Monaural Temporal Interactions

HARVEY BABKOFF*
Polytechnic Institute of Brooklyn, 333 Jay Street, Brooklyn, New York 11201

SAMUEL SUTTON†
Biometrics Research, New York State Department of Mental Hygiene, 722 West 168th Street, New York, New York 10032

The monaural temporal interaction of transients was investigated by using a “mirror-image” paradigm. A pair of unequal monaural clicks in which the less intense click precedes the more intense click by a given interpulse interval (backward masking) was discriminated from an identical pair of clicks in which the more intense click precedes the less intense click by the same interval (forward masking). The functions obtained show an initial rise in discrimination as a function of increasing interpulse interval ($\Delta t$) followed by a leveling of the curve at a high discrimination level for $\Delta t$'s of up to approximately 8–10 msec, followed by a decrease in discrimination to approximately 12–15 msec, followed by a second increase in discrimination at $\Delta t$'s greater than 15 msec. Comparing the discrimination of mirror-image click pairs to forward masking and to backward masking alone indicates that monaural temporal interactions exist at intermediate interpulse intervals even though forward and backward masking are no longer evident. At these intervals, the discrimination is unrelated to the perception of temporal order. The shape of the functions and the $\Delta t$ range over which it is evident are dependent upon the relative intensities of the two clicks comprising the pair. At longer intervals (greater than 15 msec), perception of temporal order is the dominant cue. Possible mechanisms are discussed.

INTRODUCTION

Masking experiments with transients involve a more intense (“masking”) stimulus, a less intense (“probe”) stimulus, and a temporal interval ($\Delta t$) separating the two stimuli. Masking may occur in either the forward (more intense stimulus precedes the less intense stimulus) or backward (less intense stimulus precedes the more intense stimulus) direction. The traditional view of masking has been that it involves a decrease in auditory sensitivity (measured by a probe or masked stimulus) brought about by an intense or masking stimulus. Presumably, the masking stimulus serves to prevent or diminish the neural registration of the probe stimulus at peripheral and/or central loci in the auditory system. The probe stimulus in this view is essentially the psychophysical tool for measuring the temporal extent and form of the decrement in neural sensitivity.

An alternative view emphasizes that the important feature of masking is the amount and extent of interaction between masking and probe stimuli of various intensity levels and interpulse ratios. Implicit in this view is the notion that spatiotemporal patterns of neural activity evoked by both members of the pulse pair (masking and probe stimuli) may be present in the auditory system even at very short interpulse intervals. However, the means by which sensory information is processed in time allows for interaction within the sensory channel of the peripheral or neural correlates of the masking and probe stimulus. It is the nature of this interaction at short interpulse intervals which gives rise, behaviorally, to masking phenomena.

By focusing on the concept of interaction between the more intense and the less intense members of a pulse pair, it becomes possible to formulate a further question: Is interaction necessarily over at the $\Delta t$ separation at which a pulse pair may be discriminated from a single pulse, or can one obtain evidence for interaction beyond the interpulse intervals at which such discrimination is possible? Our approach to answering this question was to design a discrimination experiment utilizing “mirror-image” pulse pairs. Figure 1 illustrates the three stimulus paradigms we have used to study monaural temporal interaction by manipulating interpulse interval as the independent variable and using the
three-alternative temporal forced-choice (3ATFC) as the psychophysical method. The first two panels marked “Forward Masking” and “Backward Masking” illustrate the paradigm used in a previous study (Babcock and Sutton, 1968) in which three sets of stimuli are presented in each trial. The test stimulus (T) consists of a pair of unequal level monaural clicks, the first of which is more intense, separated by variable amount of time, $\Delta t$, while the comparison stimuli (C) consist of single clicks equal in level to the more intense (first) member of the test stimulus pair. The temporal order of the three stimuli is varied randomly from trial to trial and the subject is instructed to select the stimulus that is different from the other two. In the forward-masking paradigm, the more intense click precedes the less intense click, while in the backward-masking paradigm, the comparison stimuli are the same, but the test stimulus differs in that the less intense click precedes the more intense click by a variable amount of time. The subject’s instruction is the same, i.e., to select the stimulus that is different from the other two.

