

Perceptual Development and Auditory Backward Recognition Masking

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Three amplitude-discrimination experiments within a backward masking task were carried out to study whether young children have a slower rate of perceptual processing than do adults. Rate of processing was defined within an explicit model of perceptual performance that allows the investigator to determine if rate is responsible for developmental differences in auditory discrimination. A developmental difference in discrimination ability was compensated for by increasing the psychophysical difference between the test tones in the backward masking task. No developmental differences in rate of perceptual processing were observed. A quantitative model of perceptual processing gave similar estimates for the rate of perceptual processing in children and adult subjects. Although there are differences in discrimination ability, there appear to be no differences in rate of perceptual processing for children and adults.

In the present study, we examined the development during childhood of auditory perceptual processing, auditory discrimination in particular. Our concern was with the temporal course of the initial stage of processing involved in encoding and perceptual recognition. There is a popular belief that young children have a slower rate of perceptual processing than do older children for both visual (e.g., Blake, 1974; Morrison, Holmes, & Haith, 1974) and auditory (Tallal, 1973) information. The consequences of such age differences would be particularly significant in the case of auditory processing. That is, in visual processing in reading, for example, a slower rate of processing could be compensated for by longer fixation times. In contrast, in auditory processing of speech, a slower rate of processing may not be compensated for because it is not always possible for the listener to control the duration of spoken language. Despite this apparent importance for language development, the development of temporal aspects of auditory processing has received relatively little empirical investigation.

The empirical support for age differences in rate of perceptual processing is complicated by the possibility of other processes contributing to the obtained age differences in performance. For example, older children have faster auditory word-recognition latencies (Cirrin, 1983, 1984; Tyler & Marslen-Wilson, 1981) and identify synthesized syllables at faster presentation rates (Tallal, 1973). Although consistent with age-related increases in the rate of auditory processing,

these findings may also reflect age-related differences in auditory discrimination. Although infants discriminate most phonetic contrasts (Aslin, Pisoni, & Jusczyk, 1983), both phonetic discrimination and spoken word recognition improve during childhood (Burke, 1975; Templin, 1957; Wepman, 1958). Indeed, the absolute threshold for auditory perception decreases during childhood (e.g., Roche, Siervogel, Himes, & Johnson, 1978), and there is improvement in other auditory sensory processes such as temporal acuity (Irwin, Ball, Kay, Stillman, & Rosser, 1985). Thus, younger children may require more time for auditory perceptual processing because discrimination and identification of the stimulus is more difficult for them. Isolating age differences in rate of processing requires accounting for the difficulty of the identification across age.

In this study, we explored the development of auditory perceptual processing by examining children's ability to identify pure tones in a backward masking task. The backward masking paradigm has been a valuable technique for examining the temporal course of perceptual processing of visual (Breitmeyer, 1984) and auditory (Kallman & Massaro, 1983) stimuli. In auditory backward recognition masking, a brief target stimulus is followed, after a variable interstimulus interval (ISI), by a second stimulus (the mask). The amount of time that the target information is available in preperceptual memory can be carefully controlled by manipulating the duration of the ISI. The accuracy of young adults' target identification increases as ISI lengthens to about 250 ms. (Cowan, 1984; Hawkins & Presson, 1986; Kallman & Massaro, 1983; Massaro, 1970b).

The backward masking results have been explained in the framework of a model of auditory information processing in which the target sound is transduced by the listener's sensory system and stored in a preperceptual auditory store that briefly holds a single auditory event (Massaro, 1972, 1975a). Processing of the target sound is necessary for perceptual recognition. The mask replaces the target in the preperceptual auditory store and terminates any further reliable perceptual processing of the target, but it does not work retroactively. Masking does not reduce the amount of information that is obtained before the occurrence of the mask; it can only preclude further processing.

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In backward masking, young adults' performance typically asymptotes at an ISI of roughly 250 ms, and this interval has been interpreted as reflecting the duration of the preperceptual auditory store (Cowan, 1984; Kallman & Massaro, 1983). That is, the mask no longer affects performance because the preperceptual trace is no longer available for processing. A slower rate of perceptual processing for children, a shorter duration for preperceptual memory, or both would lower the accuracy of perceptual recognition. On the other hand, if the duration of the preperceptual store and processing rate are constant across age, performance of both children and adults should asymptote at 250 ms.

Although the question addressed in this article is primarily an empirical one, its interpretation is fundamentally a theoretical matter. The result of central interest is the increase in performance accuracy with increases in ISI. Our interpretation of this result is that subjects have continuous information about the test stimulus and that this information accumulates gradually with the processing time available before the onset of the mask. The rate and asymptote of the masking function can only be interpreted in the framework of a quantitative model of the perceptual recognition process (Anderson, 1963; Massaro, 1970b). In such a model, it is essential to distinguish between the potential information that is given unlimited processing time and the rate of reaching that level of information (Massaro, 1977). Increasing the discriminability between the test alternatives should increase the asymptote but not necessarily the rate of the masking function.

The three masking functions shown in Figure 1 represent the performance of 3 different young adults in the first study of auditory backward recognition masking (Massaro, 1970a). The two test alternatives were brief tones (20 ms) differing in frequency, and the subjects identified the test tone as high or low in pitch. Performance was measured in d' values rather than percentage correct to provide a more valid measure of perceptual processing. Relative to percentage correct, d' values have been shown to be less contaminated by decision biases in the task (Green & Swets, 1966; Massaro, 1989). The d' measure can be conceptualized as the z -score distance between means of two distributions of events corresponding to the two different test tones. Larger d' values correspond to a greater distance, which signifies better discrimination between the two test tones. The masking function gives the changes in this discrimination. The functions in Figure 1 can be described accurately by a negatively accelerated exponential growth function of processing time.

$$d' = \alpha(1 - e^{-\theta t}). \quad (1)$$

The parameter α is the asymptote of the function and θ is the rate of growth to the asymptote. The value e is the natural antilogarithm of 1. This function can be conceptualized as representing a process that resolves some fixed proportion of the potential information that remains to be resolved per unit of time. The same increase in processing time gives a larger absolute improvement in performance early compared with late in the processing interval.

