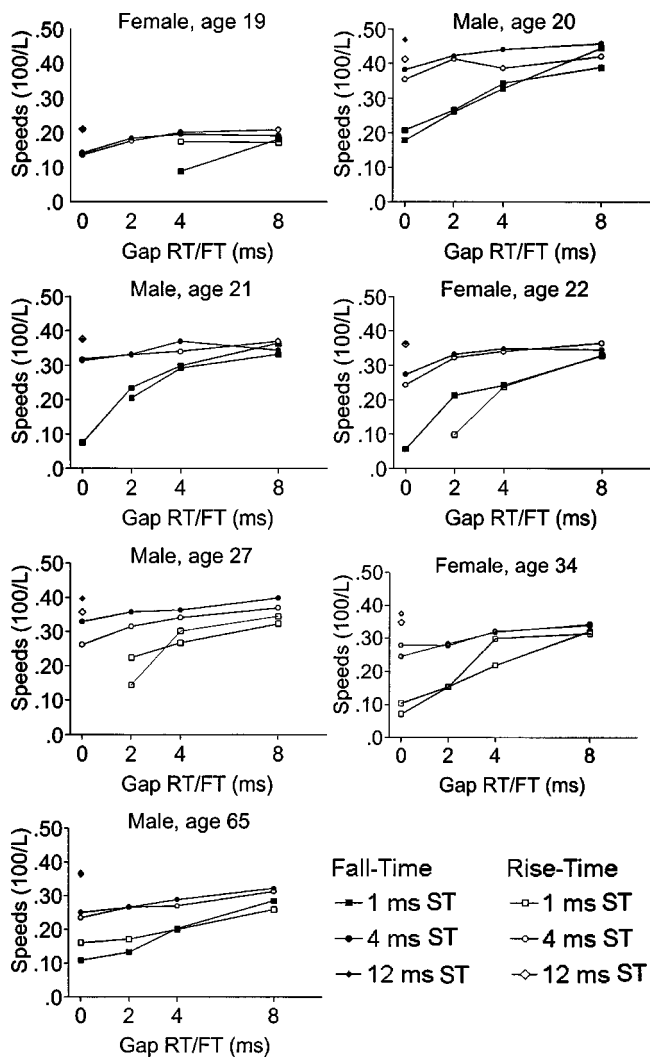


FIG. 4. Individual subject response speeds (1/Latency) shown with increasing gap RT and FT for each of the three gap silent times.

than does detectability. Mean response speeds across subjects are shown in Fig. 5, and were again nearly identical for both the variable-RT and variable-FT conditions. The ANOVA shows that there was no significant difference in detectability between the FT and RT conditions for equal gap silent time [$F(1,6) < 1, p > 0.75$]. The data for both FT and RT condi-

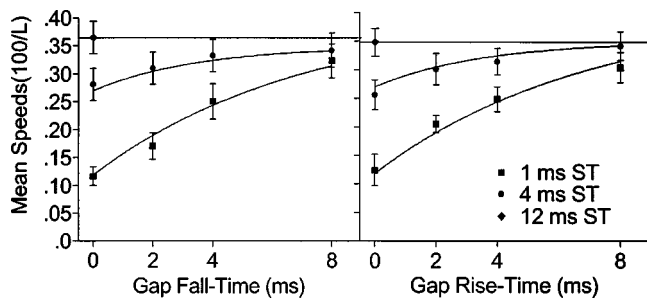


FIG. 5. Mean response speeds for gap FT (left panel) and RT (right panel). Error bars denote standard errors of the mean, while the within-subject standard error is 0.012 for the RT condition and 0.013 for the FT condition. The data are well described by two exponential functions fitted to the mean of the aggregated RT and FT data for each of the 1- and 4-ms silent time conditions. The 12-ms speed is shown with a dashed line to indicate the asymptotic response speed.

tions are shown with exponential functions of the form

$$RS = RS_{\text{Max}} - A \exp(-t/\tau), \quad (2)$$

so that response speed, RS , approaches the asymptotic maximum response speed, RS_{Max} , with a time constant, τ , and free fitting parameter, A . The curves were obtained by fitting to the mean of the RT and FT data for each of the 1- and 4-ms silent-time conditions. The exponential fits describe the data well, with $R^2 = 0.9971$ and 0.9990 for the 1- and 4-ms silent-time conditions, respectively. These curves illustrate that the response speed has a more gradual approach to asymptote than does the detection data and highlights the similarity of the RT and FT data. The 12-ms gap response speed is shown on each graph in Fig. 5 with a dashed line to indicate the asymptotic response speed, which the other curves approach with increasing gap RT/FT.