The mirror-image paradigm is illustrated in the right-hand panel of Fig. 1 marked “Backward versus Forward Masking”. In this paradigm, the subject is required to discriminate a pair of unequal level monaural clicks (the test stimulus), in which the less intense member of the pair precedes the more intense member of the pair (backward masking) from two other monaural pairs of clicks (the comparison stimuli) in which the more intense member of the pair precedes the less intense member of the pair (forward masking). The members of both the test and comparison pairs of stimuli are separated by the same interpulse interval. The subject is instructed to respond in the same way, i.e., by selecting the stimulus that is different from the other two. Thus, in this design: (1) the total energy in the test and comparison stimuli is always the same; (2) both test and comparison stimuli consist of the same number of clicks; and (3) the temporal interval ($\Delta t$) separating the less intense from the more intense click is always the same for the test and the comparison stimulus. That is, when $\Delta t$ is manipulated for one pair (test), it is manipulated in an equivalent manner for the other pairs (comparison). This design allows the study of intrapulse interactions that may be present, even though the subject may be able to discriminate such pulse pairs (either forward- or backward-masking mode) from a single pulse.

What predictions can be made for an experiment that requires the subject to discriminate mirror-image pulse pairs from one another? In our previous experiment (Babcock and Sutton, 1968) we found that forward masking is much more extensive than backward masking, and that for the backward mode, masking, even for the largest interpulse ratio (masking click, 70 dB; probe click, 15 dB) does not extend beyond 2.5-3.0 msec. For smaller interpulse ratios, it ends even earlier. If interactions between the members of pulse pairs terminate when the pulse pair can be discriminated from the masking (more intense) pulse alone, we should expect that once the forward-masking mode can be discriminated from a single pulse and the backward-masking mode can also be discriminated from a single pulse, discrimination between the mirror-image pairs should fail, since there is no basis upon which to discriminate the two modes from one another, unless, of course, temporal order can be discriminated, i.e., if the subject can perceive that in the forward-masking mode the more intense stimulus precedes the less intense one and identify this order as different from the order of stimuli in the backward-masking mode. However, previous studies in the area of temporal discrimination (Hirsh, 1959; Hirsh and Sherrick, 1961; Babcock and Sutton, 1963; Rutschmann and Link, 1964; Rutschmann, 1966;
Fig. 2. Data for subject JL incorporating the three experimental paradigms illustrated in Fig. 1. Percent correct discrimination (corrected for chance guessing) is plotted on the ordinate as a function of interpulse interval (Δt in milliseconds) on the abscissa in logarithmic steps. On the left, the interpulse ratio is 25 dB; the sensation level of the more intense click is 40 dB, of the less intense click, 15 dB. The parameter is the masking paradigm: forward masking, backward masking, and backward versus forward masking (note Fig. 1 for explanation). On the right, the sensation level of the more intense click is 60 dB, of the less intense click, 35 dB. Interpulse ratio (Δt, the ratio of the more intense to the less intense click) is thus 25 dB.

Thor, 1968; Homick, Elfen, and Bothe, 1969) indicate that unless interactions of some sort exist between two stimuli, the ability to discriminate temporal order is not manifested behaviorally until the stimuli are separated from each other by 15–20 msec. If, however, interaction between members of the pulse pairs constituting the two masking modes has not terminated even though masking has ended, then one may still be able to discriminate the two modes from one another at temporal separations that extend beyond the range within which each mode is discriminable from a single pulse.

I. APPARATUS AND METHOD

The apparatus permitted independent control of the order of the members of a click pair, and the intensity and temporal relationships of the monaurally presented clicks, as well as the length of the intertrial intervals and the intervals between test and comparison stimuli. The apparatus, the frequency response of the earphone (Sharp HL-10 circumaural), and the acoustic characteristics of the click are described elsewhere (Babkoff and Sutton, 1966, 1968).

The subject was seated in a sound-treated booth. A panel in front of the subject had a warning light and three feedback lights marked 1, 2, and 3 aligned with three response buttons. A trial consisted of the presentation of three stimuli. The three stimuli were spaced 0.53 sec apart. The subject was instructed to listen to all three stimuli, to choose which one of the stimuli differed from the other two, and to record his choice by depressing the response button corresponding to the temporal position of the "different" stimulus. If the choice was correct, the light aligned with the depressed button automatically turned on, informing the subject of the correctness of his choice. The psychophysical method was, thus, a 3ATFC procedure with knowledge of results.