In practice, however, the individual differences are usually much larger than those shown in Figure 1. In that case, it is

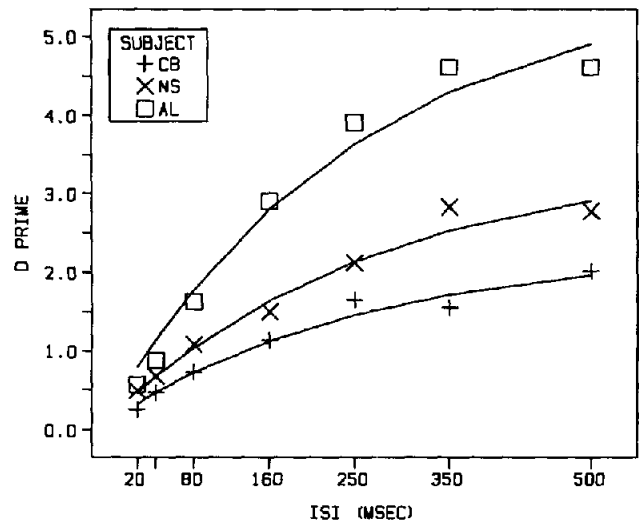


Figure 1. Identification of the test tone, measured in d' units as a function of the silent interval between the test and masking tones: results for three subjects. (ISI = interstimulus interval. From "Perceptual Processes and Forgetting in Memory Tasks" by D. W. Massaro, 1970, *Psychological Review*, 77, p. 559. Copyright 1970 by the American Psychological Association. Adapted by permission.)

necessary to adjust the difficulty of the task for each subject individually—usually by adjusting the physical differences between the test tones in the masking task. Figure 2 gives some representative results for 3 different subjects (Kallman & Massaro, 1979). Large individual differences were found, and it was necessary to titrate the difference between the test tones to eliminate floor and ceiling effects in the task. Using this procedure, it is possible to measure performance in a range in which the rate of processing can be reasonably determined.

The three curves in Figure 1 and in Figure 2 can be accounted for by differences in asymptote, with no differences in rate (Massaro, 1970b). In Figure 1, the differences in asymptote are reflected in differences in α , whereas in Figure 2, the differences in asymptote are reflected in the differences between the two test tones. Thus, the distinction between asymptote and rate provides a more refined interpretation of well-known differences among individuals in the processing of pitch and other attributes of tones. The success of the model in accounting for individual differences in terms of asymptote, rather than of rate, also presents the possibility that developmental differences might exist for asymptote but not for rate. There is, however, little evidence on this issue because there have been no developmental studies of auditory backward recognition masking.

Several studies of visual backward masking have reported that identification of the target usually improves with increases in the ISI but that older children or adults show a larger improvement than do younger children (e.g., Blake, 1974; Gummerman & Gray, 1972; Liss & Haith, 1970; Miller, 1972; Welsandt, Zupnick, & Meyer, 1973). The most popular conclusion from these results is that the rate of processing increases during childhood. However, this conclusion is weakened because, in general, these studies did not equate the difficulty of stimulus identifi-

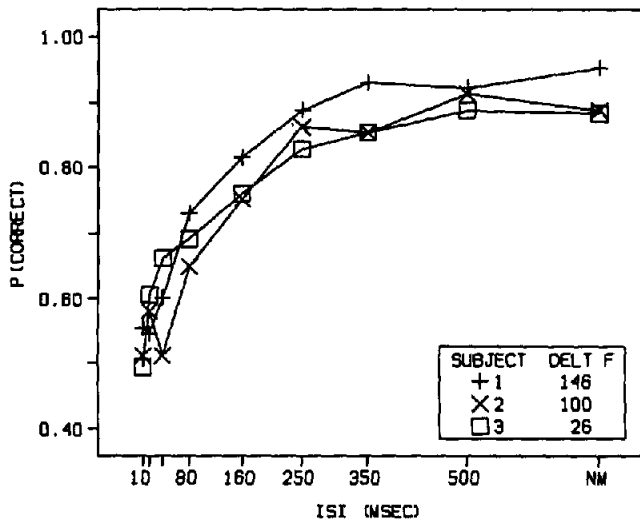


Figure 2. Percentage of correct identifications of the test tone as a function of the silent interval between the test and masking tones. (The Δf values give the frequency difference that was required for each of the three subjects. ISI = interstimulus interval. From "Similarity Effects in Backward Recognition Masking" by H. J. Kallman and D. W. Massaro, 1979, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 5, p. 118. Copyright 1979 by the American Psychological Association. Adapted by permission.)

cation across age. Young children asymptoted at a lower performance level (Miller, 1972) or had poorer performance in no-mask conditions (Blake, 1974), suggesting that identification of the stimulus was more difficult for them independent of the time available for processing. In other studies, the level of performance at very long ISIs or on no-mask trials was at ceiling across age (Welsandt et al., 1973). With ceiling effects, one cannot assume that the difficulty of the identification task is equivalent across age because the performance ceiling can camouflage any differences in asymptote that may be present. Other visual masking studies have shown that older children achieve a specified level of accuracy at a shorter ISI than do younger children (Arnett & DiLollo, 1979; Nettelbeck & Wilson, 1985), but this effect cannot be attributed to processing-rate differences because the difficulty of the task was not equated across age. A more appropriate method for studying rate of processing in these tasks without a confounding of identification difficulty is to adjust exposure duration or intensity to equate performance at a level below ceiling at very long ISIs or on no-mask trials.

In a masking study by Lawrence, Kee, and Hellige (1980), the size of the target was adjusted separately for kindergarteners, third graders, sixth graders, and college students to give 75% correct recognition on no-mask trials. The target was an arrow pointing in one of four directions; smaller arrows had to be used with older subjects to equate identification performance with that of the younger subjects. Using these stimulus conditions, Lawrence et al. did not obtain the Age \times ISI interaction found in previous studies. When Lawrence et al. used a target that gave 100% correct recognition with no mask for all subjects, an Age \times ISI interaction occurred, reflecting a more

rapid improvement across ISI with increasing age. If the interaction had been caused by age differences in rate of processing, then it should have occurred when the difficulty of target identification was controlled at 75% correct on no-mask trials. The interaction might have been simply the result of younger children's having a more difficult discrimination task, even though all groups were at performance ceiling with no mask. Lawrence et al. also found age differences in forward masking when performance was at performance ceiling, and they concluded appropriately that this result also precluded attributing the backward masking findings to differences in rate of visual processing. Although developmental differences occur, these differences do not necessarily mean that children have slower rates of visual information processing than do adults. We agree with Wickens (1974) that "some irreducible maturational differences in processing are present" (p. 739). In the spirit of Lawrence et al.'s study, the goal of the present study was to identify the locus of these age differences in auditory discrimination.