C. Discussion

This experiment examined the effects on detection and response speed for gaps in noise having ramped offsets or onsets. Detection of gaps was not impaired by ramped onset of the trailing marker: for a given gap silent period, adding a ramped edge to either the leading or the trailing marker improved gap detectability and response speed, and this improvement was the same regardless of which marker possessed the ramp. This result in humans stands in contrast to the finding of Ison *et al.* (2002) in mice using the same ramped-edge gap stimuli, that ramped edges on the trailing marker impair gap detection relative to ramps on the leading marker. However, the result here is consistent, at least qualitatively, with energy or loudness detector models of gap detection (e.g., Florentine *et al.*, 1999). Examination of Figs. 3 and 5 suggests that the detectability and response speed data for different silent durations in both the variable-RT and FT conditions would superimpose if they were appropriately shifted or rescaled on the time-axis. If gap detection relies on detecting energy fluctuations of the sound envelope, then the addition of RT and FT serves to increase the effective duration of gaps. Rescaling the gap duration in terms of the silent gap plus the appropriately weighted ramp duration provides an effective gap duration,

$$t_{\text{eff}} = ST + m \text{ RT (or FT)}. \quad (3)$$

Previous studies of the detectability of partially filled gaps in broadband noise indicate that decrements of 35% to 50% of the carrier all produce MGTs of 2–3 ms (Forrest and Green, 1987) and that sound level within the gap has little effect on gap thresholds as long as the decrease in the carrier is at least 5 to 10 dB below the initial sound level (Penner, 1975; Irwin and Purdy, 1982). These studies suggest that MGT and t_{eff} are determined by the time that the envelope remains below some minimum decrement.

The weighting factor, m , in Eq. (3) reflects how much the ramp time contributes to t_{eff} . Large values of m indicate that most of the ramp contributes, and that small decrements are sufficient to enhance t_{eff} . Conversely, if large decrements in the carrier are needed in order to increase t_{eff} , then the

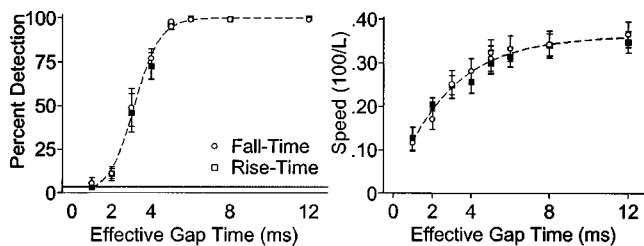


FIG. 6. Group mean detectability and response speed data with standard errors of the mean plotted against effective gap duration, $t_{\text{eff}} = ST + 0.5RT$ (or FT). Rescaling yields simple curves that collapse all the experimental data irrespective of silent gap duration or RT/FT condition.

contribution of ramps will be less and the value of m will be smaller. For linear ramps, if this minimum decrement is X in dB, then

$$m = 10^{-X/20}. \quad (4)$$

The range of m expected from these previous studies is 0.32 to 0.63 for 10- to 4-dB decrements, respectively. For $m = 0.5$, t_{eff} corresponds to the time between the 50% amplitude, or -6 dB points of the gap envelope. Figure 6 shows the detectability and response speed data of Figs. 3 and 5 replotted against this effective gap duration, using $m = 0.5$. The three different silent time data sets for both variable-RT and variable-FT conditions rescale onto a single logistic and exponential curve for the detectability and response speed data, respectively. These functions have characteristic time constants, m and τ , which have 95% confidence intervals of 2.93–3.36 ms and 2.25–3.29 ms, respectively. The rescaling yields similar characteristic time constants for the two experimental measures, supporting the conclusion that subjects were responding to effective gap duration owing to an energy detector like mechanism, and not differentially to particular features of the gap envelope. It is notable that the rescaling may not be unique. The detectability data can be rescaled with m between 0.3 and 0.55 (corresponding to decrements of 4 to 7 dB) to also produce satisfactory rescaling, such that a single sigmoidal function describes all the detection data with $R^2 > 0.990$. However, R^2 decreases rapidly for $m > 0.5$, so this value was used above for simplicity.

