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DEVELOPMENTAL CHANGES IN SOUND LOCALIZATION PRECISION UNDER CONDITIONS OF THE PRECEDENCE EFFECT

A Dissertation Presented

by

RUTH Y. LITOVSKY

Submitted to the Graduate School of the
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In dedication to my mother, who instilled within me the desire to learn and respect for education, whose love and support have been a tremendous source of inspiration. With all my love.

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ABSTRACT

DEVELOPMENTAL CHANGES IN SOUND LOCALIZATION PRECISION UNDER CONDITIONS OF THE PRECEDENCE EFFECT

SEPTEMBER, 1991

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In enclosed spaces, the first sound that reaches the ears emanates directly from the original source, and is followed by reflections of the same sound off nearby surfaces. The ability to suppress the echoes is thought to minimize distraction and facilitate accurate localization of the original sound source. The ability to give perceptual priority to the original sound source under these conditions has long been known, and has been termed the "law of the first wave-front", or the "precedence effect" (PE). This phenomenon has been studied with respect to whether subjects perceive the presence of the lagging sound. Past developmental research on the PE has only considered the precision with which the leading or lagging stimulus can be located to a hemifield. Moreover, little attention has been paid to the influence that echoes exert on localization accuracy for the leading sound.

The present study investigated localization precision of children and adults in the presence of a simulated echo. Localization precision was measured using the minimal audible angle (MAA) task, which indicates the smallest change in the location of a sound that can be reliably discriminated. Three age groups were tested: 18-months, 5-years, and adults. Each age group was tested with one single-source (SS) stimulus, and two precedence effect (PE) stimuli: LEAD, in which the original sound shifted from midline and the echo remained at midline, and LAG, where the reverse occurred. Subjects were tested using an adaptive, 2-down/1-up, psychophysical algorithm.

For all age groups, MAA thresholds were smallest for SS, larger for LEAD and largest for LAG. For all three stimulus conditions, the 18-month-olds' thresholds were significantly larger than those of either 5-year-olds or adults. Five-year-olds' MAA thresholds for SS sounds were very near to those of adults. However, their thresholds for the PE stimuli were significantly higher than those of adults', and closer to those of 18-month-olds.

When multiples of the same signal are presented, the number of binaural temporal cues that must be compared multiplies, thereby decreasing the accuracy for sound localization. When the lagging sound is inaudible as a separate auditory event, the auditory system presumably treats the leading and lagging sound as components of the

same auditory percept, and uses both signals to compute the position of the sound source. This accounts for higher thresholds under the LEAD as compared to the SS condition. Further, in localization tasks the leading sound, which signals the onset of an auditory event, is assigned perceptual dominance thereby diminishing the nervous system's interaural sensitivity for the later-arriving echo. This accounts for the higher thresholds under the LAG condition compared to the SS condition. This and related work has raised important questions concerning the neural mechanisms involved in spatial hearing in adults and children, especially those aspects which involve an active suppression of superfluous signals.

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CHAPTER I

LITERATURE REVIEW

The present study explored developmental changes in localization precision during late infancy, early childhood and adulthood. The aim was to fill the existing gap in the literature between infancy and adulthood, and to describe some fundamental aspects of sound localization precision in the presence of echoes and its development. This chapter will review the existing literature on sound localization and its ontogeny, concentrating on situations in which simulated echoes are presented.

A. Sound localization in humans

Auditory functioning is used by many animals for maneuvering in the environment, as well as identifying sounds produced by other members of their species. Similarly, many animals depend on their auditory capacity for interactions with members of other species, particularly during predator-prey interactions. In either case, the ability to locate the source of a sound may be crucial to the survival of individuals. Elucidating the mechanisms underlying the processing of auditory stimuli is a matter of great interest. In pursuing this aim, scientists have documented, in detail, the phenomenology of auditory localization in various species, focusing especially on humans.

Systematic studies of human localization began over a hundred years ago and have generated a substantial body of literature on this topic. An important conclusion arising from this work is that the binaural system renders auditory signals more accurately localizable than they would be with a monaural system (Durlach & Colburn, 1978; Zurek, 1979). Sound travels in auditory space in such a way that auditory stimuli, emanating from a given location, reflect from nearby surfaces. Each ear thus receives multiple arrays of information, which undergo a computation process and are transformed into a unitary coherent stimulus (Durlach and Colburn, 1978; Moore, 1988). This transformation, whose exact mechanism remains to be fully explained, allows listeners to perceive distinctly the spatial location of the stimulus of interest.

The tympanic membranes of the two ears are separated by an interaural distance, and this is the main source of binaural cues. Information from the two ears merges in the brainstem, and is transmitted to higher levels in the central auditory pathway. Unlike animals such as the barn owl, humans do not possess a neuronal substrate for a map of auditory space. Rather, a location in space can only be represented in the nervous system through on-line computation and comparison of the cues that reach the two ears (Brugge, 1991; Moore, 1988). A great deal of the underlying mechanisms and their development remain to be elucidated.

The most extensive literature on sound localization in humans comes from work with adult listeners. Only in the last couple of decades have investigators begun to describe sound localization capacities in infants and children. This is not surprising, since adults understand verbal instructions and are capable of performing a wide range of tasks. Whereas, few rigorous methods for testing infants have been developed. As will be discussed below, one cannot ask infants what they hear. Rather, one must elicit behavioral responses which can be detected and measured reliably. A great deal of progress has recently been made in developing protocols for testing infants, resulting in a monumental increase in our understanding of infant auditory capacity, including auditory localization.

Another reason researchers focused on adults may have been a reluctance to study a developing system before fully understanding the basic capacities of the mature system. However, this rationale does not explain why much of the developmental auditory research has concentrated on the infancy period, neglecting almost entirely the early childhood years. In particular, very little is known about sound localization at the ages when children acquire adult level performance. A major aim of the present study was to document the localization capacities of young children compared to that of adults.

1. Localization by Adult Listeners

Human listeners with intact binaural hearing are capable of utilizing various cues, derived from the physical separation between the two ears, in order to determine accurately the position of a sound in space. A sound that is presented on the horizontal plane will arrive first at the nearer ear, and then travel around the head, subsequently arriving at the further ear. This interaural time difference (ITD) supplies the listener with a cue as to the position of the sound. For high-frequency short-wavelength signals the head and its appendages form an acoustic shadow and thereby provide the second major localization cue, an interaural difference in sound level (ILD). In a natural auditory environment, there are additional interaural differences caused by the listener's head, body and pinnae, as well as objects in the environment (for review, see Durlach & Colburn, 1978; Searle, Braida, Davis & Colburn, 1976), however these factors will not be discussed here.

Two studies on adult listeners are considered to have laid the groundwork for much of the thinking about binaural sound localization. Stevens and Newman (1936) and Mills (1958) showed that the ability of a listener to localize pure-tone stimuli is better at frequencies less than 1 KHz, or greater than 4 KHz, but is relatively poor at the intermediate frequencies. These researchers speculated that in the mid-frequency region neither ITD nor ILD are sufficient for accurate sound localization. In addition, they found that acuity of sound localization decreases gradually as the sound sources are displaced away from midline on the horizontal plane. These findings established the primary importance of ITD and ILD for sound localization, and served as the basis for much of the subsequent work in both psychoacoustics and auditory physiology.

The ILD-ITD dichotomy serves as the basis for what has come to be known as the "duplex theory" of sound localization, described as early as the turn of the century (Rayleigh, 1907; cited in Blauert, 1983). This theory has been generally accepted for over 40 years, although various aspects have been severely questioned. The "duplex theory" assigns a dual nature to binaural sound localization, such that localization of low-frequency sounds is dependent on ITD, whereas localization of high-frequency sounds depends more on ILD. The upper frequency limit on the use of ITD's is thought to have a neuronal basis. Auditory neurons fail to lock-on to the phase of the signal, and thus cannot supply the appropriate temporal information for binaural analysis (Moore, 1988).

This frequency-related dichotomy has been questioned, and the original argument has weakened substantially. For instance, human listeners are capable of lateralizing complex high-frequency stimuli using only ITD's (McFadden & Pasanen, 1976; Nuetzel & Hafter, 1976). Furthermore, physiological work has shown that neurons can phase-lock to the envelope waveform of high-frequency tones (Yin & Kuwada, 1984; Yin & Chan, 1988). Whatever the virtues of the duplex theory, it cannot explain how localization occurs in the absence of interaural differences, such as in monaural conditions, or on the median vertical plane (Wightman, Kistler, & Perkins, 1987).

One paradigm commonly used for assessing sound localization precision and testing the limits of the auditory system, has been to study detection acuity for the physical displacement of a sound. This is otherwise known as the minimum audible angle (MAA): the smallest angle that a sound must shift, before a change in its position is reliably detected (Mills, 1958). Numerous studies have used this and similar procedures to describe adults' localization precision for various auditory stimuli. It has been shown that MAA's are smallest when the sound is complex; when the source is located at or near the intersection of the horizontal and anterior median planes; and, when the angle of displacement is in the horizontal plane (Gardner and Gardner, 1973).