The three experiments converged on an optimal method of controlling for overall performance differences between children and adult subjects. In Experiment 1, the difficulty of the task was adjusted to give near-perfect performance on a block of no-mask trials presented before the experimental trials. In Experiment 2, the difficulty of the task was adjusted during the first 2 days of the experiment to give near-perfect performance on no-mask trials. In Experiment 3, the difficulty of the task was continuously adjusted throughout the experiment to give an average of 75% correct performance.

Experiment 1

Method

Subjects. Three 8-year-old children of university faculty and staff and 3 university students (ages 20, 26, and 29 years) were subjects. All subjects in this and the subsequent experiments were able to perform the task, so that no subjects were eliminated. Each subject had four experimental sessions and was paid for his or her participation using a payoff scheme based on the number of correct responses. Payment ranged from \$1.00 to \$3.50 per session for each subject.

Materials and apparatus. The stimuli were recorded on audiotape using a digitally controlled oscillator (Wavetek model 155) controlled by a PDP-8/L computer. During the experimental sessions, a Sony TC-270 tape recorder was used with Grason Stadler attenuators calibrated in 1-dB steps to each channel. The attenuators allowed the intensity of each channel to be independently adjusted. Output from the attenuators was mixed and presented binaurally through headphones.

Each trial consisted of a standard tone, a comparison tone, and, except on no-mask (NM) trials, a masking tone. The standard and comparison were 20-ms 1000-Hz sine waves separated by a 500-ms silent interval. The mask was a 200-ms 1000-Hz triangle wave that followed the comparison tone on $\frac{1}{8}$ of the trials by a variable ISI of 10, 40, 80, 160, 250, 350, or 500 ms. On $\frac{1}{8}$ of the trials, no mask was presented. These eight "masking" conditions occurred with equal probability. There were 6 s between trials, during which time the subject responded.

For "same" trials, the standard, comparison, and masking tones were recorded on Channel 1, and for "different" trials, the standard and masking tones were recorded on Channel 1 and the comparison tone on Channel 2. The attenuator for Channel 1 was set at a fixed level

for all subjects during all sessions. Thus, the standard and comparison on "same" trials remained at a fixed intensity, as did the standard on "different" trials and the mask on all trials. The attenuator controlling Channel 2 (i.e., the comparison on "different" trials) was adjusted for each subject. The level of the standard and comparison was about 84 dB SPL. On "different" trials, the comparison was attenuated from this initial level.

Procedure. In the first session, a difference threshold was determined for each subject. There were 512 trials with the standard and comparison tones but with no mask. An ascending and descending method of limits was used to determine the amount of attenuation of the comparison required for the subject to detect a loudness difference from the standard. The goal was to converge on the minimum intensity difference that gave threshold performance of 100% correct. Subjects were instructed that sometimes the two tones would be the same loudness and that sometimes the second tone would be a little softer. They were told to respond *same* or *different*; if they were not sure, they were to take a guess. They were told that they would receive 1¢ for each correct response, and after each response, they were told whether or not it was correct.

In the second session, subjects received 96 no-mask trials and then 432 masking trials. The intensity of the comparison tone was reduced 5 dB below the difference threshold value determined in the first session. This was necessary because pilot work had shown that the difference threshold for no-mask trials was too difficult a discrimination during the masking trials. Before the masking trials, subjects were instructed that there would now usually be a third tone as well but that their task was the same and that they should try to ignore the third tone. Again, they were told to respond on each trial and to guess when unsure, and feedback was given after each response. An essential part of the materials, at least for the younger subjects, was \$5.00 of nickels and pennies piled in front of the experimenter. Periodically, an appropriate amount, depending on the number of correct responses, would be moved to the subject's pile. With the younger subjects, a break was taken at frequent intervals during all sessions to calculate their earnings, count out the correct coins, and place them in a pile.

The third and fourth sessions each consisted of 432 masking trials and provided the experimental data. For most subjects, a session could be completed in about 1 hr and could be done in a single day. For the younger subjects, however, it was occasionally necessary to extend a session over 2 days when it became clear that they could not sustain their concentration at one sitting. Testing for each subject was completed within 1 week.

Results

The difference threshold for each subject is shown in Table 1. The younger subjects had higher thresholds, and these values do not overlap for the two age groups. That is, the children required a greater difference in intensity between the standard and comparison to perform as accurately as the adults. The mean performance during the initial 96 no-mask trials in Session 2 using these threshold levels was 96% correct for 8-year-olds and 98% correct for adults.

The percentage correct at each ISI is shown in the left panel of Figure 3 for each age group for the third and fourth experimental session combined. The first 16 trials in each session were eliminated from the analysis, yielding a total of 104 trials over both sessions for each subject at each of the ISI masking conditions (including NM), or a total of 312 observations for each data point. Performance improved for both age groups as the ISI increased, $F(7, 28) = 24.04$, $p < .001$. Although there was no main effect of age, the difference in performance be-

Table 1

Intensity Difference (in dB) Necessary for Criterion Detection of Loudness Difference on No-Mask Trials

Group/subject	Difference
Experiment 1	
Child	
1	7
2	7
3	9
Adult	
1	5
2	6
3	4
Experiment 2	
Child	
1	8
2	7
3	12
Adult	
1	6
2	2
3	4

tween the children and adults increased at longer ISIs, $F(7, 28) = 2.10$, $.05 > p < .1$. Thus, the strategy of adjusting the difficulty of the task in a preexperimental no-mask condition was not successful in equating the difficulty of the task for the children and adults.

Although the children were less accurate than the adults, especially at the longer ISIs, this age difference in performance cannot be attributed to differences in the rate of processing information or in the duration of preperceptual store. Children also had poorer performance in the no-mask condition. The no-mask trials presented among masking trials (see Figure 3) were more difficult for both age groups than the no-mask trials presented alone in the first session; the adults' performance fell from 98% correct to 83%, and the children's from 96% to 75%. Thus, it seems that whenever difficulty is introduced by the presence of masking trials, it occurs for both children and adults. The somewhat larger absolute difference for children than for adults was not significant, and, even if it were, the interaction would not necessarily be meaningful because percentage correct is not necessarily an interval scale (Krantz, Luce, Suppes, & Tversky, 1971; Loftus, 1978).

It is clear that to control task difficulty across age, changes in the intensity of the comparison tone should be made on the basis of performance during masking trials. Our second experiment was similar to the first, except that the comparison tone was adjusted during the second session to maintain equal overall performance across age on masking trials.