In this experiment reaction speeds were measured and showed a slower approach to asymptote than did the detectability data, but also demonstrated significant systematic differences among the readily detectable gaps. This is noteworthy since the method of constant stimuli usually leads to psychometric functions that are very steep around an operational threshold. While these gaps had near 100% detectability, responses to them showed differential latencies, with faster speeds for longer gaps. This increase in response speed is continuous with the process of detection, as subthreshold gaps, when detected, are responded to more slowly than the more readily detectable stimuli. Consequently, reaction speeds appear to provide a useful measure of the perceptual equivalence and salience of stimuli that are above the detection threshold, consistent with previous findings (e.g., Kohfeld *et al.*, 1981a, b).

The stimuli used in this experiment were selected to test in humans the effect seen in mouse IC single units, and also

behaviorally via prepulse inhibition, that ramped edges on the trailing gap marker led to decreased gap detectability. These mouse data depend on brainstem processing, and there is the possibility that in psychophysical experiments humans make use of cues that are not strongly coded in the brainstem, but which are perhaps more important in cortical processing. Gaps in the current experiment had at least one abrupt edge, raising the possibility that listeners made equally good use of abrupt marker offset or onset information to assist detection. Experiment 2 was designed to test the hypothesis that gaps having either a single abrupt edge or two abrupt edges have higher detectability than those with two ramped edges.

IV. EXPERIMENT 2: EFFECTS OF ZERO, ONE, OR TWO RAMPED EDGES

A. Methods

The results of experiment 1 suggest that humans do not make special use of onset information to detect brief gaps in noise with ramped edges, but rather do so by detecting overall energy fluctuations. In experiment 2, gap stimuli were constructed to compare differential detectability among gaps that should have the same detectability according to one such energy detector model, but which have zero, one, or two ramped edges.

There were seven participants in experiment 2 (five men and two women) aged between 19 and 22, with a median age of 19 years. Participants were each tested on a single day and were presented with four blocks of trials. Each block contained ten presentations of each gap type (described below) and the no-gap control so that each condition was presented a total of 40 times. Each trial block lasted approximately 9 mins and participants were given the opportunity to take a short rest between blocks.

Gaps in the noise carrier were presented on each trial, except for control trials on which there was no gap in the noise. Gaps were constructed with various combinations of ramped and abrupt edges to have equal effective gap duration, t_{eff} , using $m = 0.5$. There were two series of gaps, the “2-ms series” and “3-ms series” with t_{eff} of 2 or 3 ms, respectively. Each series consisted of five gap-types: (1) an abrupt edged gap (“square”), (2) a gap with an abrupt leading marker offset and 2-ms ramped trailing marker onset (“rising”), (3) a gap with a 2-ms ramped leading marker offset and abrupt trailing marker onset (“falling”), (4) a gap with two 1-ms ramped edges (“fast”), and (5) a gap with two 2-ms ramped edges (“slow”). To illustrate these stimuli, Fig. 7 shows the 2-ms series of gaps; the 3-ms series has the same shaped edges, but the total gap durations are 1 ms longer by extending the duration of the silent portion of the gap.

The percent detection and response speed data were each subjected to a two-way within-subject repeated measures factorial ANOVA. The two factors were (1) effective gap duration and (2) gap type, and the number of levels in each factor were, respectively, 2 and 5. Otherwise, the treatment of these data followed the pattern used in experiment 1.

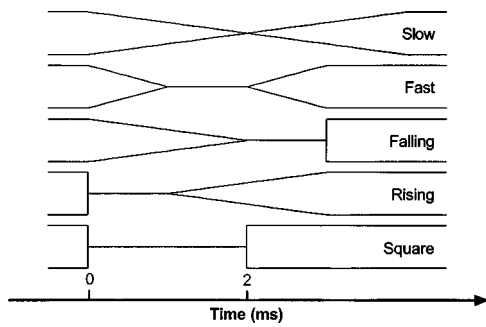


FIG. 7. Schematic representation of temporal gap stimuli used in experiment 2. All five gaps have $t_{\text{eff}}=2$ ms, according to Eq. (3) with $m=0.5$.

B. Results

Individual subject data for gap detection are shown in Fig. 8. Gap detectability increased with increasing gap duration between the 2- and 3-ms series of gaps and within series seem to show increasing detectability between the “square” and the “slow” gaps. The variability among subjects appears greater than in experiment 1. This might reflect an increase in the subjects’ decision uncertainty as the stimuli were deliberately chosen to lie on the steepest region of the psychometric function.