Under optimal conditions, the detection of very small angular differences have been reported. Some examples of MAA are: 1.8° (King and Laird, 1930), 2° (Ford, 1942), 1-2° (Snow, 1953; cited in Blauert, 1983), 1-2° (Mills, 1958), 1.5° (Gardner, 1968), 0.1° (Perrott, Marlborough, Merrill and Strybel, 1989). One notable effect is that for sounds on the transverse plane, listeners often experience a certain amount of front-back confusion. This latter finding was initially reported over a hundred years ago (Thompson, 1882; Rayleigh, 1907 (cited in Blauert, 1983), and has been replicated numerous times since (Stevens and Newman, 1936; Wallach, 1949; Hochberg, 1966). There is no question that adults are capable of using a variety of physical cues to discriminate accurately changes in the position of a sound in space. The developmental course of this ability, which remains to be understood, is discussed below.

2. Developmental Studies

In recent years there has been a growing interest in tracking the development of sound localization accuracy. It has become clear that young infants, and children to an extent, have much less accurate sound localization than adults. The process by which the immature auditory system develops into that of an adult is poorly understood and deserving of much investigation and analysis.

a. Children

The existing database on older children's auditory capacities is quite small, especially in comparison with infants. Most studies with children usually concentrate on school-aged as opposed to pre-school-aged children. It has been suggested, though, that the latter age, which encompasses a period of rapid speech and language development, may be a good time to assess changes in auditory capacity (Neuman and Hochberg, 1983; Wightman, Allen, Dolan, Kistler and Jamieson, 1989). As a result, most studies with pre-schoolers have tended to concentrate on auditory components related to language development, such as temporal resolution and acuity. Very little is known about other auditory capacities in young children, such as spatial resolution.

Children's temporal acuity improves continuously, only reaching adult performance in the teen-age years. An example has been found in auditory fusion, a monaural task in which the interval between two sounds is varied, and the listener is asked to judge whether they perceive one or two sounds. Davis and McCroskey (1980) delivered diotic pairs of pulses with different inter-pulse intervals over headphones, to children between the ages of 3-12 years. They reported that auditory fusion, i.e the ability to detect shorter time intervals, improves rapidly and in an orderly fashion from

3-8 years of age, stabilizing between 9 and 12 years of age. These findings were consistent with those of Tallal (1978), who found that children do not reach adult-like performance on auditory temporal tasks until the age of 9. Lowe and Campbell (1965) tested children at the ages of 7 and 14 years, measuring the onset-time difference between two stimuli necessary for temporal order to be judged. They found that children's mean threshold was about 10 msec higher than that of adults (36 msec versus 20-25 msec).

The results of Davis and McCroskey's (1980) study were initially questioned by some investigators who sought to replicate and extend these findings (Irwin, Ball, Stillman and Rosser, 1985; Wightman et al., 1989). Irwin et al. (1985) argued that given the same sensory stimuli, younger children may be more reluctant than older children to report hearing two sounds rather than one. In such a case, developmental differences would be confounded with willingness to cooperate in the task. Davis and McCroskey themselves also acknowledge that since they used the method of limits, it is possible that the age differences obtained represent a change in criterion placement, rather than perceptual capacities.

Using more rigorous psychophysical methods, which were aimed at being criterion-free, Irwin et al. (1985) studied temporal acuity in children 6-12 years of age. Their results were consistent with those of David and McCroskey (1980), also showing that temporal acuity improved significantly with age, and reached adult levels by the age of 11. In the most recent investigation, Wightman et al. (1989) studied gap detection thresholds as a function of age, and reported monotonic decreases from 3-5 to 7 years, and from 7 years to adult performance. Wightman et al. (1989) maintained that some differences were due to lack of attention in the younger age groups, but that sensory components influenced performance as well. Thus, regardless of methodology there appear to be significant maturational changes in auditory temporal acuity between the pre-school and teen-age years.

Another temporal parameter, which has traditionally been studied in evaluating psychoacoustical constraints on speech perception, is reverberation time. Various studies have demonstrated an increase in children's ability to perceive degraded speech as a function of age (Elliott, 1979; Elliott, Connors, Kille, Levin, Ball and Katz, 1979; Neuman and Hochberg, 1983). It has been suggested that in a reverberant environment, the reflected energy overlaps with the primary signal, introducing temporal masking, and hence degradation of speech identification (Knudsen and Harris, 1950). In a developmental study of 5-13 year old children, Neuman and Hochberg (1983) found that, in the presence of reverberation, there is a significant increase in phoneme identification as a function of age, but only for binaural stimuli.

Overall, these findings suggest that at least some aspects of auditory temporal processing are not fully developed by the time that children enter school, and may take at least 10 years to fully mature. It would be interesting to assess other aspects of temporal acuity in children, such as those involved in sound localization. Although such work has been conducted with infants (e.g. Ashmead, Davis, Whalen & Odom, in press), similar work has not been done on children.

b. Infants

Developmental work on sound localization has for the most part concentrated on one type of response: the natural tendency of infants to turn their heads toward attractive and novel sounds in the environment. Muir (1985) suggested that the presence of such a response indicates that we are born with some form of spatial representation. Work on the development of auditory localization began with reports by some investigators that newborn infants reflexively flick their eyes in response to sounds (Turkewitz, Birch, Moreau, Levy and Cornwell, 1966; Wertheimer, 1961), and anecdotal evidence that newborns turn their heads toward sounds (Wolff, 1959). The first conclusive demonstration of newborns' ability to orient to sounds, however, was not provided until a decade ago (Muir & Field, 1979). Using a modification of the Brazelton neonatal test (Brazelton, 1973), these authors tested newborn infants' capacity to localize sound to one of two hemifields. In this first study as well as others that followed, infants were presented with two mechanically shaken rattles, 20 cm from the head. One rattle produced sound and the other was silent. Although slow to initiate a response, newborns turned toward the sounding rattle on 74-90% of the trials, which was significantly greater than the frequency of head turning toward the silent side. These results suggest that infants are born with a tendency to orient toward sound in the environment, and have been replicated numerous times (Clifton, Morrongiello and Dowd, 1984; Clifton, Morrongiello, Kulig and Dowd, 1981; Field, DiFranco, Dodwell and Muir, 1979; Field, Muir, Pilon, Sinclair and Dodwell, 1980; Morrongiello, Kulig and Clifton, 1982; Morrongiello, Kulig and Clifton, 1984; Muir, Abraham, Forbes and Harris, 1979).

The unambiguous performance of newborns contrasts sharply with that of slightly older infants. On the same task, the frequency of head turning to the sound falls to chance level at about 2 months of age, but reappears close to the age of 4 months. This result was obtained both with longitudinal (Muir et al., 1979; Field et al., 1980) and cross-sectional (Clifton, Morrongiello, & Dowd, 1984; Muir, Clifton, & Clarkson, 1989) studies. This developmental trend, described by Muir et al. (1989) as a U-shaped function, has received several different interpretations. Possibilities which have been considered but refuted include: developmental changes in the infants' willingness to participate in the task (Muir et al., 1979); habituation to the auditory stimulus; and, visual competition (Muir, 1982; 1985; Muir et al., 1979).

The hypothesis favored by both Muir (1982) and Clifton (Clifton et al., 1984) is one that considers cortical maturation. It has been suggested that between the age of 2-3 months there is a biological progression from an initially coordinated, reflexive head turn toward sound, to a voluntary behavior. They described the newborn response as a neonatal reflex which is lost due to cortical development and modulation of subcortical reflexes, with cortically mediated responses developing around 4 months of age (Clifton et al., 1984; Muir, 1985). In support of this idea, these authors have provided cross-sectional evidence that the reappearance of the head orienting response at about 3-4 months of age occurs at about the same age as when the precedence effect is first observed. The precedence effect is also thought to depend on a moderately well developed auditory cortex (Clifton, et al., 1984; Muir et al., 1989).

Thus far, developmental localization capacities have only been described in terms of discrimination between the two hemifields. As infants' head control improves with age, it is possible to utilize this behavior to study finer localization capacities. For example, head turning behavior can be used to measure infants' minimal audible angle (MAA; Mills, 1958). For this purpose infants are trained to discriminate changes in the position of an ongoing sound, and are provided with visual reinforcement for correct head turns on test trials.

The first developmental comparisons of MAA did not appear until recently. Cross-sectional studies on infants between 6-18 months showed a progressive improvement in MAA thresholds both along the horizontal and vertical dimensions (Morrongiello, 1988; Morrongiello and Rocca, 1987). Whereas at 6-months infants could detect horizontal shifts starting at 12°, by 18 months MAA thresholds were as low as 4°, which is close to adult performance. Ashmead, Clifton and Perris (1987) tested 6-month-old infants and found similar but slightly higher MAA thresholds, with a mean of 19°, compared with 1-2° for adults. The authors considered various methodological issues which might account for these differences. Although they acknowledge that methodological problems have not been fully resolved, they conclude that the data represent true developmental difference in auditory acuity, especially since results for infants and adults were based on similar psychophysical strategies.

