Developmental changes in the precedence effect: Estimates of minimum audible angle

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The precedence effect refers to an auditory phenomenon which occurs when two similar sounds are presented from different locations with a brief delay, and only one sound is heard whose perceived location is dominated by the first source. Although the lagging source is not localized as an independent event, under some conditions, adults are able to extract its directional cues. Developmental studies suggest that this ability changes during development. However, those studies have used stimulus configurations which minimize the measurement of that ability. In the present study adults were first tested under several conditions, and the one which produced optimal performance was chosen for testing children. Using the minimum audible angle (MAA) task in the azimuthal plane, performance was compared for a single-source condition and two precedence conditions: in lag discrimination the lagging source changed location while the lead remained at midline, and in lead discrimination the reverse occurred. Subjects were 18 months old, 5 years old, and adult. Significant improvements in MAA occurred with an increase in age, especially in the precedence conditions. Within each group, performance was significantly better in single-source condition, followed by the lead and the lag discrimination. © *1997 Acoustical Society of America.* [S0001-4966(97)03709-0]

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INTRODUCTION

The precedence effect refers to an auditory phenomenon which occurs when two similar sounds are presented from different locations with a brief delay, and only one sound is heard whose perceived location is dominated by the first source (Wallach *et al.*, 1949; Blauert, 1983; Zurek, 1987). Although listeners are aware of the presence of the second source, under many conditions they find difficulty in extracting its directional information. While this difficulty is high when the leading and lagging sources are on opposite hemifields and separated by 80° or by large interaural-time differences (Wallach *et al.*, 1949; Zurek, 1980; Yost and Soderquist, 1984; Freyman *et al.*, 1991; Divenyi, 1992), it is reduced when the two sources are nearer (Perrott *et al.*, 1989; Saberi and Perrott, 1990; Shinn-Cunningham *et al.*, 1993; Litovsky and Macmillan, 1994; Litovsky *et al.*, 1996).

Developmental studies with humans suggest that the precedence effect is not present at birth, but appears at 4 to 5 months of age. At that age, the delay at which the lagging source is localized as an independent auditory event is longer than it is at 5 years or adult (Clifton, 1985). However, 5-year-olds' performance is only similar to adults' for simple, transient stimuli, such as clicks, but worse for longer, more complex stimuli (Morrongiello *et al.*, 1984). Hence 5 years of age may reflect a transitional stage in the development of the precedence effect (Clifton, 1985; Litovsky and Ashmead, 1997).

Interpretations of these findings are tricky, for the data suggest that when the precedence effect does appear during infancy it may be *stronger* than it is in children or adults, although increased thresholds may simply be due to the infants' inability to extract directional information from the lagging source. Note that in those studies the leading and lagging stimuli were presented from opposite hemifields, maximizing the physical separation between them. Since this stimulus configuration is thought to reduce listeners' ability to extract directional information from the lagging source, the present study was aimed at investigating conditions under which performance is optimal, at least in adults. The task of choice, which has been used extensively with single-source stimuli in young infants and children (e.g., Ashmead *et al.*, 1987; Morrongiello, 1988) was the minimum audible angle (MAA) in the azimuthal plane, estimating the smallest lateral difference in the position of a sound that can be detected reliably (Mills, 1958). Since the tasks used in previous developmental studies on precedence only required that listeners identify the hemifield containing the lag, more precise localization was not measured. Thus an additional benefit of the MAA task is that it allows one to measure developmental changes in localization precision under conditions in which the precedence effect occurs.

Adults were first tested on a classic *fusion* task, in which they reported whether they heard one fused auditory image or two separate sound sources, for lead-lag delays ranging from 2 to 12 ms. The duration of each burst was either 4 or 25 ms, and the longest delay at which adults reported hearing one source on less than 25% of trials was chosen for the MAA procedure. The data were then compared with those of Litovsky and Macmillan (1994) who used 6-ms noise bursts. Finally, the stimulus duration for testing children was chosen to match the one that resulted in the smallest MAAs in adults' lag-discrimination. Figure 1 illustrates the three con-