Mean gap detection probabilities across participants

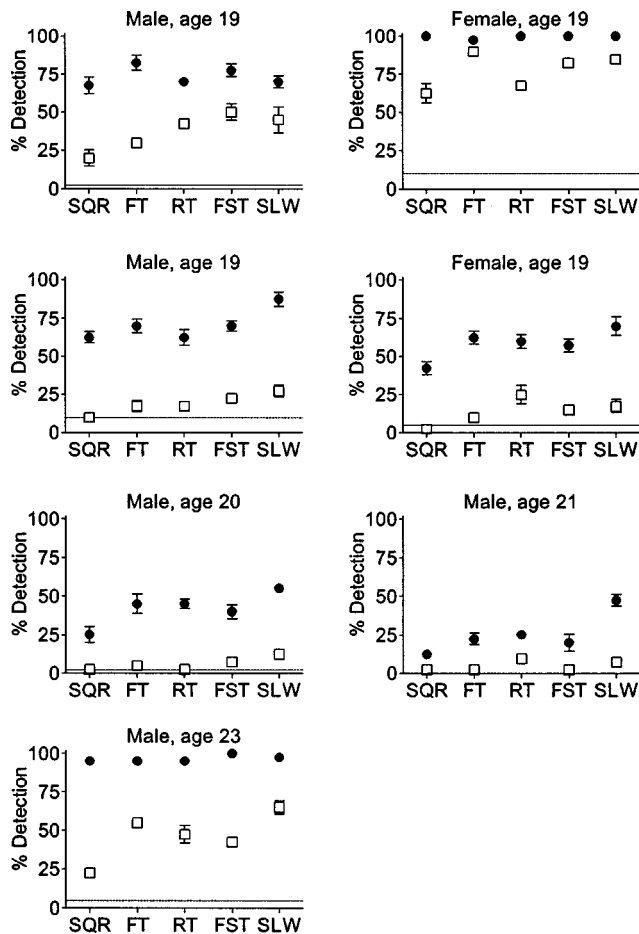


FIG. 8. Individual subject gap detection data shown for the “2-ms” (open squares) and “3-ms” (filled circles) effective gap duration series consisting of gap types “square,” “falling,” “rising,” “fast,” and “slow” depicted in Fig. 7. Data show means and standard deviations across four sessions.

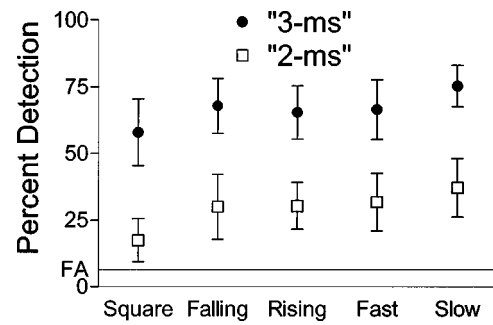


FIG. 9. Group average detectability and standard errors of the mean, for the “2-ms” and “3-ms” effective gap duration series. The within-subject standard errors are 2.7% for the 2-ms series, and 2.6% for the 3-ms series.

were calculated and are shown in Fig. 9. The ANOVA reveals a strong effect of gap duration between the two series, $F(1,6)=59.2$, $p<0.001$, and of gap type within the series, $F(4,24)=27.15$, $p<0.001$, but no interaction, $F(4,24)<1$, $p>0.97$. In order to identify the source of these differences, subsequent ANOVA were performed with particular conditions. There was a significant difference between the “square” and “falling” gaps, $F(1,6)=50.73$, $p<0.001$, and between the “fast” and “slow” gaps, $F(1,6)=8.63$, $p<0.05$. There was no significant difference among the “falling,” “rising,” and “fast” gaps, $F(2,12)<1$, $p>0.84$. Statistical power analysis indicates that this experiment had a 70% chance of detecting a difference in detectability of 5% with 95% confidence, and in fact the mean detectabilities of these three types of gap vary by less than 2%.

Response speeds (not shown) were again calculated from latencies of trials with “Yes” responses. Compared with experiment 1, speeds were more variable among subjects, but the ANOVA demonstrated significant effects of gap duration, $F(1,6)=22.99$, $p<0.01$, and gap type, $F(4,24)=3.66$, $p<0.05$, with no interaction, $F(4,24)=1.48$, $p>0.2$.

C. Discussion

In this experiment, detectability and response speeds were measured for gaps that have one, two, or no abrupt edges. Two series of gaps were designed to have the same equivalent gap duration based on Eq. (3) with $m=0.5$. While the results of experiment 2 suggest that a different value of m would be more appropriate, they confirm the findings of experiment 1, namely that human listeners (1) make use of FT and RT to increase effective gap duration and (2) do not make use of information from abrupt changes in the acoustic envelope to assist detection.