Experiment 2

Method

Subjects. Three 6½- to 7-year-old children of university faculty and staff and 3 university students (ages 25, 26, and 35) were subjects.

Procedure. The materials, apparatus, and procedure were the same

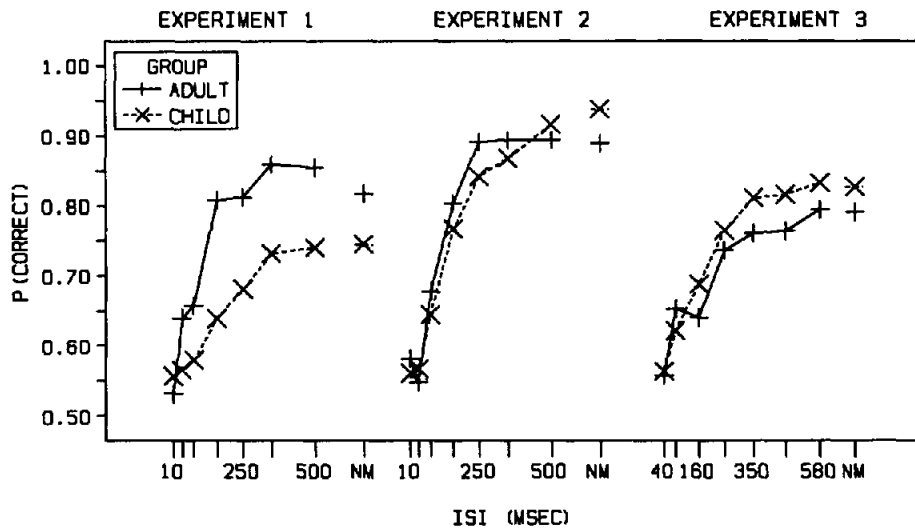


Figure 3. Percentage of correct identifications of the test tone as a function of the silent interval between the test and masking tones. (The curve parameter is children versus adults. The three panels from left to right correspond to the results of Experiments 1, 2, and 3, respectively. ISI = interstimulus interval.)

as in Experiment 1, with a few exceptions. The initial intensity of the standard and comparison was about 87 dB, slightly greater than in Experiment 1; the procedure was altered primarily to include an adjustment of the intensity of the comparison tone on the basis of performance on masking trials. In the first session, each subject received 384 no-mask trials during which the difference threshold was determined in the same way as in Experiment 1. The second session consisted of an initial block of 32 no-mask trials followed by 400 trials including all eight masking conditions. The intensity of the comparison in this session began at the difference threshold level and was decreased by the experimenter through the attenuators so that each subject's performance averaged approximately 75% across all conditions. This was intended to produce comparable overall performance for the two age groups, indicating that the task was equal in difficulty for the two groups. The third and fourth sessions used this intensity level for the comparison, and each of these sessions consisted of 400 trials.

Results

The difference thresholds in Experiment 2, as presented in Table 1, show an age difference similar to that obtained in Experiment 1. The masking functions for Sessions 3 and 4 combined are shown for each age group in the middle panel of Figure 3. As in Experiment 1, the first 16 trials in each session were eliminated from the analysis, yielding a total of 48 trials at each ISI for each subject in each session and a total of 288 observations for each data point in Figure 3. As in Experiment 1, performance improved for both age groups as the ISI increased, $F(7, 28) = 103.43$, $p < .001$. The interaction of group and ISI was not significant, and no other effects approached significance (for all F s, $p > .2$). Thus, there appears to be age constancy in backward masking.

Experiment 3

As can be seen in the middle panel of Figure 3, performance in Experiment 2 was near or at ceiling for the three longest ISIs

and the no-mask condition. Overall performance continued to improve during the experiment, and, therefore, adjusting task difficulty before the experiment itself was not adequate. Experiment 3 provided a more sensitive test of differences between children and adults by adjusting the difficulty of the task continuously throughout all sessions of the actual experiment to keep overall performance at 75% correct. If children process amplitude information at a slower rate than do adults, the children's masking function should differ in both rate and asymptote. The children's masking function should be above the adults' masking function at short ISIs and below it at long ISIs. This predicted crossover interaction follows necessarily from a processing-rate difference when overall performance is constrained to be 75% correct for each group. We also increased the number of ISIs greater than 250 ms in Experiment 3 to provide a more sensitive test of developmental differences in rate of perceptual processing. Finally, we decreased the time required for each trial by eliminating the comparison tone. Subjects heard only a single target tone to be identified as loud or soft.

Method

Subjects. Five 6½- to 7-year-old children of university faculty and staff and 5 university students between the ages of 18 and 22 years were subjects.

Materials and procedure. The stimuli were recorded in the same way as in Experiments 1 and 2, except that the standard tone was eliminated so that there was only one target tone on each trial. The subjects' task was to decide if the target was the "soft" tone or the "loud" tone. The loud tone and the mask were recorded on one channel of the tape, and the soft tone was recorded on the other. Only the intensity of the soft tone was changed during the experiment to adjust the difficulty of the discrimination. On ⅓ of the trials, the mask followed the target tone by a variable ISI of 40, 80, 160, 250, 350, 460, or 580 ms. As in the previous experiments, no masking tone was presented on ⅓ of the trials.

In the first session, each subject received 96 no-mask trials followed

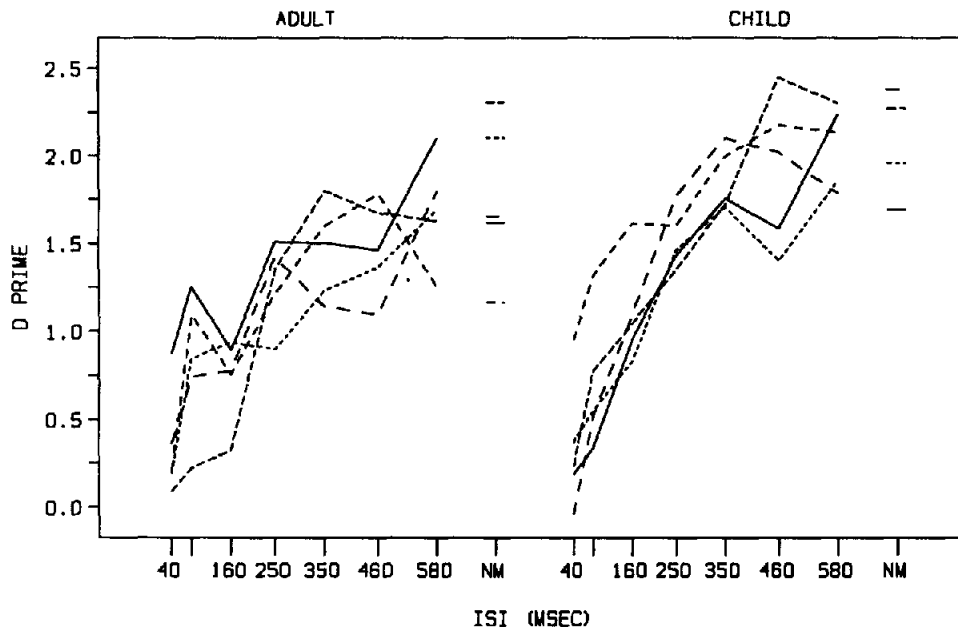


Figure 4. Percentage of correct identifications of the test tone as a function of the silent interval between the test and masking tones for the 5 adults (left panel) and 5 children (right panel) in Experiment 3.