In the attempt to delineate the source of developmental differences in MAA thresholds, Ashmead et al. (in press) investigated whether infants' sensitivity to ITD was a limiting factor for precision on the MAA task. They found that infants aged 16, 20 and 28 weeks had MAA thresholds in the range of 50 to 75 microseconds, with no apparent age difference. These thresholds were significantly lower than would be predicted from the free-field MAA studies, indicating that sensitivity to ITD did not limit sound localization precision. The authors speculate that age differences in MAA tasks may reflect the capacity to integrate various localization cues and to utilize them in localization tasks.

Findings such as these are significant in improving our understanding of the development of sound localization accuracy, especially with simple sound sources. What would be of further interest, is the development of sound localization accuracy under more complex stimulus conditions. One such situation arises in reverberant environments, such as when echoes of the original sound sources are presented. Questions of this nature may be asked in the context of an auditory phenomenon called the precedence effect, which will be discussed in detail below.

B. The precedence effect in humans

1. Introduction

For many years psychoacousticians have been perplexed by why it is that in a reverberant environment we are not aware of the multitudes of echoes surrounding us. Considering the physical parameters of echoes, one might expect that we would hear a long sequence of separate sounds. One workable explanation is that echoes are suppressed by the brain, to allow for functional localization in a reverberant environment. This possibility has been termed the precedence effect, which according to Gardner (1968) was initially described and reported over a hundred years ago by Henry (1849; cited in Gardner, 1968). Because it was independently reported by a variety of researchers since then, it has been referred to in the literature under a few different names, i.e. "the law of the first wavefront" (Cremer, 1948), the "Haas effect" (Haas, 1949; cited in Gardner and Gardner, 1973), the "first-arrival wavefront" (Blauert, 1971; 1983), and the "auditory suppression effect" (Blauert, 1983). All of these terms essentially describe the same phenomenon, whereby, in the localization of an auditory event, an earlier sound predominates over a later arriving sound. Of the various terms, "precedence effect" will be used in the present work, since it is the most familiar in the field of psychoacoustics (Zurek, 1987).

The precedence effect (PE) has been a topic of growing theoretical pursuit in psychoacoustics, specifically because of what it reveals about the process of sound localization. It has also been of interest to developmental psychologists, because of what it illustrates about the development of binaural mechanisms, while anatomists have investigated this phenomenon for its usefulness in understanding cortical function. Despite the large number of studies on the PE, most of the what is known has not yet been incorporated into basic theories of binaural hearing, nor has a model of the development of the PE in the brain been set forth. One of the purposes of this study is to test some basic hypotheses concerning the development of echo suppression mechanisms in the human brain. Prior to reviewing the infant literature in this topic however, it important to discuss some of the major findings in the adult literature. This review may provide a basis for understanding some of the functional mechanisms underlying the PE.

2. Studies with adults

The PE occurs when two binaural sounds are presented with a brief delay between them, and are perceived by the listener as a single auditory event, whose exact localization is determined heavily by the position of the earlier sound. The PE is thought to have practical significance in a situation which requires a listener to localize sound in a reverberant environment. Waves that are reflected off nearby surfaces reach the ears later than the original sound source. Although they are not perceived as separate events, later arriving sounds influence the quality of the sound as well as its perceived position. Although sound localization accuracy is often not radically impaired, it is less acute than when a single source (SS) sound is being heard.

Studies on the PE have been conducted both with loudspeakers in a free-field listening environment and over headphones. The latter method is referred to as sound lateralization, whereas a task in free-field is one of sound localization (Yost & Hafter, 1987). There are limitations to the use of either method, although certain problems are more unique to lateralization studies, such as applying many findings to real-life situations. One common problem with the use of headphone studies is that the sound is often internalized and heard "inside the head" (Wightman et al., 1987). Although headphone studies often try to address issues of localization, work in free-field may be more ecologically valid for direct understanding of how sound localization mechanisms function in the real world. It is for this and other reasons that the current investigation tested infants' localization capacities in free-field. However, previous knowledge gained from earphone studies will be included in the discussion below.

Much of the interest that researchers have shown in studying the PE has involved the temporal boundaries within which the PE is effective. Blauert (1983) has described a temporal progression of delays between two identical sounds, which results in different auditory perceptions. For most stimuli in which the right and left sound sources are at equal distances from midline, and at short delays up to about 1 msec, the auditory event is perceived as being between the two sound sources. If the delay is increased above 1 msec, but is still very short, the auditory event is localized at the position of the leading loudspeaker, and the echo is not perceived as a separate auditory event. The presence of the echo is however noticeable, in that the spatial extent of the auditory image is greater than when the echo is absent. Finally, when the delay is increased further, the auditory event separates into two, each perceived at the location of their respective loudspeakers. This last delay, at which the precedence effect breaks down, and the second auditory event becomes audible, is often referred to as the "echo threshold".

In what has now become a classic study of the PE, Wallach, Newman and Rosenzweig (1949) described a fundamental paradigm, which has been replicated both in free-field and over headphones numerous times (for review see Blauert, 1983; Zurek, 1987). In the basic paradigm of Wallach et al. (1949), an identical pure-tone sound is delivered to two loudspeakers, but with a short time delay between them. Originally the authors created this situation by placing one loudspeaker nearer to the listener than the other. This was first done without compensating for the natural difference in level which would result, and subsequently was replicated by increasing the level of the further loudspeaker to match that of the closer one. In both situations, listeners localized the auditory event at the position of the closer loudspeaker. Sound from this loudspeaker had arrived at the ears a few milliseconds (msec) before sound from the farther loudspeaker, which indicated that the PE was operative. In a further examination of the phenomenon, the loudspeakers were kept at the same distance, but one led the other in actual time by 7 msec. Again, the leading loudspeaker dominated the listeners' perception of the location of the sound.

Along with establishing and providing evidence for the PE, Wallach et al. (1949) discovered that the magnitude of the PE, as indicated by the time delay at which the lagging sound can be heard as well, is to a large extent determined by the nature of the stimulus. With simple clicks the sound image is dominated by the closer loudspeaker at very short delays, on the order of 3-5 msec. But only a small increase in the delay is required for sound from the farther loudspeaker to be heard as well. This was later replicated by Bekesy (1960). With orchestral music, which is presumably more complex in nature, a greater time delay (approximately 40 msec) is necessary for this to occur. Wallach et al. (1949) also reported that in general, as the bandwidth of a stimulus is narrowed, the temporal distinction between the "leading" and "lagging" sounds was obscured.

In studies that followed, further evidence was provided to support this finding. Haas (1951) studied the necessary compensation in level of the lagging sound, which would give it as much perceptual weighting in determining localization of the auditory event. He made measurements with speech stimuli, and found that the sound level compensation required for the later arriving sound to be heard is much greater than it is with simpler, more punctate stimuli. Leakey and Cherry (1957) also created a lagging sound by changing the distance of the loudspeakers from the listener. They presented paired speech sounds to the left and right of the listener, but also added a broadband noise being emitted from a central loudspeaker. They found that adding the noise disrupted the PE, but that as the level of the noise relative to the speech was decreased, the PE became operative. The disrupting effect of noise on the PE was also reported using click stimuli by Thurlow and Parks (1961). These authors were also the first to note that the PE is still present when the loudspeakers are asymmetrical relative to the listener's head. The PE is functional not only for sounds that are presented on the horizontal axis, but for stimuli that are presented on the front-back axis as well (Blauert, 1971).

Another approach to studying echo threshold, has been to examine how various characteristics of a click train that precedes a test click, influence echo threshold. The first study of this sort was conducted by Thurlow and Parks (1961), who presented click trains to listeners, and asked them to report whether they heard one or two sounds. When listening to click trains at a rate of 5/sec, subjects reported that after a couple of seconds they experienced echo suppression. The authors suggested that there may be a "build up" of echo inhibition through time. In a more recent observation, Clifton (1987) reported a "breakdown" in echo suppression during a click train, following a switch in the locations of the leading and lagging sounds. This observation suggested that the PE may be thought of as a dynamic process which depends upon stimulation preceding its occurrence. Using this paradigm, Clifton and Freyman (1989) tested echo thresholds following the switch, as a function of echo delay and click rate. Subjects in this study reported a "fade out" of the audibility of the echo, in other words, a "build up" of echo suppression. This phenomenon occurred regardless of the delay or rate, but seemed to build up over time during the train. It was unclear however as to whether time, rate or number of clicks were the most significant aspects of the click train.

Clifton and Freyman (1989) also observed that the "fade out" occurred even before the switch in location of the leading and lagging sounds, indicating that the switch paradigm is not necessary in order to observe dynamic processes in the PE. Further investigation by Freyman, Clifton, and Litovsky (in press) suggested that the number of clicks in a train, rather than the rate or duration at which they are presented, is the most significant factor influencing shifts in echo suppression during a click train. Based on these studies, the PE may be thought of as a process by which inhibition of echoes in the environment changes, depending on the characteristics of ongoing stimulation.