The choice of the 3ATFC technique as the psychophysical tool in our investigation of monaural temporal interaction depends upon its ability to provide: (1) a correction for chance guessing and (2) a more sensitive measure of threshold (e.g., often half the value obtained with the method of constant stimuli; see Blackwell, 1953; Lewis, 1967; Kietzman and Sutton, 1968). These aspects of the 3ATFC, however, are fulfilled by the fact that within each trial, the test stimulus may occur randomly in any one of the three temporal intervals, and its occurrence within each interval is equally probable. Within these limits, however, the independent variable (Δt in this experiment) may be randomized by trial, or Δt may be fixed within a block of trials and blocks of different Δt's may be randomized within and across experimental sessions. Since a comparison of both methods within the same well-trained subject yielded no evidence of differences, data collected by both methods are presented below. However, for a given subject, only one of these modifications of the 3ATFC method is used for all experimental sessions. All comparisons of experimental results for the same subject are therefore made with reference to the same method.

II. RESULTS

A. Experiment I

We obtained data on two subjects incorporating the three experimental paradigms illustrated in Fig. 1.

The data for these subjects are shown in Figs. 2 and 3 plotted as percent correct discrimination corrected for chance on the ordinate as a function of interpulse interval (Δt) in milliseconds on the abscissa. Data were collected for several different levels of the more intense click as well as for several different interpulse intensity ratios (Δt, the ratio of the more intense to the less intense click). For the subject JL, the paradigm to be tested (e.g., forward, backward, and backward versus
forward) was randomized by blocks within an experimental session. Both the independent variable, $\Delta t$, and the temporal position of the test stimulus were randomized by trial. Each point in Fig. 2 is based on an $N$ of 60. For subject SK (Fig. 3), the order of experimental paradigms to be tested was randomized by blocks within a session. The independent variable $\Delta t$ was also randomized across blocks for each experimental paradigm, and the temporal position of the test stimulus was randomized by trial. Each point in Fig. 3 is based on an $N$ of 50.

The data indicate that, as found in previous studies, for all conditions masking of transients is greater for the forward than for the backward mode. This is seen by the fact that the curve for the forward-masking paradigm is displaced to the right (in the region of longer $\Delta t$'s) of the curve for the backward-masking paradigm. The extent of masking depends upon masking click intensity as well as interpulse ratio.

The result of interest, however, is the fact that the curves for the backward- versus forward-masking paradigm also rise with the other curves, indicating increased discrimination as $\Delta t$ increases from 1 to 3 msec. This curve, however, is a nonmonotonic function of $\Delta t$. The curve either remains at a high (80%–100%) discrimination level as $\Delta t$ increases to 5–6 msec for high interpulse ratios, and then decays (i.e., discrimination fails) as $\Delta t$ increases further, or the curve drops to a low discrimination level at rather short $\Delta t$'s for low interpulse ratios. The role of interpulse ratio is investigated in Expt. II. The important aspect of the mirror-image data, however, is that they indicate that at high interpulse ratios monaural temporal interactions exist at short interpulse intervals even though forward and backward masking are no longer evident. This is evidenced by the fact that although both the forward- and backward-masking paradigms are easily discriminable from the comparison stimulus (which is equal in level to the more intense member of the test pair), at interpulse intervals longer than 3 insec the percepts generated by the two types of stimulus configurations (the backward mode as compared to the forward mode) are sufficiently different so that they are almost as easily discriminable from one another as each is discriminable from a single click. This is seen much more clearly with the higher interpulse ratios. Note especially the right half of Fig. 3, in which the interpulse ratio ($\Delta I$) is 30 dB. Under these conditions, the backward-masking mode is discriminable from the forward-masking mode at levels of from 90% to 100% from $\Delta t$'s of 3–7 msec, although both the forward- and backward-masking modes are equally well (100% level) discriminable from a single pulse at these temporal separations. Discrimination of the backward mode from the forward mode then drops to 50% as $\Delta t$ is increased to 10 msec, while the forward-masking mode and the backward-masking mode are each easily discriminable from a single pulse (at a 100% level of discrimination).

**B. Experiment II**

The second study was undertaken to help specify some of the stimulus parameters that may be involved in this type of discrimination of mirror-image pairs of unequal level transients. In this investigation, two well-trained subjects were tested on the forward- versus backward-masking paradigm at several different interpulse ratios as well as at several different intensity levels. The interpulse intervals ($\Delta I$) ranged from 0.5 to 14 msec. The experimental method was again a 3ATFC technique. For both subjects, $\Delta I$ was randomized by trial, and the experimental conditions (i.e., the different interpulse ratios and intensities) were randomized by block. A block consisted of 50 trials.