by 176 masking trials. On the first four no-mask trials, subjects were told whether the target tone was loud or soft. On subsequent trials, they were to respond *loud* or *soft* and were given verbal and monetary feedback, as in the earlier experiments. The intensity difference between the loud and soft targets was adjusted if necessary to maintain a specified level of performance. During the 96 no-mask trials in Session 1, if the subject made less than three errors in a block of 16 trials, the discrimination was made more difficult by increasing the soft tone 1 dB in intensity. If there were more than three errors, the discrimination was made easier by decreasing the soft tone 1 dB.

Sessions 2 through 6 each consisted of 352 experimental trials. The intensity of the soft tone was increased 1 dB if the subject made three or fewer errors on three consecutive blocks of 16 trials, and was decreased 1 dB if the subject made five or more errors on three consecutive blocks. It should be noted that the intensity was changed between blocks of trials so that every masking condition was tested the same number of times at each intensity level.

Results

As in the previous experiments, the first 16 trials in each session were eliminated, yielding 21 observations for each subject for each test tone at each ISI in each session. Performance during the last four sessions was analyzed; the first two sessions were treated as practice days. The procedure of adjusting difficulty throughout the experiment was successful, with the children and adults averaging 74% and 71% correct, respectively. The right panel of Figure 3 shows the overall percentage of correct judgments as a function of ISI, with group as the curve parameter. Figure 4 gives the masking functions for each subject. An analysis of variance (ANOVA) was carried out on the percentage of correct judgments, with test tone, session, ISI, and group as factors. As in the previous experiments, there was a main effect of ISI, $F(7, 56) = 47.3$, $p < .001$, indicating that

discrimination improved with increases in the ISI. Group, session, and interactions with these variables did not reach significance.

The only other significant result was an interaction between test tone and ISI, $F(7, 56) = 7.91$, $p < .001$. Figure 5 plots this interaction, showing that performance at the short ISIs was poorer and improved more for the soft than for the loud test tone. This result replicates previous masking studies of loudness and shows that the masking tone has an additional effect of increasing the apparent loudness of the test tone (Massaro & Idson, 1978). Thus, performance is better at short masking intervals for the loud tone than for the soft tone. In addition, performance is better for the soft tone when no masking tone is presented.

In addition to the percentage-correct analyses, d' values were computed. The proportion of "loud" judgments (averaged across the last four sessions) given to the loud test tone was defined as the *hit rate*, and the proportion of "loud" judgments given the soft test tone was defined as the *false-alarm rate*. The ANOVA on d' values replicated the analysis on percentage correct. With respect to the developmental contrast of interest, group did not interact with ISI, $F(7, 56) = 1.401$, $p = .223$. The effect of ISI was significant, $F(7, 56) = 42.3$, $p < .0001$. The effect of group was also significant, $F(1, 4) = 5.92$, $p < .05$, indicating a slight performance advantage for the children.

The d' results for the means for each group were computed first by averaging the proportions across subjects within a group and then by computing d' values. Equation 1 was fit to the d' values using the parameter estimation routine STEPIT (Chandler, 1969). For each group, estimates of α and θ were determined to maximize the fit between the predicted and observed results. These predicted and observed masking functions are plotted in Figure 6. As can be seen, the lines predicted

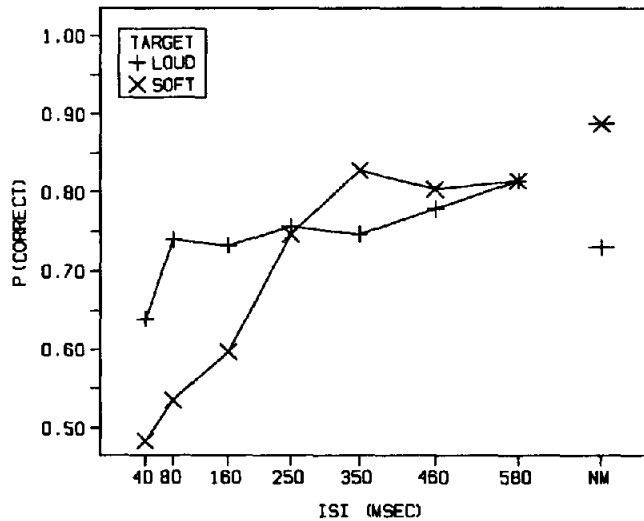


Figure 5. Percentage of correct identifications of the test tone as a function of the silent interval between the test and masking tones. (Experiment 3; the curve parameter is the loud versus the soft test tone. ISI = interstimulus interval)

by Equation 1 come close to the observed points. The estimated value of θ was 5.01 for adults and 5.03 for children. The estimated value of α was 1.70 for adults and 2.02 for children. The parameter values and root-mean-square deviation values for the fit are shown in Table 2. As can also be seen in Figure 6, the model gives a good description of the improvement in performance with increases in processing time. The good fit of the model and the fact that the parameter estimates for rate of processing did not differ much for the children and adult subjects is strong evidence for constancy in the rate of processing