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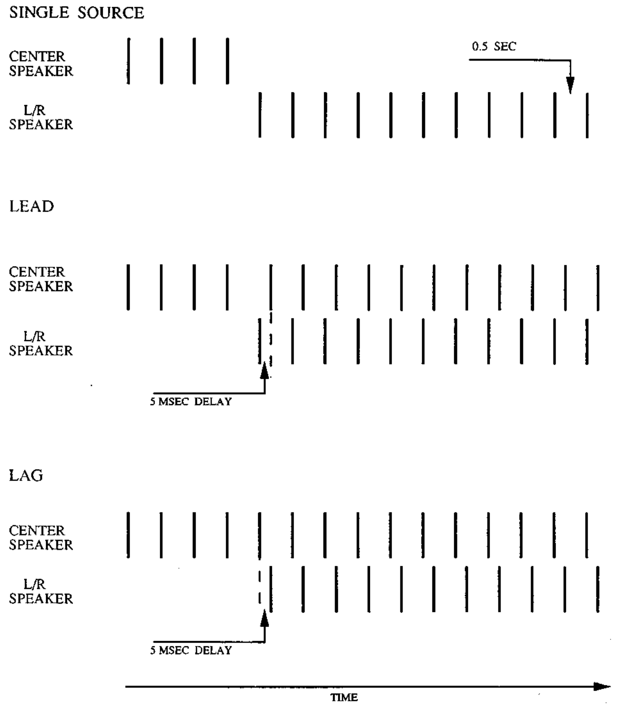

FIG. 1. Configuration of auditory stimuli. Three trial types are shown: single source, lead discrimination, and lag discrimination. All three trial types began with a single stimulus from the center loudspeaker, presented at a rate of 2/s. In single-source trials a single stimulus was then presented from either the right or left speaker. In lead and lag discrimination there were pairs of noise bursts with a 5-ms delay. In lead discrimination the leading source was presented from the left or right and the lagging source from the center. In lag discrimination the lagging source came from the left or right and the leading source from the center.

ditions that were used for the MAA tasks. In the single-source condition, a sound was presented from the middle of three speakers, and shifted randomly to one of two speakers (L or R). The other two conditions extended the task to precedence-effect stimuli: In lead discrimination, the leading source was presented to the left or right, and the lagging source from the middle. In lag discrimination, the lagging source was presented from either the left or right, and the leading source from the middle. While lag discrimination probes listeners' ability to discriminate changes in the location of the lagging source, lead discrimination reflects listeners' ability to overcome potentially confusing directional information from the lagging source.

Subjects were tested at ages 18 months, 5 years, and adult. At 18 months, MAAs are low (4°; Morrongiello, 1988) compared with adults (1° to 2°; e.g., Gardner, 1968; Mills, 1958; Hartmann and Rakerd, 1989; Saberi and Perrott, 1990; Litovsky and Macmillan, 1994). However, at 18 months, the precedence effect may not be fully developed due to incomplete maturation of the auditory cortex (Dekaban, 1970) which is thought to be involved in the ability to perform on some precedence tasks (Cranford and Oberholtzer, 1976; Whitfield *et al.*, 1978; Clifton, 1985). Five years of age may reflect transition in the development of binaural hearing, hence it is ideal for measuring developmental changes in source discrimination under conditions of the precedence effect. In addition, MAAs with single-source stimuli have not been previously measured at this age, hence this study bridges a gap in published data regarding changes in MAA between infancy and adulthood.

I. METHOD

A. Subjects and design

None of the children or adults had a known history of hearing impairment. All children were tested using the stimulus with 25-ms duration. Children groups included thirty-six 18-month-olds (12 males, 24 females; mean age of 18 months, 3 weeks), and thirty-six 5-year-olds (19 males, 17 females; mean age of 5 years, 4.4 months). Within each age subjects were randomly assigned to one of three groups ($N=12$ each) according to stimulus type (single source, lead or lag discrimination).

Adult subjects were undergraduate students at the University of Massachusetts. Their hearing was screened so that pure-tone sensitivity matched in the two ears within 10 dB or less, with detection levels no more than 20 dB above those of normal levels at frequencies ranging between 250 and 8000 Hz. Twenty-four subjects (8 males and 16 females; mean age=20 yr, ranging between 19–21 yr) were tested, 12 in the 4-ms condition and 12 in the 25-ms condition. Each adult listener was tested on single source, lead and lag discrimination, with the order of the three stimulus conditions randomly assigned.