In Fig. 4, the data are plotted as percent correct discrimination on the ordinate as a function of the interpulse interval ($\Delta I$) in milliseconds on the abscissa. Data
for subject JR ($N = 60$ per point) are plotted on the left of Fig. 4; data for subject AN ($N = 55$ per point) are plotted on the right of Fig. 4. The parameter of the curves is interpulse ratio; the different panels within a figure depict data for different intensity levels. The data in Fig. 4 have the same general shape as the data for the forward- versus backward-masking mode shown in the previous figures, i.e., an initial rise in discrimination level at the very short $\Delta t$'s, followed by an asymptote or leveling at a high discrimination level, followed by a decrease in discrimination as $\Delta t$ is increased still further. The point to be noted is that the major effect of increasing the interpulse ratio at all of the intensity levels used in this study (ranging from 30 to 70 dB) is to shift the entire function to the right, i.e., to a longer $\Delta t$ range. This point should be emphasized because shifting the entire function to the right results in a continuation of a high discrimination level into a longer $\Delta t$ range. Thus at the shorter $\Delta t$'s, e.g., 2.0 msec, the discrimination of the backward- from the forward-masking mode is at a higher level when the interpulse ratio is 10 dB than when the interpulse ratio is 35 dB, while at the longer $\Delta t$'s, e.g., 6–8 msec, the discrimination of the backward- from the forward-masking mode is at a higher level when the interpulse ratio is 35 dB than when the interpulse ratio is 10 dB.

C. Experiment III

The following experiment was performed on one well-trained subject (SK) using the 3ATFC random by block design described above to examine the shape of the curve relating the discrimination of backward from forward masking to interpulse interval when the interpulse interval is extended to 20–24 msec.

Fifteen different experimental conditions were tested in this experiment. The level of the more intense pulse ranged from 20 to 60 dB. Data for these experimental conditions are shown in Fig. 5. Each point is based on an $N$ of 50. Data are grouped by $\Delta I$ (column) and by the level of the more intense stimulus (row) to facilitate comparison. Note that all of the functions showing data for a $\Delta I$ of 20 dB and above show an initial ascending limb followed by a leveling at a high discrimination level, followed by a descending limb, followed finally by a second ascending limb. Note, finally, that the descending limb of the function does not approach 0% discrimination level for $\Delta t$'s of 20 dB or more before the curve begins to show the second ascending limb. That is, the effect of a large displacement to the right (effected by increased $\Delta I$) is to reduce the dip in the right descending limb of the function (i.e., to reduce the decrease in discrimination level). The descending

The Journal of the Acoustical Society of America 463
The data presented above (Figs. 2–4) indicate that interaction between the members of pulse pairs of unequal intensity extends into a Δt range in which masking in the formal sense is no longer evident and that the extent of this interaction is a function of the interpulse ratio. These data are, therefore, consistent with the hypothesis stated in the introduction that spatiotemporal patterns of neural activity evoked by both the more intense and the less intense members of the pulse pair are present in the nervous system even at very short interpulse intervals. The means by which sensory information is processed in time allows for interaction within the sensory channel of the neural correlates of both members of the pulse pair. It is the nature of this interaction that gives rise to the discrimination phenomena at intermediate interpulse intervals which is revealed by the mirror-image discrimination technique.

What is the nature of this interaction that extends from 3 to 8 or 10 msec? Since the Δt range within which this interaction is evident is shorter than 15–20 msec, it appears reasonable to conclude on the basis of the literature cited above that the subject’s ability to perceive the temporal order of the stimuli (i.e., whether the less intense pulse precedes or succeeds the more intense pulse) is not the basis of his ability to discriminate mirror-image pulse pairs. The shape of the functions (Figs. 2–5) also support this contention, since the discrimination of temporal order, when it is not dependent upon some complex interaction of the two stimuli whose order is to be perceived, is a monotonic function of interpulse interval (Hirsch, 1959; Hirsh and Sherrick, 1961; Babkoff and Sutton, 1963; Rutschmann, 1966; Thor, 1968; Homick, Elfen, and Bothe, 1969).

The fact that in these data there is a decrease in discrimination as Δt is increased argues against the presence of a temporal order cue in the 3- to 8-msec range and indicates that it is the difference in interaction between the two masking modes that generates different perceptual cues and allows for the discrimination between the two masking modes. This interaction is a decreasing function of interpulse interval. Therefore, as Δt increases beyond 10 msec, the extent of interaction between the more intense and less intense members of the pulse pair decreases, and the difference between the perceptual cues generated by the two masking modes decreases, thus resulting in a decrease in discrimination level. Since at these intervals (Δt's shorter than 15 msec) temporal order cannot yet be distinguished, it cannot serve as a cue to discriminate the backward-from the forward-masking modes.