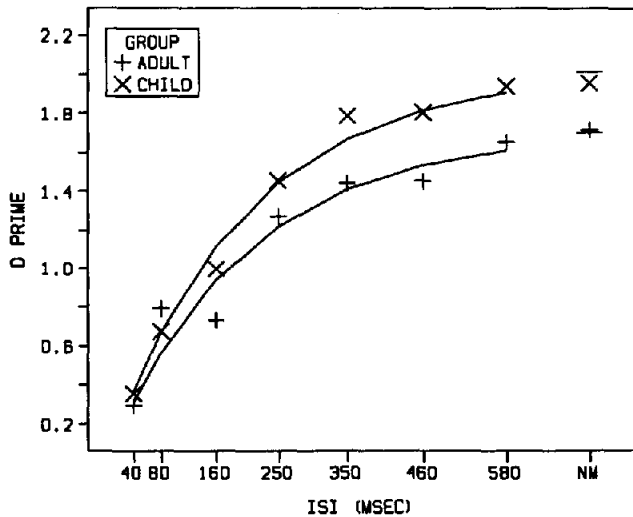


Figure 6. Performance measured in d' values as a function of the silent interval between the test and masking tones. (Experiment 3; the curve parameter is children versus adults. The 95% confidence interval for each point is $\pm .248$. ISI = interstimulus interval)

Table 2
Parameter and Root-Mean-Square Deviation
Values for Group Means

Group	α	θ	rmsd
Adults	1.7033	5.0099	.116
Children	2.0158	5.0254	.064

across development. Thus, the mathematical analysis supports the ANOVA of d' and percentage correct values showing no developmental differences in rate of processing when differences in information are controlled.

Of concern in the present series of experiments is a lack of power—a Type 1 error of failing to reject the null hypothesis when it is, in fact, false. It is possible that children do process amplitude information at a slower rate but that we simply failed to detect this difference because of low power. Thus, it is necessary to determine the degree to which the present experiments were sensitive to developmental differences in rate of perceptual processing. We adopted the strategy of testing a few subjects in each experiment intensively rather than testing many subjects for just a few observations. We believe that this strategy is valuable because of the increased fidelity that is achieved in intensive testing with many repeated measures for the same subject. The critical hypothesis tested in Experiment 3 is whether the children's masking function differs from the masking function of adults. Given that overall performance for a given subject was constrained to be about 75% correct, significantly different masking functions would necessarily produce a crossover interaction between group and ISI.

To address the power issue, a Monte Carlo analysis was carried out to obtain some idea of the amount of power that we had in Experiment 3. This analysis was carried out on both percentage correct and d' . An overall percentage-correct score was computed for the results of each subject at each ISI (pooled over test tone and the four sessions of the experiment proper), and an ANOVA was carried out on these values. The group factor did not interact with ISI, $F(7, 32) = 1.052, p = .407$. Similarly, there was no Group \times ISI interaction for d' values, computed from the hits and false alarms of each subject at each ISI, $F(7, 32) = 1.401, p = .223$. The MS s for these two nonsignificant Group \times ISI interactions were used as the estimates of variability in the Monte Carlo analysis.

Given the observed variability in the rate of processing in adults (Kallman & Massaro, 1979; Massaro, 1970b), we believe that a meaningful difference in the rate of processing between children and adults should be at least a factor of 2 or 3. In the first analysis, we assumed that it was important to detect a θ difference of 5 ($\theta = 2.5$ for children and 7.5 for adults). Given that the difficulty of the discrimination task was systematically varied to maintain performance around 75% correct, a significant difference in θ values would also result in a significant difference in α values. That is, if children process the test tone at a slower rate than do adults, then their performance will necessarily be better than that of the adults at short ISIs and poorer than that of the adults at long ISIs. Thus, it was necessary to obtain the appropriate α values with θ values of 2.5 and

Table 3
Number of Significant Hypothetical Experiments (of 1,000) in the Monte Carlo Analysis (Experiment 3)

Children's/adult's θ	d'	Percent correct
2.5/7.5	990	967
3.0/7.0	874	801
3.5/6.5	548	489
4.0/6.0	244	201

Note. Significance was at the .05 level. θ = rate of perceptual processing.

7.5 for children and adults, respectively, given the constraint of similar overall performance. Specifying the rate of processing and the overall level of performance necessarily constrains the value of α . Thus, STEPIT was used to compute the α values for the children and the adults by constraining performance to be 72.7%—the value actually obtained in Experiment 3. These α values were 2.51 for children and 1.60 for adults.

An average masking function in d' units was generated for the children using $\alpha = 2.51$ and $\theta = 2.5$. Similarly, an average masking function was generated for the adults using $\alpha = 1.60$ and $\theta = 7.5$. Using the variability estimated from the actual experiment, we carried out a hypothetical experiment by creating two groups of five simulated subjects each by adding this variability to the average masking functions. The variance was assumed to be normally distributed, with a mean of 0 and a standard deviation of 0.283. An ANOVA was then carried out on these data. We repeated this for 1,000 hypothetical experiments. For the d' values, 990 of the 1,000 experiments showed a significant Group \times ISI interaction at the .05 significance level. This interaction was significant for 967 of the 1,000 experiments, using the percentage correct values. Thus, the Monte Carlo analysis indicates that our experiment was sensitive to a difference of 5 in rate of processing between children and adults.

This Monte Carlo analysis was repeated for θ differences of 4, 3, and 2. The θ and estimated α values are given in Table 3. As can be seen, Experiment 3 was sensitive to a θ difference of 4 or 5, but not 2 or 3. Figure 7 gives the expected masking functions for the four θ differences. As can be seen, θ differences of 2 or 3 produce fairly small differences and might not be considered to be psychologically significant. Thus, we can conclude that Experiment 3 provided a reasonably powerful test of the hypothesis that children and adults differ by a factor of 2 or 3 in rate of perceptual processing.

Our conclusions obviously have limited generality. One cannot verify the null hypothesis (or any hypothesis). The null results for amplitude discrimination might not hold in other domains, although backward recognition masking appears to be similar for pitch, amplitude, timbre (Hawkins & Presson, 1986; Massaro, 1975a), and speech (Massaro, 1975b).

Discussion

In summary, a backward masking task was used to measure the development of auditory perceptual processing. When a brief target stimulus is followed by a mask, perceptual process-

ing of the target is terminated. This task allows one to determine the time course of perception; an important issue is whether young children have a slower rate of perceptual processing than adults. We defined rate of processing within an explicit model of perceptual performance, which allowed us to determine if rate was responsible for the observed developmental differences in amplitude discrimination. A quantitative model of perceptual processing gave similar estimates for the rate of perceptual processing in children and adult subjects. Thus, we conclude that school-age children process amplitude information at the same rate as adults.