Another aspect of binaural auditory stimuli which appears to be necessary for the PE to function, is transience of the onset of the stimulus. That is, a rapid beginning in an auditory stimulus. Transients are thought to facilitate sound localization in rooms because they trigger the PE (Hartmann, 1983; Rakerd and Hartmann, 1986). In fact, without the PE, sound localization may be poor due to misdirection by cues in the steady-state sound field (Rakerd and Hartmann, 1986). This effect, now termed the Franssen Effect (see Blauert, 1983; pp. 280-281) was first described by Wallach et al. (1949), and subsequently by numerous other investigators (Thurlow, Marten, and Bhatt, 1965; Perrott, 1969; Gaskell, 1983; Scharf, 1974; Hartmann, 1983; Rakerd and Hartmann, 1985; Rakerd and Hartmann, 1986). The Franssen effect is created when a pulsed sine-wave is partitioned into two components, one of which contains the steady-state and the other the onset and offsets components. If each component is subsequently delivered to a separate loudspeaker, and the transients are presented a few msec prior to the steady-state components, the loudspeaker which delivers the onset components dominates the perception of the entire auditory image. In fact, this is true even when the steady-state portion lasts for several seconds, and has been shown to function for pure-tone stimuli (Thurlow et al., 1968; Scharf, 1974). Finally, in free-field, the onset of a stimulus is not very important for low-frequency stimuli (Perrott, 1969; Hartmann and Rakerd, 1985).

Hartmann and Rakerd (1989) have proposed some explanations for the importance of transients and of their abrupt onset for localization in free-field. First, it is thought that the envelope of the abrupt sound provides a cue for localization which is absent in stimuli with a slow onset. Second, an abrupt signal which is a broadband sound, is bound to excite more neurons in the auditory nerve. This in return, would enable information to arrive at the central auditory pathways through more channels, and to dominate localization judgments. Rakerd and Hartmann (1986) have reported that short onset durations have the effect of enhancing localization accuracy by reducing a constant error component. As the onset duration increases however, the effectiveness of enhancing sound localization accuracy decreases monotonically. This is especially true when the stimulus is a pure tone, but with noise stimuli, the onset effects on localization are more negligible. These findings may be understood in light of suggestions by other authors (Zurek, 1980; Blauert, 1983; Hartmann, 1983) that noise stimuli which are composed of a succession of small impulses, are analogous to a series of transients which invoke continual binaural inhibition as an aid to localization.

Thus far, the PE with loudspeakers in free-field has been the focus of this section. Studies of the PE have often been conducted using the lateralization paradigm with headphones, which allow precise control of the stimulation to each ear. As has been discussed above, lateralization studies, to a large extent, invoke a perception of the stimulus being "inside the head". Earphone studies have however, provided some very interesting findings on the relationships between interaural time, level and other cues, which may be correspond to their occurrence during the presentation of a PE sound in free field. The variables which are often manipulated in such studies are either the timing differences between the two ears on the first, or second click pair, or both. In separate studies, Bekesy (1930; cited in Blauert, 1983), and Langmuir et al. (1944; cited in Zurek, 1987) measured the strength of the first sound and the interaural differences necessary to induce perceptual lateralization of the fused image. Wallach et al. (1949) also described the magnitudes and combinations of time delays necessary to compensate for lateralization, which would perceptually center the image. They concluded from their own study that the lateralization effect of the first and second clicks in a pair literally cancel each other out.

In more recent studies, Zurek (1980) and Gaskell (1983) measured just-noticeable differences (JND) using a forced-choice paradigm, and provided evidence for the PE by demonstrating that the JND for the lagging sound was greater than that for the leading sound. Zurek (1980) also suggested that a listener's sensitivity to interaural differences during the leading sound leads to a reduction in the sensitivity to the same differences in the lagging sound. Based on this result Zurek asserted that the PE may result from neural inhibition that is activated after the onset of the leading sound, and that effectively blocks interaural information momentarily, which would explain loss of interaural sensitivity for the lagging sound. In an attempt to replicate the findings of Wallach et al. (1949), Yost and

Soderquist (1984) presented subjects with the same 4-click stimulus complex. They did not find evidence to support the conclusions of Wallach et al. Rather, they reported that the first and second clicks in a dichotic stimulus interact, in such a way that listeners perceive the lateral position of the image as different from that in a diotic stimulus. The second click in the pair, although not heard as a separate auditory event, seems to influence the overall lateral position of the auditory stimulus. This phenomenon may be partly due to the width of the image produced by the dichotic stimulus, which could induce more variability in judgments of lateral position.

It is evident that acousticians usually study the PE either as a sound localization mechanism in free field, or as a lateralization phenomenon through headphones. Although the PE can also be thought of as a process especially necessary to deal with the problem of sound localization in real rooms. Only in the last decade have there also been some advances toward experimenting with localization of sound in rooms with reverberations. Hartmann (1983) studied how early reflections of a broadband noise disrupt sound localization accuracy, compared with accuracy in an absorbent room. He found that when subjects were asked to identify the location of an original sound, reverberations did not significantly alter localization acuity of a broadband noise, but that they did for a steady noise. In fact, the effects seem to also depend heavily on the geometry of the room in question. Hartmann and Rakerd (1985) reported that subjects' localization accuracy on the azimuthal plane decreased significantly when reverberations were introduced with single walls on the left or right, compared with that in anechoic rooms. These studies suggest that the later arriving reverberations, although not perceived as separate auditory events, influence localization of the original sounds. Zurek (1980) also discussed the fact that the leading sound in a pair largely determines the localization of the auditory event, but that the lagging sound may still have some influence, such as pulling the auditory image in its direction.

In the accuracy studies described above, absolute loudspeaker identification was used. However, similar findings have been reported using a different paradigm. Perrott et al. (1989) presented subjects with PE sounds, where the leading signal was presented at 0° azimuth, and the lagging sound was at a position to the right or left of midline. In a task similar to the MAA paradigm (Mills, 1958), subjects were asked to identify the hemifield from which the lagging sound was presented. Whereas MAA thresholds for single source sounds were approximately 1°, thresholds for the PE sounds were elevated by 2°-4°. The authors maintain that this reduction in accuracy is indicative of the inability of the auditory system to completely suppress influence of echoes on sound localization in a reverberant environment. The larger MAA thresholds with the PE condition could also be due to a spread in the auditory image caused by the echo, which may render the image harder to localize. A condition which was lacking in this study, was that of MAA thresholds for a shifting in the leading sound, when the lagging sound remains at midline. For, it is usually the leading, or original sound, which listeners need to localize, not the echoes. In order to draw conclusions about localization performance in reflective environments, it is thus necessary to examine the level of accuracy for the leading sound.

These issues lead one to question how the leading and lagging sounds are each treated in the brain, how they are weighted in relation to one another, and how they interact when the lagging sound is still inaudible, to result in one coherent percept.

3. Developmental studies

a. Children

The literature on children's perception in PE tasks is much more sparse than that with either adults or infants. This is not surprising, in view of the fact that many classical auditory localization capacities have not really been investigated with this age group. In localizing PE sounds, the brain must compare various temporal parameters of the multiple arrays of sounds that arrive at the ears. Perception of PE stimuli might therefore also fall under the category of temporal perception, an area of research which has received a little more attention with pre-school children. There are two studies with children however, which have been conducted on PE perception, and have yielded some very interesting findings.

Morrongiello, et al., (1984) tested children at 5 years of age on a variety of PE stimuli. This study used a staircase method, with both ascending and descending series, as well as a method of constant stimuli, to find thresholds for echo detection. With a click-train stimulus (3 msec clicks), the children's thresholds were not significantly different from those of adults, ranging from 11.25-13.25 msec, depending on the procedure. Subjects were also tested with a more complex stimulus, consisting of a tape-recorded rattle, shaken rhythmically at rate of 2/sec. Regardless of the procedure used, children's thresholds were higher than adults, ranging from 28.43-31.25 msec, versus 23.56-27.46 msec, respectively. These results are not easy to interpret, since the study was not designed to investigate how stimulus complexity is related to thresholds. Rather, the rattle stimulus was employed for the sake of comparing children's and adults' data with those of infants. One suggestion made by the authors is that higher thresholds could be related to fusion over longer time intervals, as was found by Davis and McCroskey (1980).