B. Auditory stimuli

Stimuli were 4- or 25-ms wideband (500 to 8500 Hz) noise bursts with 2-ms rise–fall times. Pilot testing in our lab as well as by others (Zurek, personal communication) suggests that the precedence effect may depend on the token of noise chosen. Hence on each trial the noise bursts were selected independently from a long segment of the noise. In lead and lag discrimination trials the two bursts consisted of the same token of noise. Stimuli were computer generated with 16-bit precision, converted to analog form at 20 kHz (TTES-QDA1), low-pass filtered at 8500 Hz (TTE J1390), and tape-recorded (Teac X-300). During testing the prerecorded stimuli were amplified and played back from the same tape recorder over loudspeakers. The sounds were presented at A-weighted levels of 50–52 dB (B&K 2204 SLM) over a background level of 28 dBA, as measured at the approximate position of the subject's head. The time sequence for a trial for each of the three stimulus conditions is presented in Fig. 1. Each trial consisted of 15 noise bursts, presented at a rate of 2/s. In the single-source condition the first four noise bursts were presented from midline, followed by 11 noise bursts from either the right or left speaker. Lead- and lag-discrimination trials also began with four single-source noise bursts from midline. In the 11 bursts that followed there were two noise samples per burst, with the onset of one delayed relative to the onset of the other by 5 ms. In lead discrimination the leading source came from the right or left and the lagging source from the middle; in lag discrimination the opposite occurred.

C. Apparatus

The study was conducted in a sound-attenuated room, 3.5×4.0 m. Subjects sat facing an arc-shaped apparatus spanning 110° of an imaginary circle in the azimuthal plane with the subject at the center of a 1.65-m radius. Adults and 5-year-olds sat on a chair and 18-month-olds were seated on their parent's lap. Parents wore masking head phones which obscured all directional information to avoid the possibility of them systematically cueing their children in either direction. The arc was covered by a dark curtain to hide the three loudspeakers (Radio Shack model Minimus-7). Speaker responses were measured with a sound-level meter (B&K) at the approximate position of the listener's head, and all speakers had matching frequency responses within 1 to 2 dB for all frequencies between 100–8000 Hz. During all trials one loudspeaker remained at midline while the other two were positioned at equal angles to the left and right of midline.

Adjoining the testing room was a control room from which the session was monitored. A video deck (Panasonic GX2 1950) and television monitor in this room received input from a video camera inside the testing chamber. The investigator in this room viewed the subject's behavior and administered reinforcement following correct responses. Two identical sets of reinforcers were positioned at 60° to the left and right; each set consists of two mechanical toys which, when activated, provided a visual/auditory display known to be attractive to infants (Trehub *et al.*, 1981). Each toy was enclosed within a smoked-plexiglass box so that it remained invisible to the subjects except when activated. A video camera was positioned above the curtain at midline with output to one monitor behind the curtain, and another monitor in the outside control room. This double output allowed both experimenters to view the subjects' behavior during the session, which was especially important for testing 18-month-olds, whose responses were measured in terms of correct head-turning behaviors towards the appropriate loudspeaker.

D. Procedure

1. Testing adults in the fusion experiment

In order to establish which delays were most appropriate for measuring MAAs using lead-lag noise pairs, adults' perception of whether the lead and lag were fused was measured. On each trial the lead and lag were presented from 0° (front) and 30° right, respectively. This source separation of 30° was chosen so that it exceeded the MAAs of all age groups. The delays between the lead and lag included 2, 4, 6, 8, 10, and 12 ms. Within each block of trials there were 60 trials, consisting of ten repetitions of each delay, presented in random order. Each block was repeated five times, for a total of 50 trials per delay. On each trial listeners were instructed to report whether they perceived one fused auditory image, or two separate sound sources. The longest delay at which adults reported hearing one source on less than 25% of trials was chosen for testing on the MAA procedure. The aim was to identify a delay that is below echo threshold (Blauert, 1983), at which there might be some effect of both the lead and lag on sound localization precision.