The only positive finding of preperceptual memory or of rate differences in the processing of sound has come from infants tested in a nonnutritive sucking procedure (Cowan, Suomi, & Morse, 1982). The infants were given repeating pairs of vowels in which the first vowel in the pair changed. To the extent that the infants recognized these differences, they should have showed less habituation to continuous presentation of the vowel pairs. Extending the interval between the vowels of a pair is analogous to the manipulation of ISI in backward masking. The infants in the previous study revealed a release from backward masking with 400 ms between the onsets of the vowels but not with a 250-ms stimulus onset asynchrony. If 250 ms is taken as the asymptote in adult research, it appears that infants may have a slightly longer auditory store. Although this finding could be consistent with the lack of maturation of the cortex in infants, it is difficult to make a direct comparison between the widely different tasks used with the two populations. Relative to preperceptual memory, a longer term auditory memory might play a much more fundamental role in the infant task than in the standard masking task, and this may be responsible for the differences that have been observed (Kallman & Massaro, 1979, 1983). In addition, given the negatively accelerated form of the masking function, it is difficult to distinguish between 250- and 400-ms asymptotes. In fact, a number of typical backward masking studies (Massaro, 1970b) have had some slight improvement in performance beyond the 250-ms interval; thus, preperceptual auditory store may extend somewhat longer than this value.

The Rate Versus Asymptote Distinction

The distinction between asymptote and rate components of a backward masking function is a fundamental, if not easily formulated, enterprise. The function and its two parameters are meaningful only if performance does not show floor or ceiling effects. With floor or ceiling effects, estimation of the parameters is not meaningful because more than one set of parameters can describe such a function. If performance is not at the floor and asymptotes are not at a level of performance below perfect accuracy, the parameters of Equation 1 are uniquely constrained by the results.

Similar issues have been confronted in the study of the development of long auditory storage that lasts on the order of seconds (Engle, Fidler, & Reynolds, 1981). One of the most popular paradigms is the suffix effect, in which a list of items presented auditorily for serial recall is followed by a terminal item. Even though the final item does not have to be recalled, it

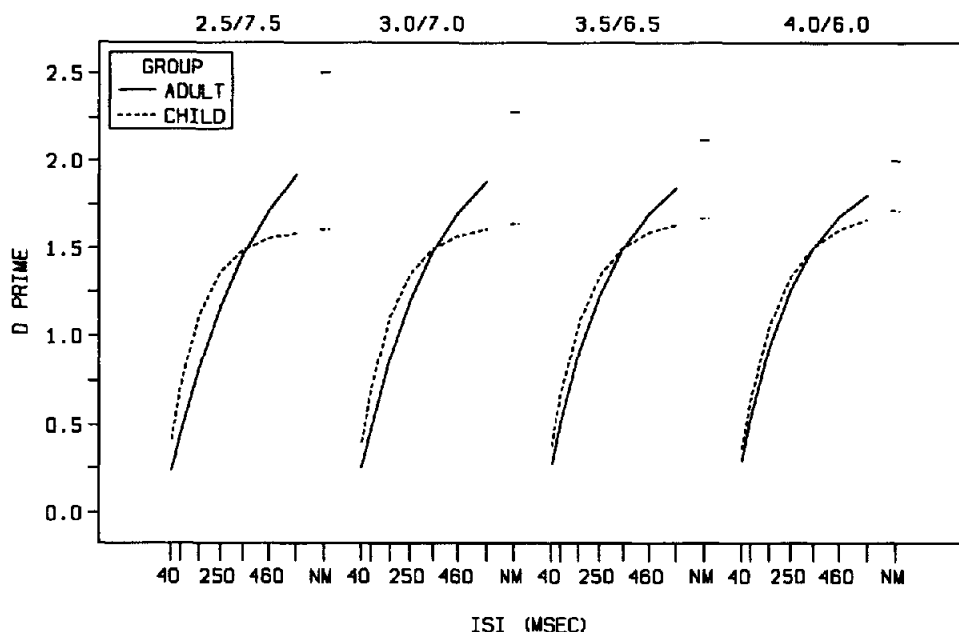


Figure 7. Expected masking functions for the four θ differences measured in d' values as a function of the silent interval between the test and masking tones. (The curve parameter is the children versus the adult predictions. The 95% confidence interval for each point, based on the observed variance in Experiment 3, is $\pm .248$. ISI = interstimulus interval.)

interferes with recall of the final items in the list. Developmental studies using identical stimulus lists across age are susceptible to floor and ceiling effects that preclude any meaningful interpretation of the results. To overcome this problem, Engle et al. (1981) determined each individual's digit span and varied list length with respect to that span. Even though younger children required shorter list lengths, the suffix effect could be assessed without an overall difference in performance. Using this basis of comparison, comparable effects were observed among 7- and 11-year-olds and adults.

Studies failing to account for rate and asymptotic performance in backward masking are ambiguous with respect to locating developmental differences in perceptual as opposed to sensory, memory, or decision processes. As an example, Walsh and Prasse (1980) performed a systematic series of visual masking studies across the adult life span. The dependent variable was the amount of target energy (by varying target duration) that was necessary to escape masking. As might be expected from the arguments developed in this article, this value was greater for old than for young adults. That is, the old require a longer ISI than the young to escape masking. These results cannot be taken to reflect differences in the rate of perceptual processing, however, because they might simply reflect a loss of visual acuity with age. Supporting this conclusion is the finding of similar results for pattern masking and luminance masking. The former could be conceptualized as reflecting the time course of the perceptual process, but the latter can be accounted for in terms of temporal integration of sensory information (Turvey, 1973). Thus, the differences observed in both pattern and luminance masking are most easily accounted for by differences in overall sensitivity rather than by differences in

both the temporal course of the perceptual process and the sensory integration process.

Our view complements the view of Salthouse (1982), who also questioned the strategy of comparing different groups of subjects who are at different performance levels. As an example, consider the argument that the elderly have less ability to divide attention between two simultaneous tasks (Burke & Light, 1981). If performance on a single task is poorer for the elderly relative to younger adults, the decrement observed in the dual task will probably be greater for the elderly subjects independent of any age difference in attention. In fact, depending on the overall levels of performance, the interaction might go in either direction because of statistical reasons even though there is no difference in dividing attention (Chapman & Chapman, 1973). More generally, an interaction of some independent variable with age is not necessarily diagnostic when the overall level of performance is not equated between the different groups of subjects.