The only other study on children's perception under conditions of the PE, is one which was concerned with performance of children with temporal lobe epilepsy. Hochster and Kelly (1981) tested children ranging from the ages of 6-16 years, who either had normal hearing, monaural hearing loss, or temporal lobe epilepsy. The stimuli used were click trains presented at a rate of 1/sec, with delays ranging from 1-16 msec. Normal hearing subjects performed well on the task, and were able to localize both SS sounds, and leading sounds in PE stimuli. Monaurally impaired subjects responded correctly to SS sounds presented on the same side as the normal ear, but responded incorrectly to SS sounds presented to the damaged ear. These findings suggest the importance of binaural cues for sound localization. On PE trials, monaural subjects tended to refer to the side of the normal ear. Finally, children who had suffered brain damage performed well when localizing the SS sounds. However, they showed severe impairment in localizing the leading sound in a PE stimulus, primarily under conditions of long delays. The authors suggest that this deficit is associated with central neurological deficits, as opposed to peripheral loss.

b. Infants

Investigators who have studied the PE in infants were initially motivated by evidence that this phenomenon may be subserved by the auditory cortex (see Clifton, 1985 for review). Clifton and colleagues predicted that the PE would not be observed in newborns, whose cortex is very immature compared with that of 6-month-olds. In the older infants however, the PE may not be fully refined, and perception of PE stimuli may be different than it is for older children and adults.

In a series of studies with infants and children, Clifton and colleagues have described a developmental progression in behavioral responses to PE stimuli. These studies have provided a strong basis for theoretical considerations on the function and mechanisms that may be involved in the PE. In all the studies which will be discussed, auditory stimuli were emitted from two loudspeakers, positioned at 90° to the right and left of the listeners. The response measure used was lateralized head turning in direction of the stimulus. This behavior was chosen because, as has been discussed above, it is naturally elicited in response to novel or interesting stimuli in the environment.

The first studies in this domain were conducted with newborn infants, who were expected by the authors to turn their heads correctly on SS trials, but not towards the leading sound on PE trials. The stimuli employed were ones which would be easily localized to the leading side by adult subjects. Clifton, et al., (1981) presented newborn infants with equal numbers of SS, PE and control (simultaneous onset) trials. The delay between leading and lagging signals on the PE stimulus was 7 msec. Whereas the infants displayed head turning behavior on 58% of SS trials, this behavior was observed on only 11% of PE, and 17% of control trials. Since the same behavior was used to measure responses on stimuli of varying complexity, differences amongst the conditions could not be attributed to much other than sensory perception. The authors thus interpreted the infants' differential behaviors as possible indications of a relatively immature auditory cortex. In order to process PE stimuli, the brain must suppress localization information from the lagging side, and give priority to the leading side, a task which the brain of newborns may have been unable to perform.

Although these results were clear, they led to the concern that the delay employed was not ideal for perception of the PE in newborns. In a follow-up study (Morrongiello, et al., 1982), the delay was varied between 5, 20, and 50 msec. Regardless of the delay however, the earlier findings were replicated. Infants turned their heads on 46% of SS trials, but only on 3-4% of PE trials. These results confirmed the conclusions drawn by Clifton et al. (1981), that newborn infants do not perceive the PE similar to the way that adults might. The next age group to be investigated was 5-6 months. Since the cortex tends to develop rapidly during the first half year of life, the authors speculated that this age period may display some interesting developmental changes if the PE is cortically mediated. In addition, by this age the head turning response is usually well developed, and infants are highly competent on this type of task. Hence, testing was conducted for 5-month old infants, using delays of 7 msec (Clifton et al., 1984). This age group was reported to turn toward the leading signal in PE sounds as smoothly and accurately as they did toward SS stimuli. By 5-6 months of age then, the PE seems to be fairly established in human infants.

If newborn infants do not seem to have the PE, and 5-month-olds do, then the logical question is, when does the phenomenon develop? The next age group chosen was 6-9 weeks, because this period in life may be associated with other critical developmental changes. The authors reported that comparisons between the different stimuli were rendered difficult, because head turning behavior seems to be very unreliable at this age (Clifton, et al., 1984). Click train stimuli (Clifton et al., 1984) or the rattle stimulus used successfully with newborns were ineffective in eliciting head turning around 2-months of age. However, when a tape-recorded human voice was used, the infants responded slightly above chance level on SS trials. On PE trials their responses were distributed randomly between the leading and lagging sound. Hence, by 2 months of age infants do not seem to have a functional echo suppression mechanism, at least not as measured by head turning behaviors.

In addition to being interested in the age at which the PE appeared in infants, Clifton and colleagues were interested in the temporal parameters influencing the PE, and how they differ developmentally among infants, children and adults. Morrongiello, et al., (1984) habituated infants to the leading sound, and trained them to turn their heads towards the lagging sound whenever they heard it. The purpose of this study was to establish thresholds for audibility of the lagging sound. Infants were presented with lead-lag delays that varied from long (where the echo was clearly heard), to short (where the echo is not heard and echo suppression is evident). Results revealed that infants had mean thresholds of 25.33 msec, compared with about 12 msec for both children and adults. One possible explanation for these developmental changes, which is suggested by the authors, is an immaturity in the central auditory nervous system. For example, infants might require longer storage time for auditory stimuli, as was shown by Cowan, Suomi and Morse (1982), which would explain why they would require a longer delay in order to hear the lagging sound. In addition, young infants have not undergone complete neural myelination in the central nervous system (Yakovlev and Lecours, 1967), which in adults is thought to facilitate speed of neuronal conduction (Hecox, 1975).

It is always difficult to assess differences in behavioral findings in terms of neuro-anatomical development. This is especially true when not enough is understood about the direct influence of neuro-anatomical development on functional maturity. A recent investigation of PE thresholds in pre-term infants has shed some light on this question (Burnham, Taplin, Henderson-Smart, Earnshaw-Brown, & O'Grady, under review). Burnham and colleagues investigated whether the emergence of the PE in infancy is a function of post-natal auditory experience, or auditory cortex maturation. They studied three groups of infants: pre-terms at 10 months chronological age, and 7 months corrected age, and full-terms at 7- and 10-months chronological age. The two stimuli used were a rattle sound and a 3 msec click, identical to those employed by Morrongiello et al. (1984). PE thresholds for both stimulus types were equivalent for infants at the same corrected age. But comparison of infants with the same chronological age revealed lower thresholds for the full-term than pre-term infants. Results of this study are important in indicating that the PE develops as a function of maturation rather than experience.

C. The precedence effect in non-human mammals

The developmental findings with infants inspired an additional approach to investigating the onset of behavioral localization in mammals. Ashmead, Clifton and Reese (1986) tested German Shepherd Dog pups repeatedly during the first 6 weeks of life, in order to compare the appearance of localization for SS and PE sounds. This study revealed that at the time that behavioral localization for SS sounds was functional (around 16 days of age), localization capacity for PE sounds had not yet developed, and was still undeveloped when testing ended around 40 days. The apparent delay in localization of PE stimuli resembles the findings with human infants which have been described above. The authors suggested that such a developmental trend may be common to mammalian species.

In addition to behavioral work, much of the evidence in support of theories of auditory function arises from lesion studies. A common procedure is to compare the performance of animals on a task of auditory discrimination or localization, prior to and following surgical ablations. By noting whether animals' performance shows behavioral deficits, or remains intact or readily restorable, one can gain insight into the association between neuroanatomical regions and functional integrity.

Bilateral ablation of the auditory cortex has long been known to impair some aspects sound localization ability (Neff, Diamond and Casseday, 1975; Neff, Fisher, Diamond and Yela, 1956). However, the degree of the impairment varies with the behavioral task (Heffner, 1978), as well as the stimuli which are employed (Elliott and Trahiotis, 1972). For instance, following bilateral ablation of the auditory cortex, monkeys are unable to locate the source of a brief sound if required to walk towards it (Heffner and Masterton, 1975). In contrast, they are able to indicate the direction of the sound by pressing a lever or by making a reflexive head turn in the direction of the sound (Heffner and Masterton, 1975; 1978; Ravizza and Masterton, 1972; Thompson and Welker, 1963).

These results indicate that the cortical deficit in sound localization may not strictly be due to sensory impairment. There are several possible explanations of how the ability to localize sound has been disrupted in these animals. Cortical ablation seems to have less effect on responses which are completed either before or immediately after the sound is turned off. Thus, it may be that the animals suffer some sort of an amnesia, so that they are unable to remember the source of a sound long enough to complete a more protracted response, such as walking towards it (Heffner and Masterton, 1975; Neff et al., 1975; Ravizza and Diamond, 1974). Not unrelated, a second explanation is that the animals might have difficulty in attending to the stimulus (Neff et al., 1956). This latter explanation suggests that the animals may be distracted on auditory tasks, and this renders their performance poor once the sound has been turned off (Heffner, 1978). Lastly, one could explain the deficit in terms of a missing connection between auditory and motor functions. Ravizza and Diamond (1974) have suggested that sound localization is a three-step process: An animal must first identify the locus of the object; next it must store spatial information about it; third it must respond, for example, by moving towards the object. Thus, auditory cortex ablations may lead to a disruption in the connections between the mechanism for detecting the location of a sound, and the one for initiating a behavior towards the sound (Ravizza and Diamond, 1974; Ravizza and Masterton, 1972).