2. Testing procedure for 18-month-olds on the MAA task

Experimenters wore masking earphones to avoid cueing subjects regarding stimulus location. Each trial was initiated by attracting the subject's attention to the center speaker. The stimulus was initiated once the child was facing the center speaker directly. An experimenter ''judged'' whether the subject's behavior indicated a shift of the sound to the right or left. A correct judgment, and hence response, resulted in activation of a reinforcer on the correct side for 5 s. An incorrect judgment resulted in a time-out period of 5 s. If no head turn was made during the 5 s after the stimulus shifted from midline, the trial was considered a nonresponse trial in which no reinforcement was delivered and a 5 s time-out period ensued. Three observers were trained on judging head turning responses. Percent agreement for the three observers for all judgments in this study were: A and $B = 95\%$; A and $C = 96\%$; B and $C = 94\%$.

3. Testing procedure for 5-year-olds and adults on the MAA task

Subjects were asked to center their heads and look at a target positioned at midline at the onset of each trial. They were instructed to point toward the right or left hemifield once the sound shifted away from midline, and to guess if they did not perceive an obvious change. Following a correct response children were presented with the toy that was used with 18-month-olds on the correct side. Adults were given feedback concerning the correct side by activation of a light bulb. For both ages incorrect responses were followed by a 5-s time-out period and no other feedback. Prior to test trials, subjects had to meet the criterion of correct responses on four out of five consecutive single-source practice trials with loudspeakers at 55°, and were allowed a maximum of ten trials to reach criterion. Ten children were excluded from the final sample due to suspicion of hearing impairment ($N=2$) or loss of interest in the task ($N=8$). Four adult subjects were tested but excluded from the final sample due to failure on the screening hearing test.

4. Adaptive method and MAA estimation

Changes in angular separation of the loudspeakers were determined using the classic two-down/one-up method of Levitt (1971) which seeks the 71% correct point on a psychometric function. The initial angles were chosen to yield high accuracy at each age-stimulus combination, as determined during pilot testing. For single source and lead discrimination with 18-month-olds and all stimuli with 5-year-olds, the starting angle was 55°. For lag discrimination with 18-month-olds it was 75°, and for adults in all conditions it was 30°. Step sizes of angular change were determined by a modified version of PEST (Macmillan and Creelman, 1991, see Chap. 8; Litovsky and Macmillan, 1994), with the following additional rules for increased estimation accuracy

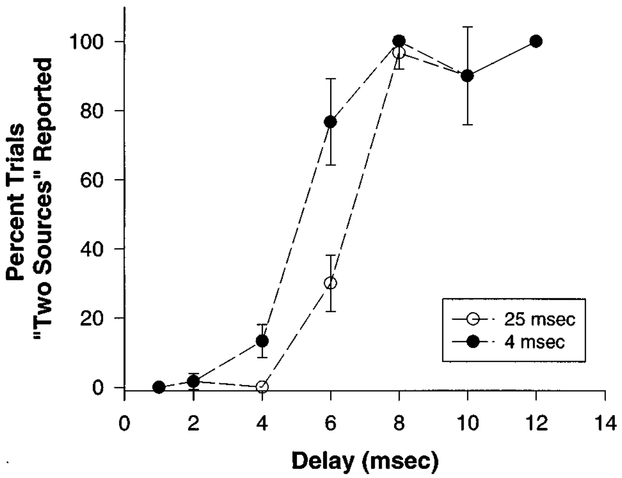

FIG. 2. Percent of trials on which listeners reported hearing ''two sources'' are plotted as a function of delay, for noise bursts that are either 25 or 4 ms in duration. Lead and lag sources were at 0° (front) and 30° right, respectively. Data are average and standard deviations for three listeners.