We believe that the cued partial-report task developed by Sperling (1960) has not always been used appropriately to assess developmental differences in the rate of perceptual processing. In this task, performance accuracy decreases systematically to a performance asymptote with increases in the ISI between the test display and the partial report cue. Early studies by Haith and colleagues (Haith, Morrison, & Sheingold, 1970; Haith, Morrison, Sheingold, & Mindes, 1970; Sheingold, 1973) have been interpreted as demonstrating an absence of developmental differences in the time course of perceptual recognition. The results, considered together, appear to be rather unreliable given the discrepancies in performance differences across delays of the partial report cue. Gummerman, Ersoff, and Leitner

(1975) found large differences between children and adults using a similar task. Adults revealed a longer time course across ISI to reach asymptote compared with children. If the partial-report advantage relative to asymptotic performance were taken as an index of the duration of preperceptual memory, adults would be considered to have this memory for a longer period than do children. However, other interpretations are possible because the task involves a number of component processes such as detecting the indicator cue and switching attention to the cued position. If children took longer for either or both of these processes, their function would reach asymptote earlier than would the function for adults even if the duration of preperceptual memory and the rate of readout were equivalent for the two groups (Averbach & Coriell, 1961)

Sensory and Cognitive Contributions to Performance

Why do we find a developmental difference in asymptote that can be compensated for by increasing the psychophysical difference between the test tones in the backward masking task? There is evidence to implicate sensory, memory, and response processes. Both infants and preschool children appear to be less sensitive to absolute and relative sound intensity than are adults (Eagles, Wishik, Doerfler, Melnick, & Levine, 1963, cited in Pick & Pick, 1970; Elliot & Katz, 1980; Roche, Siervogel, Himes, & Johnson, 1978; Schneider, Trehub, Morriongiello, & Thorpe, 1986; Sinnott & Aslin, 1985). Morse and Cowan (1982) reported that infants are anywhere between 10 and 30 dB less sensitive to sound than adults. Sinnott and Aslin (1985) found that infants could discriminate intensity differences only if these differences were anywhere from 1 to 10 dB greater than those discriminated by adults. Eagles et al. (cited in Pick & Pick, 1970) found an increase in absolute sensitivity with increases in age from 5 to 12 years, but we have not found a study of relative discrimination of intensity in this age range. One possible basis for poorer sensitivity in younger children is that although the middle and inner ear are about the same size as those of adults, myelination is not complete at birth.

Consistent with the suspected differences in auditory sensitivity between children and adults is the child's poorer discrimination of fundamental speech contrasts. Children have been observed to be less sensitive than adults to differences in vowel duration. Krause (1982) varied vowel duration to create a continuum of vowels between /bip/ and /bib/. Increasing vowel duration led to a systematic increase in the identification of the voice alternative, and this function was steeper for adults than for 3- and 6-year-olds. Similarly, the discrimination of the voicing of stop consonants (Zlatin & Koeningsknecht, 1975) and the place of articulation of fricatives (Massaro, 1987; Phatate & Umamo, 1981; Synder & Pope, 1970) has been shown to improve with development. Massaro (1987) studied discrimination of an auditory /ba-/da/ continuum; adolescents revealed better discrimination of this continuum than did preschoolers.

With respect to memory, there is evidence for the development of an articulatory loop—a system for subvocally repeating words and phrases (Hitch & Halliday, 1983). Better memory has been shown for faster rates of articulation and has been interpreted in terms of the efficiency of subvocal rehearsal. There is also evidence that older children can articulate at a

faster rate than younger children (Hitch & Halliday, 1983). Thus, the adults in our experiment may have been more efficient in rehearsing the test tones throughout the experiment. More accurate rehearsal for the adults would enable them to perform a more difficult task, giving them an advantage over the children.

Response processes might also account for some of the differences between adults and children. Cirrin (1984) found differences in lexical decision times between children and adults that might be adequately accounted for by response processes. There were very similar influences of word frequency and age of acquisition with spoken words across age and similar effects of codability and frequency in picture naming across age. The effects of these variables should have interacted with age if perceptual and memory processes were responsible for the age differences. The overall performance difference with age seems more reasonably accounted for by response processes in the task.

Another conceptualization of auditory backward recognition masking is in terms of temporal summation on the basis of integration in the auditory sensory system (Cowan, 1984; Zwillocki, 1969). According to this view, neural activity is largest at stimulus onset and decreases to an asymptotic level by about 200 ms. The neural activity is integrated across time, with the most recent activity weighted most heavily in terms of the sensory representation. Backward masking would be explained by the integration of the test and masking tones, with a greater contribution of the mask at shorter ISIs. Cowan (1984) demonstrated that Zwillocki's (1969) quantitative model of this process and Massaro's (1970b) model make indistinguishable predictions. In the framework of Zwillocki's model, the equivalence of rate effects across age would imply identical periods of temporal integration. Given either of the two models, the differences in asymptote could be interpreted in terms of differences in auditory sensitivity, maintaining the appropriate memory representations of the test tones, efficiently matching the stimulus input with the memory representations, and holding a fairly constant decision criterion. Any or all of these differences could conceivably lead to asymptotic differences in performance without differences in rate of processing.

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Butcher, Geen, Hulse, and Salthouse Appointed New Editors, 1992-1997

The Publications and Communications Board of the American Psychological Association announces the appointments of James N. Butcher, University of Minnesota; Russell G. Geen, University of Missouri; Stewart H. Hulse, Johns Hopkins University; and Timothy Salthouse, Georgia Institute of Technology as editors of *Psychological Assessment: A Journal of Consulting and Clinical Psychology*, the Personality Processes and Individual Differences section of the *Journal of Personality and Social Psychology*, the *Journal of Experimental Psychology: Animal Behavior Processes*, and *Psychology and Aging*, respectively. As of January 1, 1991, manuscripts should be directed as follows:

- For *Psychological Assessment* send manuscripts to James N. Butcher, Department of Psychology, Elliott Hall, University of Minnesota, 75 East River Road, Minneapolis, Minnesota 55455.
- For *JPSP: Personality* send manuscripts to Russell G. Geen, Department of Psychology, University of Missouri, Columbia, Missouri 65211.
- For *JEP: Animal* send manuscripts to Stewart H. Hulse, Johns Hopkins University, Department of Psychology, Ames Hall, Baltimore, Maryland 21218.
- For *Psychology and Aging* send manuscripts to Timothy Salthouse, Georgia Institute of Technology, School of Psychology, Atlanta, Georgia 30332.

Manuscript submission patterns make the precise date of completion of 1991 volumes uncertain. Current editors will receive and consider manuscripts through December 1990. Should any 1991 volume be completed before that date, manuscripts will be redirected to the newly appointed editor-elect for consideration in the 1992 volume.