Similar types of experiments have been conducted in order to investigate the role of the cortex in the PE (Cranford and Oberholtzer, 1976; Cranford, Ravizza, Diamond and Whitfield, 1971; Whitfield, 1978; Whitfield, Cranford, Ravizza and Diamond, 1972; Whitfield, Diamond, Chiverallis and Williamson, 1978). Researchers have trained intact cats on a simple sound localization task, in which a SS sound was presented to a loudspeaker either on the right or left side. The cats were subsequently tested to see if the training transferred to the condition where identical signals were emitted from both loudspeakers, but one preceded the other by 3-16 msec. These animals then received unilateral cortical ablations, and were retested. Before surgery, the probability of errors were usually independent of which loudspeaker the sounds were emitted from. After surgery, performance on SS tasks remained fairly intact. In addition, the animals had no difficulty in correctly identifying the leading loudspeaker when it was located in the hemifield contralateral to the intact cortical hemisphere. However, performance on PE tasks was disrupted when the leading signal was contralateral to the lesioned side.

On the basis of these findings Whitfield et al. (1972) hypothesized that unilateral ablation of the auditory cortex destroys the laterality of a complex stimulus such as a PE stimulus, which would normally be localized on the side of the leading signal. They suggest that this deficit involves the destruction of the normal temporal order of lead-lag stimulus pairs, which abolishes the predominance which the leading signal usually receives in localization. An additional hypothesis proposed by Whitfield (see Cranford & Oberholtzer, 1976) suggests that the ablation decreases the amount of cross-inhibition that the leading sound source imposes upon the lagging sound. Since the PE involves a gradual increase in the suppression of the lagging sound as the delay in decreased, unilateral ablation essentially decreases echo threshold. The role that the auditory cortex and other central auditory structures might play in mediating the PE remains to be fully understood. It may be that only with such studies can the neural mechanisms of the PE be fully understood. Although, by investigating the behavior of humans under conditions of the PE one can extrapolate to neuronal processes that may be involved in sound localization in the presence of echoes.

D. Purpose of the present study

The purpose of the present study was to investigate developmental differences in sound localization precision, under both single source (SS) and precedence effect (PE) conditions. Past developmental research concerning the PE has never addressed the question of how echoes influence infants' and children's ability to localize the original sound source in the presence of an identical echo. Rather, loudspeakers were always positioned at 90° to the left and right of midline, and the variable that was measured was ability to detect the lag sound at various delays. Hence, localization precision under conditions of the PE could only be assessed in terms of the ability to localize a target stimulus in one of two hemifields. Clifton et al. (1984) predicted that the ability to precisely localize sounds within a hemifield would develop later for PE stimuli than for SS stimuli. This prediction has never been tested, and if we are to approach a fuller understanding of the mechanisms underlying the PE and its role in sound localization, such studies must be conducted.

At the time that the developmental precedence effect work was published, little was known about the development of finer sound localization within a hemifield, not just with PE stimuli, but even with simpler SS stimuli. Since then, a number of studies have been published, describing acuity on sound localization tasks using SS stimuli (e.g., Ashmead et al., 1987; Morrongiello, 1988). These studies, which have been reviewed above, employed the MAA paradigm, which measures the minimal shift in the position of a sound source which can be reliably detected (Mills, 1958). This measure can be obtained with infants by training them to turn their heads towards a novel location of a stimulus, using the visual reinforcement procedure. Under this condition, infants are only reinforced when they correctly discriminate a shift from midline towards the right or left.

The MAA task can be further extended to a PE situation (e.g. Perrott et al., 1989), in which both a lead and lag are present, but the latter is inaudible as a separate sound. In this situation one can present listeners with either single-source sounds, or PE sounds in which the lag is presented to the right or left with the lead at midline, or the reverse (lead on right or left and lag at midline). In case of the PE stimuli, the listener only hears one fused image, the exact location of which is unclear but determined by both sounds. This paradigm allows one to study the relative influence that the lead and lag each exert on the perceived position of a PE sound.

In this study, adult subjects were tested with the primary interest being comparison with children's performance. However, only one study exists in the literature which has tested adults in the PE LAG situation (Perrott et a., 1989). More important, no data exist on the PE LEAD situation, which is a critical condition to the assessment of the influence that an echo might have on the perceived position of a fused PE auditory image. It was imperative that Perrott et al's (1989) data be replicated, and that new information be provided for the LEAD condition. A second issue addressed with adults was the effect of stimulus duration of MAA thresholds. With a long stimulus duration (i.e. 25 msec) and a short lead-lag delay (i.e. 5 msec) there is a 20 msec overlap of the lead and lag stimuli. It is possible that such a long overlap of 80% of the duration of the noise burst may lend a great deal of perceptual weight to the lag stimulus, which may not be available if the amount of overlap were shortened. A second group of adults were tested with a short duration stimulus (4 msec), and a delay which provided no lead-lag overlap (4 msec).

In order to investigate developmental differences in MAA thresholds it was necessary to select ages at which children's MAA thresholds on SS stimuli were fairly low, reflecting a well developed mechanism for localization precision. However, these ages had to be young enough for the development of localization under conditions of the PE to be still developing. The youngest age chosen was 18-month old children, who have previously been reported to have MAA thresholds as low as 4° with SS sounds (Morrongiello, 1988). At this age however, the cortex and other brain structures are still undergoing considerable maturation, which may affect their performance on PE tasks.

The next age group was 5-years of age, at which children are known to have similar echo thresholds to adults for simple PE sounds, but higher thresholds for more complex sounds (for review, see Clifton, 1985). This difference in threshold may be indicative of a transition stage in the ability to utilize echoes of varying complexity in sound localization tasks. Children at this age have never been tested on MAA tasks. Although, they were expected to have low thresholds at least on SS stimuli, to correspond with their adult-level echo thresholds for simple sounds. No specific predictions were made concerning MAA thresholds for PE stimuli, since they could have either been similar to those of 18-month-olds, or to adults', or somewhere between the two.

Testing 5-year-old children was critical in that it could potentially set a top limit to the age at which localization precision under conditions of the PE develops (i.e. if PE thresholds turned out to be similar to adults). If children's performance was worse than adults for PE but not SS stimuli, it would indicate that precision for SS and PE sounds develops separately (i.e. if PE thresholds were higher than those of adults). The latter scenario may point to the existence of separate localization mechanisms for sounds with and without echoes.

CHAPTER II

METHOD AND PROCEDURE

A. Subjects and design (see Table 1)

Three age groups were tested: 18-month-old children, 5-year-old children, and adults. Each child age group was subdivided into 3 groups (N = 12 each) according to stimulus type. Subjects were randomly assigned to condition upon entering the laboratory and were tested with one stimulus type only. Adult subjects were tested in a within-subject design, each subject being presented with all three stimuli (SS, LEAD, LAG). The order of presentation was randomly assigned to subjects, with one of 6 possible configurations (SS, LEAD, LAG; SS, LAG, LEAD; LEAD, SS, LAG; LEAD, LAG, SS; LAG, LEAD, SS; LAG, SS, LEAD). Each configuration was presented to two subjects in each adult group. Two groups of adults were tested, which differed on the duration of the auditory stimulus and the delay between lead-lag on PE conditions. One adult group matched the conditions presented to the children, whereas the other did not.

1. Children

Letters describing the study were mailed to parents and followed up by a telephone call to make an appointment (see

Table 1: Design of study

GROUP #	N	AGE	STIMULUS	DURATION (delay)
1 - A	12	18 - mo	SS	25 ms (5 ms)
1 - B	12	18 - mo	LEAD	25 ms (5 ms)
1 - C	12	18 - mo	LAG	25 ms (5 ms)
2 - A	12	5-years	SS	25 ms (5 ms)
2 - B	12	5-years	LEAD	25 ms (5 ms)
2 - C	12	5-years	LAG	25 ms (5 ms)
3 - A	12	Adult	SS; LEAD; LAG	25 ms (5 ms)
3 - B	12	Adult	SS; LEAD; LAG	4 ms (4 ms)

Appendices A and B for sample letters). On the day of testing parents filled out a questionnaire concerning the health and medical history of their child (see Appendix C), and signed a consent form which permitted testing of their child (see Appendix D). All children included in the final sample had no known hearing disabilities according to the parents' verbal report. The final sample of 36 18-month-olds (12 males, 24 females) had a mean age = 18 months, 3 weeks (range = 16 months, 3 weeks - 20 months, 3 weeks). An additional group of 13 children were excluded from the final sample due to a history of frequent ear infections (N = 1), suspicion of hearing impairment (N = 2), or loss of interest in the task prior to reaching 7 reversals (N = 10). The final sample of 36 5-year olds (19 males, 17 females) had a

Table 2: Biographical data - 18-month-olds

SUBJECT #	AGE(mo,wk)	SEX	CONDITION
2	19.2	M	LEAD
3	20.3	F	SS
4	19.3	F	LEAD
7	20.2	M	LEAD
9	17.1	F	LAG
10	20.1	F	SS
12	20.3	F	SS
13	19.2	M	LEAD
14	16.3	F	LAG
15	20.0	M	LEAD
16	20.0	M	LAG
17	20.0	F	LEAD
19	17.2	F	LAG
21	19.2	F	SS
22	19.2	F	LAG
24	18.1	F	SS
25	20.0	F	LAG
26	20.0	F	LEAD
27	19.3	M	SS
28	17.2	F	LAG
32	19.2	F	SS
33	19.2	F	LEAD
34	19.2	M	LEAD
35	19.3	M	LEAD
36	20.0	M	SS
37	17.2	M	SS
38	20.0	F	LEAD
39	18.0	M	LAG
40	19.2	M	LAG
41	19.0	F	LAG
42	18.2	F	LEAD
44	19.1	F	LAG
45	20.0	F	LAG
47	18.2	F	SS
48	19.3	F	SS
49	18.1	F	SS

mean age of 5 years, 4.4 months (range = 4 years, 6 months - 6 years). An additional 10 children were tested but excluded from the final sample due to suspicion of hearing impairment (N = 2) and loss of interest in the task (N = 8). Biographical data for the final sample of 18-month-olds is included in Table 2, and for the children in Table 3. As a gesture of appreciation for their time and effort, at the end of the testing session each child received a gift from an assortment in the laboratory. In addition, they were given a certificate of appreciation bearing the child's name, the date of testing, and signatures of the experimenters.