In experiment 2, differential detectability was seen between “square” and “slow” gaps, and between these and the intermediate series of “rising,” “falling,” and “fast” gaps, which were themselves not detected differently from each other. These data suggest that effective gap duration does determine detectability, but this constructed measure should not be calculated from the 50% amplitude points of the gap envelope, as chosen for simplicity in the rescaling of the data from experiment 1. A better estimate of the contribution of ramps to increased effective gap duration can be made from

the data of experiment 2 by noting that the addition of 1 ms of silence between the 2- and 3-ms “square” gaps increases detectability by 40%. In the 2-ms gap series, the “rising,” “falling,” and “fast” gaps have an average increase in detectability of 11.9% compared to the “square” gap, while the “slow” gap has an increase in detectability of 20.4%. Assuming that these gaps lie on a linear section of the psychometric function, then the extra time added to the effective gap duration by the ramps is 0.29 and 0.51 ms, for a total t_{eff} of 2.29 and 2.51 ms, respectively. Working backwards through Eq. (3), the “rising,” “falling,” and “fast” gaps each have $ST=1$ ms and RT (or FT , or $RT+FT$)=2 ms leading to a value of m of 0.645. The “slow” gap has $ST=0$ ms and $RT+FT=4$ ms, leading to a value of m of 0.628. Hence a better estimate of the effective gap duration is obtained by calculating the time between the 63%–65% amplitude points of the gap envelope, or for linear ramps $t_{\text{eff}} \approx ST + 0.64 RT$ (or FT). This new approximation is not inconsistent with the data from experiment 1, and corresponds to decrements in the gap envelope of 4 dB, which as noted also rescaled the data detectability data of experiment 1 with $R^2 > 0.990$.

Statistical power analysis of the data indicates that it is reasonable to accept the null-hypothesis, that “rising,” “falling,” and “fast” gaps are not different in their detectability. This implies that gap detection by human listeners is not assisted by abrupt edge detection cues, because the “fast” gap does not have abrupt edges, but rather has the single ramped edge of the “rising” and “falling” gaps distributed evenly on both markers. A possible situation in which this conclusion would not be valid is if the auditory system had insufficient temporal resolution to resolve envelope changes of 0-, 1-, or 2-ms duration. However, the data from the two experiments reported here show differential detection when gap features are manipulated on this time scale, indicating that the human auditory system can, in fact, resolve these ramps.

V. GENERAL DISCUSSION AND CONCLUSIONS

The experiments reported here indicate that brief gaps in noise with ramped edges are detected by human listeners according to an effective gap duration, consistent at a qualitative level with energy or loudness detector models (Florentine *et al.*, 1999). Detection is not sensitive to particular envelope features, such as abruptness of onset or offset, beyond the capacity of such features to extend the effective duration of the gap. Consequently, these data do not support the expectation that abrupt changes in envelope, specifically onset information, provide additional cues for detection beyond the energy fluctuation in the carrier associated with the gap. This finding is surprising in light of results from mouse behavior (Ison *et al.*, 2002) and IC single units (Barsz *et al.*, 1998), and also from theoretical expectations. The loudness detector model of Florentine *et al.* (1999) provides good estimates of gap detection in bandpass noise based on stationary transformation of the output of an auditory filter, with discrepancies between model and data arising for low-frequency bands. To account for this discrepancy these authors drew on extant physiological data suggesting the importance for gap encod-

ing of onset responses (Zhang *et al.*, 1990), and concluded that onset information may provide additional cues to gap detection. The two experiments reported here do not support this possibility, at least for gaps in broadband noise, and for onset information with time scales of 1 to 12 ms, which are the conditions under which onset sensitive gap detection was observed in the mouse studies.

The data here suggest that there are interesting differences between the gap detection mechanisms apparently used by human listeners compared with those reported for mouse IC neurons and for acoustic startle inhibition, which seem to depend in part on features of the gap envelope. The neural mechanisms underlying the different gap detection strategies apparently employed by mice and humans are not immediately apparent. It is possible that methods for assessing gap detection that are sensitive to brainstem processing, such as prepulse inhibition, might produce a result in human listeners that would be more like that reported for mice. It is also possible that mouse IC neurons encode effective gap duration in some way that is not yet understood, but which might have implications for the general understanding of temporal acuity in the mammalian auditory system. Certainly, the importance of timing for human speech perception, as shown, for example, in voicing onset information (e.g., Kewley-Port *et al.*, 1988), indicates that humans utilize temporal information of signal envelopes, but the results of these experiments suggest that these features might be more important for discrimination rather than for detection *per se*.

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