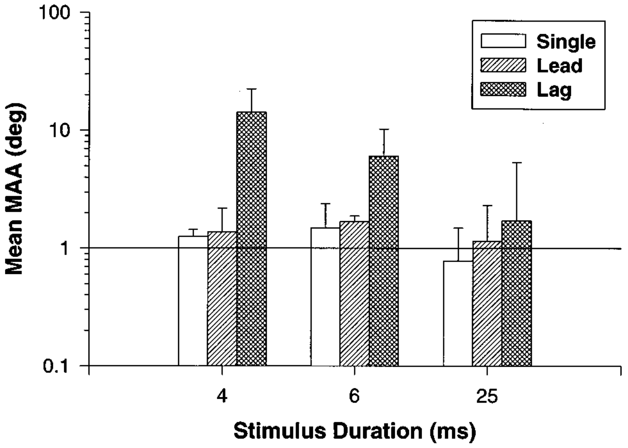

FIG. 3. Mean MAA estimates for adults, comparing single source, lead and lag discrimination, using 4-, 6-, and 25-ms stimuli. Data for the 6-ms condition are replotted from Litovsky and Macmillan (1994).

with children: (1) After two consecutive failures or nonresponse trials, a ''probe'' trial (Aslin *et al.*, 1981) was presented with the loudspeakers placed at the initial angle position. This trial type was repeated until a correct response was made, but data were not included in the estimation of MAAs. Once a correct response was made testing resumed at the angle position of the last failure. (2) A nonresponse trial was repeated at the same angle as the last and was not considered in MAA estimation. Testing was terminated once seven reversals were reached. The mean number of trials required to estimate MAA thresholds were 28.7 (range=14–50) for 18-month-olds, 27 (range=21–40) for 5-year-olds, and 26.5 (range=19–36) for adults. The proportions of nonresponse trials were 0% for adults, 1% for 5-year-olds, and 15% for 18-month-olds. MAA was estimated using maximum-likelihood rules that have been used extensively in combination with PEST (Macmillan and Creelman, 1991).

II. RESULTS

Shown in Fig. 2 is the percent of trials on which adults reported hearing two sources (rather than one fused auditory event), plotted as a function of delay for conditions in which the lead and lag noise bursts were either 4 ms in duration (filled circles) or 25 ms in duration (open circles). Listeners perceived the lagging source as an independent sound source on more than 50% of trials at a delay of 6 ms for the shorter-duration stimulus, and a delay of 8 ms for the longer-duration stimulus.

MAAs were averaged over subjects at each age for each stimulus condition. Where stated, statistical comparisons were conducted with *t* tests; significance values were set to 0.01 after applying Scheffe's adjustment for *post-hoc* contrasts. The means and standard deviations for adults are plotted in Fig. 3, comparing results in the 4- and 25-ms stimulus conditions. An additional set of data are replotted from Litovsky and Macmillan (1994) who used a 6-ms stimulus and tested subjects under identical conditions in the same room with the same apparatus. Stimulus duration has no significant effect on MAAs for single source and lead discrimination. In contrast, lag-discrimination MAAs decrease significantly with longer durations.

Plotted in Fig. 4(A) are data from the three age groups for the 25-ms stimulus, comparing single-source, lead and lag-discrimination conditions (adult data from Fig. 3 are re-