Children were recruited from birth announcements in the newspapers at the time of the child's birth. Information concerning the number of letters sent to parents, number of subjects scheduled, number of uninterested parents is listed in Appendix E. Pilot testing with 17-19 month-old and 5-year-old children revealed that in both age groups, most subjects maintain interest in the task for about 20 minutes. This time span would allow for testing each child on one stimulus variable. All children were trained with the single source (SS) stimulus, and subsequently tested with one of the three conditions. The final subject population was subdivided into three groups (N = 12 each).

Table 3: Biographical data - 5-year-olds

SUBJECT #	AGE(yr,mo)	SEX	CONDITION
1	6.0	F	SS
2	5.2	F	LAG
3	5.0	F	SS
4	4.6	M	LEAD
5	5.9	F	LEAD
6	5.6	M	LAG
8	5.4	M	SS
10	5.8	M	LAG
11	5.9	F	LAG
12	6.0	F	SS
13	5.11	F	LEAD
15	5.1	M	LEAD
16	5.1	M	SS
17	5.6	M	LAG
18	5.0	M	SS
19	5.8	F	SS
20	5.7	M	LEAD
21	5.0	F	LEAD
23	5.2	M	SS
24	5.2	F	SS
25	6.0	M	LEAD
26	5.2	F	LAG
28	6.0	M	LAG
29	5.8	F	LEAD
30	5.8	M	LAG
31	5.3	M	LAG
32	5.4	F	SS
33	5.9	M	LEAD
35	5.3	F	LAG
36	5.7	F	SS
37	5.8	F	LEAD
38	5.3	M	LAG
40	5.9	F	LEAD
42	4.8	M	SS
43	5.7	M	LEAD
44	5.7	M	LAG

2. Adults

Subjects were recruited from the undergraduate student population at the University of Massachusetts, and were granted a credit slip, which can be applied towards their grade in given psychology courses. A consent form was signed prior to testing, in which the subjects stated that their participation was voluntary (see Appendix F). Screening for hearing problems was conducted by verbally asking people if they have a history of hearing problems or if they have a cold on the day of testing. If they replied in the negative on both accounts their hearing was tested for frequencies ranging between 250-8000 Hz. No subjects were included in the final sample if for any given frequency their hearing in both ears did not match within 10 dB or less, or if their detection levels were more than 20 dB above that of normal levels. The final sample of 12 subjects in group 3-A (see Table 4) consisted of 2 males and 10 females (mean age = 20, range = 19 - 21 years). Four additional people failed the hearing test and their data were not included in the analysis. The final sample of 12 subjects in group 3-B (see Table 4) consisted of 2 males and 10 females (mean age = 21.5 years, range = 18 - 25 years).

Table 4: Biographical data - Adults

SUBJECT #	AGE (yr)	SEX	CONDITIONS ORDER
GROUP 3-A (25 ms duration stimulus; 5 ms delay)			
1	19	F	SS,LEAD,LAG
3	20	M	SS,LEAD,LAG
4	19	F	LAG,LEAD,SS
5	22	M	SS,LEAD,LAG
6	20	F	LEAD,SS,LAG
7	20	F	LEAD,LAG,SS
8	21	F	LAG,SS,LEAD
9	20	F	LAG,LEAD,SS
10	19	F	LEAD,LAG,SS
11	21	F	SS,LAG,LEAD
15	19	F	LAG,SS,LEAD
16	20	F	LEAD,SS,LAG
GROUP 3-B (4 ms duration stimulus; 4 ms delay)			
17	21	F	SS,LAG,LEAD
18	19	F	LEAD,SS,LAG
19	18	F	LAG,LEAD,SS
20	20	F	SS,LEAD,LAG
21	19	M	LEAD,LAG,SS
22	20	M	SS,LEAD,LAG
23	21	F	SS,LAG,LEAD
24	25	F	LEAD,LAG,SS
25	23	F	SS,LAG,LEAD
26	22	F	LAG,SS,LEAD
27	19	F	LEAD,SS,LAG
28	20	F	SS,LEAD,LAG

B. Stimuli

The auditory stimuli were digitally generated by a computer (AST 286) and converted to analogue form. The signals were subsequently filtered (TTES lowpass at 8500 Hz) and fed to a tape recorder (Teac X-300). During testing the pre-recorded stimulus was played back from the same tape recorder over loudspeakers. Some characteristics of the stimuli, such as the rise-fall time of individual noise bursts and the frequency range, were selected due to the relative ease in localizability of such stimuli (Hartmann, 1983). Other characteristics, such as the duration of the stimulus and the delay, were chosen on the basis of results from pilot data, which revealed the degree of echo suppression that the stimuli produced. Stimuli were selected so that precedence effect was functional, i.e. that the lagging signal could not be heard as a separate auditory event, but the position of the auditory image could still have bene influenced by the existence of the echo.

The auditory stimuli consisted of white-noise bursts, with a frequency range of 500-8500 Hz. For all children and adults group 3-A, each noise burst was 25 msec in duration, with rise and fall times of 2 msec. For adults group 3-B, each burst was 4 msec in duration, with rise fall times of 2 msec. A spectral analysis of the signal once it was played back through the loudspeakers revealed that most of the energy was at 2000-3000 Hz or below. The sound was presented at levels of 50-52 dBA, over a background level of 30 dBA, as measured at the approximate position of the subject's head. On each trial the noise bursts were presented as a continuous train at a rate of 2/s (see Figure 1 for stimulus configuration).