This interpretation implies that within the context of this experiment further increases in the temporal interval beyond the Δt at which the function returns to a low discrimination level should yield a second increase in discrimination level, since at longer Δt's temporal order can be perceived. The data presented in Fig. 5 are consistent with this prediction for all of the interpulse ratios studied in this experiment (10–50 dB).

The effect of increasing interpulse ratio is to displace the entire function to the right, i.e., into a longer Δt range. Furthermore, as emphasized above, the effect of a large displacement to the right (effected by increased Δt) is to reduce the extent of the dip in the descending limb of the function, i.e., to reduce the decrease in discrimination level (Fig. 5). The descending limb appears to merge and interact with the second rising limb of the function. This effect is more readily seen with Δt's of 30 dB and higher. A very striking example of this effect is seen for a Δt of 30 dB in which the level of the more intense pulse is 40 dB (third column, third row). This curve shows an even clearer merger of the descending and ascending limbs of the curve as there appears only a slight drop in discrimination level to 70% at a Δt of 14 msec as Δt is increased from 3 to 24 msec.

A very recent use of the forward-versus backward-masking paradigm was made by Ronken (1970) to study detection of a phase difference between idiochically presented transients. He based his study on the fact that although the power spectra of the two masking paradigms are equivalent, they have different phase spectra. Ronken used the PEST (parameter estimation by sequential testing) technique introduced by Taylor.
and Creelman (1967), which consists of manipulating the interpulse ratio ($\Delta t$) to obtain a given level of discrimination between the forward- and backward-masking paradigms at four fixed interpulse intervals ($\Delta t$: 1, 2, 5, and 10 msec). Ronken limited his investigation to a pulse sensation level of 56–57 dB. Although the PEST technique may be preferred when the experimental objective is a quick determination of a threshold, the dependence of this technique on the manipulation of $\Delta t$ effectively limits the range of investigations to the $\Delta t$ of 10 dB (the highest average threshold sound by Ronken). The dynamics of the entire psychometric function relating forward to backward masking over a large $\Delta t$ range, the effects of $\Delta t$ greater than 10 dB, and the interaction of interpulse ratio and of interpulse interval are not detectable by the use of this technique.

While it is not straightforward to argue from Ronken's data (diotic presentation of stimuli) to our monaural findings, nevertheless the possibility of similarity in mechanisms should be considered. We, therefore, carried out a computer simulation of phase spectra equations arising from mirror-image pulse pairs to test the possibility that phase spectra differences were large enough to account for our findings. Our computer simulation indicates that changes in the differences in phase spectra as a function of $\Delta t$ are minimal with interpulse ratios of 20 dB or greater at any interpulse separation. Therefore, it appears that such differences could not account for decreases in discriminability found for the intermediate range of $\Delta t$'s (i.e., the decreasing limb of the functions) at the higher interpulse ratios.

**IV. SUMMARY**

In summary, the experiments reported in this paper lend supporting evidence to the concept that masking does not necessarily involve merely the decrement in auditory sensitivity caused by intense stimulation. The data presented lend validity to the hypothesis that there is interaction between the more intense and less intense members of the pulse pair even when masking in the formal sense is no longer evident. The ability to discriminate between the forward- and backward-masking modes at the intermediate interpulse intervals (3 to 8 or 10 msec) is interpreted as arising from the fact that interaction between the members of a pulse pair differs for the two modes. This interaction would also appear to be due to central rather than peripheral mechanisms, since it occurs for interpulse intervals as long as 8–10 msec. Yet, because these intervals are sufficiently short, the interaction is likely to be "sensory" rather than attentional in its nature.

**ACKNOWLEDGMENTS**

This research was supported by the Public Health Service, U.S. Department of Health, Education, and Welfare. The authors are indebted to Robert Laupheimer and Raymond Simon for their assistance with the equipment, to Malcolm McCullough for his assistance in the program simulation of phase spectra equations, and to Dr. Morton Wallach, Director of Brooklyn State Hospital, for the provision of facilities, which made this research possible.

---

†Dep. Psychology, Columbia Univ.

*This correction took into consideration the fact that the subject could make the correct choice with an a priori probability of 0.33 on the basis of chance alone. A further adjustment was made to extend the range of values from 0% to 100%. The adjusted percent was computed as (PERCENT CORRECT − 0.33)/(1 − 0.33).

**REFERENCES**