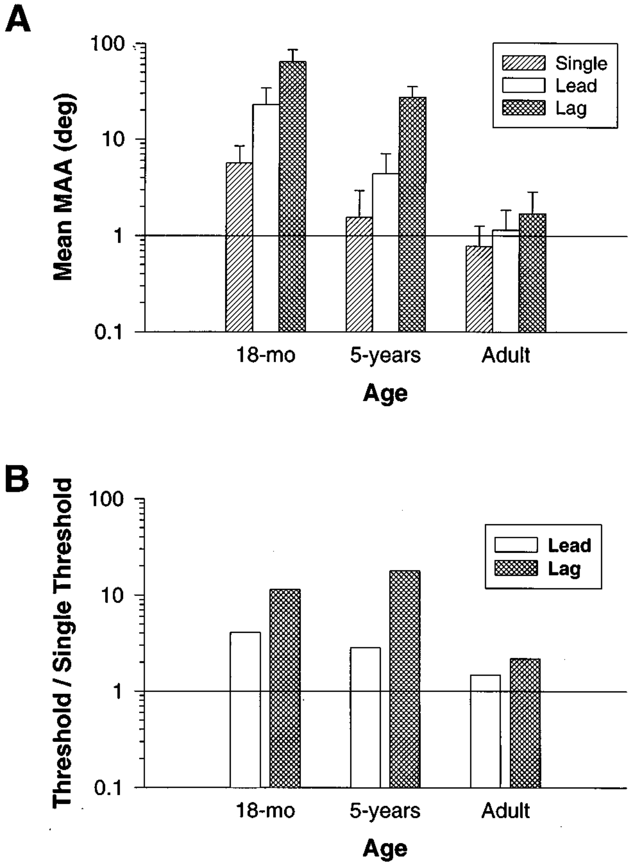

FIG. 4. (A) Mean MAA estimates for the 25-ms stimulus are plotted for each age group comparing single source, lead and lag discrimination. (B) Data from (A) were normalized within each age group by the mean MAA values obtained in the single-source condition.

plotted). Average MAAs (and standard deviations) for adults, 5-year-olds, and 18-month-olds, respectively, were 0.78 (0.48), 1.55 (1.38), and 5.65 (2.83) for single source; 1.15 (0.7), 4.40 (2.7), and 23.05 (11.07) for lead discrimination; and 1.71 (1.16), 27.5 (8.02), and 64.58 (21.6) for lag discrimination. Two aspects of the data are most noticeable. First, there is a general decrease in MAAs with an increase in age. Second, for both 18-month-olds and 5-year-olds, MAAs are substantially higher in the precedence conditions than in the single-source condition, with lag discrimination being especially high. Figure 4(B) shows the same data, normalized at each age by the mean MAA in the single-source condition. Developmental differences are still robust, maintaining the same trend that was observed in Fig. 4(A).

Statistical analyses showed that adults' MAAs are significantly lower in single source discrimination than lead discrimination ($t=2.9$), and than lag discrimination ($t=3.7$). MAAs are also lower in lead compared with lag discrimination ($t=3.3$). Thus compared with a single stimulus situation, adults' discrimination is degraded under conditions of the precedence effect, regardless whether the lead or lag is being localized. However, adults are better able to extract directional information from the leading source than from the lagging source.

Five-year-olds and 18-month-olds performed significantly better (i.e., lower MAAs) in the single source condition than either lead ($t=3.4$ and $t=6.3$, respectively) or lag discrimination ($t=3.3$ and $t=9.2$, respectively). Finally, their performance was better in lead than in lag discrimination ($t=2.9$ and $t=5.7$, respectively). Comparisons between the two age groups showed that 5-year-olds are significantly better than 18-month-olds in single source ($t=4.5$), lead discrimination ($t=5.7$), and lag discrimination ($t=3.6$), suggesting that between the ages of 18 months and 5 years children's localization precision improves significantly. Adults perform significantly better than 18-month-olds in single source ($t=5.9$), lead discrimination ($t=6.8$), and lag discrimination ($t=10.0$). They also perform better than 5-year-olds on lead and lag discrimination ($t=4.0$ and $t=3.2$, respectively). However, 5-year-olds do not perform significantly worse than adults in the single-source condition, implying that basic localization precision may have reached adult acuity by childhood, whereas precision under conditions of the precedence effect has not.

III. DISCUSSION

A. MAAs with single-source stimuli

Adult MAAs (mean$=0.78°$) are consistent with previous findings for broadband stimuli (Perrott *et al.*, 1989; Saberi and Perrott, 1990). The estimate of 5.7° for 18-month-olds is slightly higher than a previous reported value of 4.0° (Morrongiello, 1988). The difference of 41% between Morrongiello's (1988) results and the present study cannot be attributed to differences in target proportions since both studies used approximately 71% correct to estimate thresholds. A major difference however, is Morrongiello's use of the ''method-of-constant-stimuli,'' compared with the adaptive method used here. In fact, MAA estimates in 6-month-old infants have also been higher with the adaptive method (19°; Ashmead *et al.*, 1987) than the method of constant stimuli (12°; Morrongiello, 1988).

The most noteworthy finding is that 5-year-olds, on average, do not perform significantly worse than adults on the single-source MAA task. Despite the fact that 5-year-olds' mean MAA (1.55°) was twofold that of adults (0.78°), the difference was not statistically significant. The mean values are within the range of previously reported MAAs in adults (e.g., Gardner, 1968; Hartmann and Rakerd, 1989; Perrott *et al.*, 1989; Litovsky and Macmillan, 1994). It may be interesting to note that five of the 12 children actually had MAAs below 1°, while two childrens' MAAs were above 4°, which fall closer to the mean of the 18-month-old group. Hence, five years of age may represent a transitional stage during which some children have reached adult acuity in the discrimination task while other children have not. Alternatively, the variability within the 5-year-olds may represent individual differences in attentional capacities.

Nonetheless, the author is not aware of previous MAA estimates for children at any age above 24 months (Morrongiello, 1988). The value of 1.55° does fall, as expected, between MAAs of 18-month-olds and adults, suggesting that development in localization precision continues to occur between the second and fifth years of life. Since previous reports suggest that by this age children have not yet reached adult-level performance on other tasks involving temporal discrimination (Davis and McCroskey, 1980; Irwin *et al.*, 1985; Wightman *et al.*, 1989), localization precision for single-source stimuli may not depend solely on temporal acuity.

B. MAAs under conditions of the precedence effect

In the adult group the differences in means between single source, lead and lag discrimination were quite small, however, all three conditions were significantly different from one another. The finding that lead-discrimination MAAs were worse than single-source MAAs suggests that the presence of the lagging source at midline did interfere somewhat with listeners' ability to extract directional information from the lead. Thus precedence in this situation was not ''perfect.'' However, precedence did exist to the extent that lag discrimination was worse than lead discrimination. These results are consistent with previous findings on MAAs under conditions of the precedence effect (Perrott *et al.*, 1989; Litovsky and Macmillan, 1994). It has long been suggested that the precedence effect is an auditory phenomenon that diminishes the influence of directional information from echoes, thereby aiding an organism in accurately localizing the original sound source (Zurek, 1980, 1987). The finding that performance was, at all ages, significantly better in lead than lag discrimination is consistent with this notion, and with previous reports that the precedence effect gives dominance to directional cues provided by the leading source. One such measure is a just-noticeable difference in the interaural-time difference of a signal, which is not affected when the signal is the leading source, but is strongly affected when it is the lagging one (e.g., Wallach *et al.*, 1949; Zurek, 1980; Yost and Soderquist, 1984; Shinn-Cunningham *et al.*, 1993). A tentative interpretation of these results is a masking of the ''localization strength'' of the lagging source (Divenyi, 1992).

1. Effect of stimulus duration in adults

The finding that longer-duration stimuli result in increased fusion, i.e., that listeners require longer temporal separation between the lead and lag before the lag is heard, is consistent with previous reports in the literature. For example, echo thresholds for click stimuli (2–5 ms) are lower than those for noise stimuli (>8 ms; see Schubert and Wernick, 1969 and Blauert, 1983). Recent physiological studies showing neural correlates of the precedence effect in the brainstem of the cat (Yin, 1994; Fitzpatrick *et al.*, 1995; Litovsky *et al.*, 1997; Litovsky and Yin, 1993, 1997) have also found that single neurons' echo thresholds increase with longer-duration noise stimuli. The physiological findings suggest that, although both the leading and lagging responses produce increased excitability when the stimulus duration is longer, the end result is stronger suppression of the lagging response. Thus changes in duration seem to have a more potent effect on the amount of suppression produced by the lead than on the excitation produced by the lag.

The finding that longer-duration stimuli result in decreased lag-discrimination MAAs may not be a function of mechanisms that are involved in precedence *per se*. To date, there are no published data known to the author with which to compare these findings. A possible explanation is that the longer-duration stimuli provide a temporal ''tail'' consisting of the lagging source; the leading stimulus has been turned off but the lagging one continues for 5 ms. Adults may have developed a listening strategy that enables them to extract enough directional information from the tail-end of the stimulus. However, that strategy may have only succeeded in the 25-ms condition when the lagging source, after having overlapped with the lead for 20 ms, was presented by itself for 5 ms. In the lead-discrimination task listeners only had to pay attention to the beginning of the stimulus, regardless of what came after its onset, hence there were no differences in the MAAs for the different stimulus durations.

2. Developmental changes in the precedence effect

Five-year-olds performed significantly better than 18-month-olds, and adults performed better than both children groups in the two precedence tasks. The finding that developmental changes remained fairly constant after normalizing lead- and lag-discrimination MAAs by single-source MAAs [Fig. 4(B)], further suggests that MAAs under conditions of the precedence effect are not merely a by-product of a ''noisy'' single-source discrimination system.

The lag-discrimination data suggest that with an increase in age there is an improvement in listeners' ability to extract directional information from a simulated echo, i.e., a sound source that is not localized as an independent auditory event (lag discrimination). This finding is consistent with the developmental data of Clifton and colleagues (see Clifton, 1985) who measured listeners' ability to localize the hemifield containing the lagging source, and found elevated thresholds in infants and children compared with adults. That is, infants and children required longer delays between the lead and lag before they could localize the lag as a separate source, at its respective location. The higher fusion point for younger listeners could be the primary cause for the difficulty they exhibited in the lag-discrimination task.

These results might reflect different maturational stages in the auditory cortex (Clifton, 1985), which has been implicated as a necessary structure for the binaural suppression of echoes (Cranford and Oberholtzer, 1976; Whitfield *et al.*, 1978). The brain undergoes substantial growth during early childhood, with the most dramatic changes occurring in cortical regions (Dekaban, 1970; Yakovlev and Lecours, 1967). Although differences in attentional or learning processes cannot be ruled out, the nature of the precedence effect would seem to favor the cortical development explanation. Precedence is a very compelling auditory illusion, and in everyday listening situations adults seem capable of suppressing echoes in a natural manner, regardless of whether they have cognitive knowledge of the presence of those echoes. However, we can be trained to ''hear out'' the echoes and extract information from them (e.g., Saberi and Perrott, 1990). Do these findings suggest that adults have ''weaker'' precedence than children? Perhaps it is simply the case that adults are better and more experienced than children at most tasks, including ones which involve attending to directional changes in a simulated echo.

The lead-discrimination data suggest that with an increase in age listeners are better able to ignore directional information from the lagging source when that information is irrelevant to the task. Under conditions of the precedence effect adult listeners are almost always aware of the presence of the lagging source and they can discriminate between a single-source sound and a paired-source sound (Blauert, 1983; Zurek, 1987). However, the potency of precedence lies in the fact that the auditory system fails to assign a separate location to the lagging source. This ability, too, might depend on the development of sensory and cortical structures in the auditory system. Alternatively, it might rely on the attainment of cognitive and attentional skills, which undergo significant changes during early childhood (Werner, 1992; Litovsky and Ashmead, 1997).

Finally, it is interesting that 5-year-olds' single-source MAAs have reached adult-level maturity, whereas their MAAs with paired sounds have not. Possibly, this reflects a decoupling between the development of basic auditory abilities required for single-source discrimination and perhaps more sophisticated skills such as accommodating echoes. It is also possible that localization precision requires special cognitive skills in the presence of echoes that may not be available to young children. An alternative explanation may relate to stimulus parameters. Five-year-olds' ability to identify the hemifield containing the lag is only similar to adults' for click stimuli; it is significantly different than adults' for long-duration noise (Morrongiello *et al.*, 1984). The present study only tested children with the long-duration stimuli; it is possible that with short-duration stimuli performance on lead discrimination might have been similar to adults.

C. Summary

In summary, it is clear that several aspects of localization precision are undergoing developmental changes during infancy and childhood. These changes are useful for understanding the relationship between two aspects of the precedence effect, fusion, and suppression of directional cues. This study found a discrepancy between the ages at which precision matures for simple and complex tasks, suggesting perhaps, that different mechanisms might be responsible for the development of localizing single source and paired stimuli. Finally, it must be acknowledged that nonsensory factors related to the task may have contributed to developmental differences. It is therefore unlikely that precedence is merely a by-product of simple sound localization. A true test of this issue may require studies on the neurophysiological basis of precedence.

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