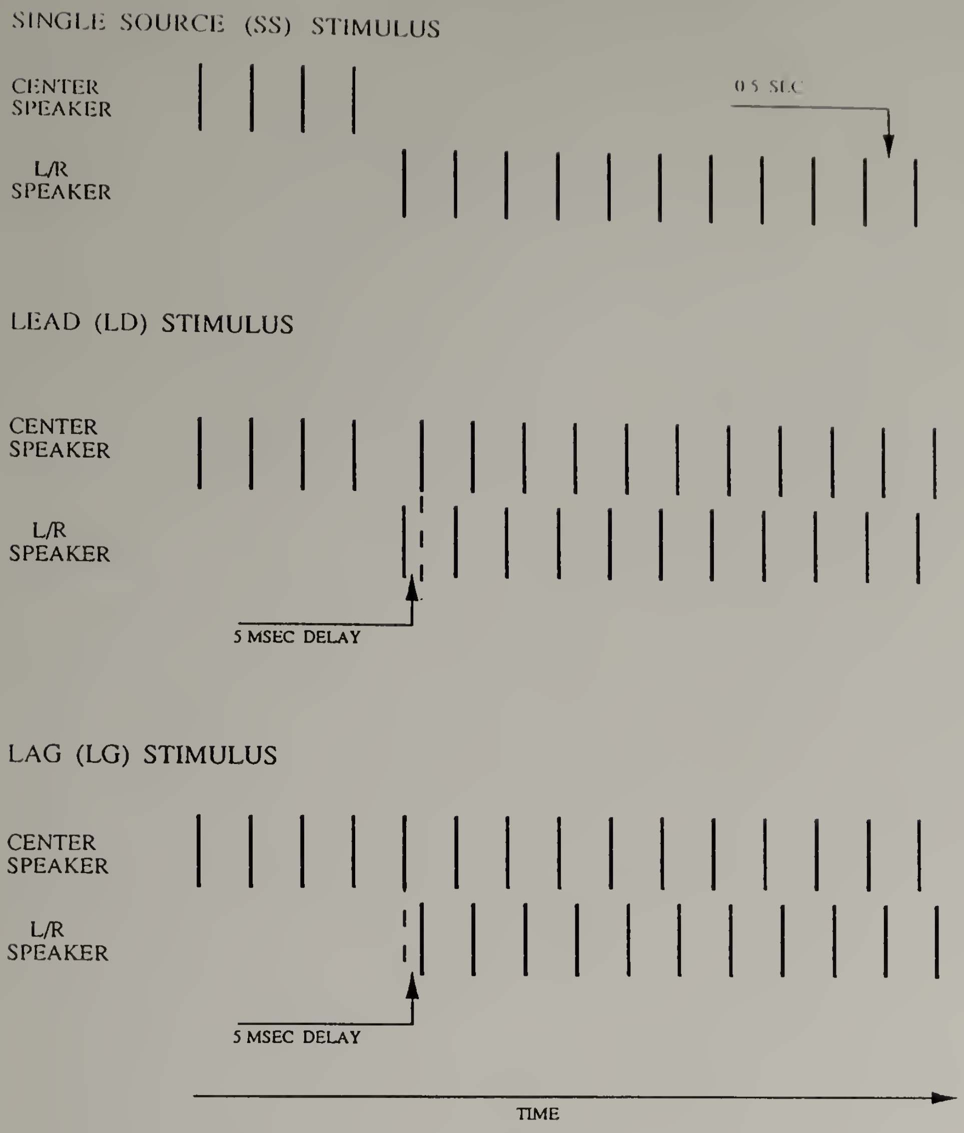

Figure 1. Configuration of auditory stimulus as it is presented from the loudspeakers. On a single trial, two loudspeaker are activated, one at midline (center) and one on either the right or left of midline. For single-source (SS) stimuli, only one loudspeaker is activated at one time. For lead (LD) stimulus, the center loudspeaker is activated first, and after 4 noise bursts it is followed by either the left or right loudspeaker with a delay of 5 msec. For lag (LG) stimulus, the center loudspeaker is activated first, and after 4 noise bursts, either the left or right loudspeakers are activated, followed by the center one with a delay of 5 msec.

C. Apparatus

The study was conducted in a sound-attenuated room, 3.5 x 4.0 meters in dimension. Adjoining the testing room was a control room, from which some of the necessary equipment was monitored. This equipment included: tape-recorder (Teac X-300) through which the sound was played back; amplifier (Onkyo A-8170); video deck (Panasonic GX2 1950) and monitor which received input from the camera inside the testing chamber; and the response box which is used by the investigator in this room to indicate the direction of an infant's head turn. In addition, a computer (IBM-PC, model AT) received input concerning a subject's response, and calculated the mathematical algorithm which determined the angular position for the loudspeakers. For each trial, this information was displayed on the computer screen.

Inside the testing chamber was an arc-shaped apparatus, from which loudspeakers were suspended at ear level, and positioned at 0-55° to the right and left along the horizontal dimension. In addition, two foam-covered stands were positioned at 75° to the right and left, to allow presentation of the stimuli at those wide angles. This was only necessary for the 18-month-old group tested on the LAG condition. Three loudspeakers were used (Radio Shack model Minimus-7) with matching frequency responses within 1-2 dBA for all frequencies between 31.5-8000 Hz. Each loudspeaker was 4" width x 7" height and subtended 4° along the horizontal plane. For all trials, one loudspeaker remained at midline, while the other two were positioned at equal angles to the left and right of midline. 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, Schneider, & Bull, 1981). The first toy is a dog which walks and barks, and the second is a rabbit which shakes a jingle-bell and brings a carrot to the mouth. Each toy was enclosed within a smoked-plexiglass box so that it remained invisible to the subjects except when activated.

The entire apparatus was enclosed behind a dark curtain to occlude the loudspeakers and experimenter, as well as the rest of the testing chamber. Subjects were seated facing the apparatus such that the position of their head was at a distance of 5 feet from the curtain. Adults and 5-year-old children sat on a chair, whereas 18-month-old children were seated on their parent's lap. Parents were asked to wear head phones which enabled them to hear the same sounds as the child heard, but which obscured all directional information.

A video camera was positioned above the curtain at midline position. The camera output was connected to one monitor behind the curtain, and another monitor in the outside control room. The purpose of the video images was to allow the experimenters both inside the testing chamber and in the adjoining control room to view the subjects' behavior during testing. This was especially important for testing the youngest children, whose responses were measured in terms of head-turning behaviors towards the correct loudspeaker.

D. Methodological considerations with young children

The present study utilized the conditioned head turning response for testing 18-month-olds. In addition, the psychophysical algorithm used to determine the angular positions of the sound were chosen for very specific reasons. The present section is aimed at justifying the behavioral measure and mathematical algorithm which were employed in this study.

In conducting developmental research on perception one must keep in mind a variety of important factors, which include response measures, stimuli parameters, and the translation of behaviors into meaningful statements about sensation and perception. A prominent issue in this field of research is that young children cannot be verbally asked what they hear, or whether they differentiate one sound from another. In order to obtain such information one needs to present children with a behavioral task that they can easily learn, and which will elicit behaviors that are consistent and easily measurable. In conducting auditory research one is faced with the additional problem that the auditory system is devoid of unique behavioral responses to stimulation. In contrast, the visual system has behavioral responses such as eye fixation and head orientation that are inherently related to that sensory system.

Aslin, Pisoni & Jusczyk (1983) present an extensive review of behavioral measures used to study hearing sensitivity with young children and infants. The authors divide the most common response measures into two classes of behaviors: (a) the auropalpebral reflex, (which involves blinking, or tightening of the eyelids); the Moro or startle reflex; changes in general body activity; and eye movements; (b) non-nutritive sucking; heart rate; evoked responses from the cortex and brainstem; and the conditioned head turn response. The difference between these two groups of behaviors is that only those in class (b) have proved useful in measuring sensory capacities that require behavioral orienting, or attentional responses to a sound source (Schneider and Trehub, 1985). These types of responses are easily elicited or modified by the presentation of changes in auditory stimuli, and seem most appropriate in the investigation of spatial localization accuracy.

Of these class (b) behaviors, the conditioned head turning response has been most widely used, since it fulfills a series of methodological requirements: 1) it has applicability over a wide age range, 2) it is non-invasive, 3) it can be easily observed and reliably measured on-line, and 4) it is sufficiently robust to provide data from a single session. The head turning response was originally developed as a conditioning orienting reflex (COR; Suzuki and Ogiba, 1961), and has since been adapted to a forced-choice procedure, in which the infant is required to turn toward one of two loudspeakers. The most common technique involves visual reinforcement of a correct head turning response, which can be effectively functional by about 5-6 months of age (Moore, Thompson and Thompson, 1975). The procedure was originally used as a go/no-go discrimination task, but was later modified into a two-alternative-forced-choice paradigm (2AFC; Trehub, Schneider and Endman, 1980).

In conducting perceptual research and trying to compare performance of infants and young children with that of adults, the 2AFC paradigm provides numerous advantages over the go/no-go procedure, as discussed by numerous authours (MacMillan & Creelman, 1991; Trehub et al., 1986). First, it eliminates the need for control (no stimulus) trials, which are essential with the go/no-go task in order to measure baseline behavior. Second, the 2AFC minimizes any concerns about response bias, by requiring two rather than one loudspeakers to the test protocol. Third, every trial adds to the data set, seeing as the response on every trial is either correct or incorrect, whereas only correct trials add to the data set in a go/no-go task. Fourth, by eliminating a fixed-response interval subjects who are slow to respond can be included in the sample, leading to lower attrition rates. The advantages of the 2AFC are especially marked when subject pools are limited.

The 2AFC paradigm has proved particularly most useful for exploring developmental auditory psychophysics, and the relationship between sensory capacities and behavior. There are two basic approaches used to determine a child's detection thresholds; the method of constant stimuli or adaptive procedures. The method of constant stimuli has been used widely (for example see: Morrongiello and Rocca, 1987; Trehub, et al., 1980; Trehub, Schneider and Bull, 1981; Trehub, Thorpe and Morrongiello, 1985). It involves the repeated presentation in random order, of several predetermined stimulus levels such as angular position or sound level. In using such a procedure, one has to select a range of stimuli in advance, which must extend from very poor to excellent performance levels. In this case the psychometric functions obtained are used to estimate threshold levels. However, it must be noted that these functions are based on groups means, and are not representative of individual subjects' data, due to limitations in the number of trials that individuals can be tested on. In order to attain sufficient information at all performance levels, and to insure that the proper range is covered for every subject, one is forced to run many conditions and a very large number of trials. Consequently, two types of sacrifices are necessary. First, since each child must be tested on many predetermined stimulus levels, it is difficult if not impossible, to obtain thresholds for individual children. Second, in order to obtain thresholds for a given age group, a very large N size is usually required. An investigator who has virtually unlimited access to a subject population may not be worried by this limitation. However, if dealing with a limited subject pool one must take this fact into consideration when designing a threshold study.

Adaptive methods have also been used extensively in infancy perception research (for example see: Aslin, Pisoni, Hennesy and Perey, 1981; Ashmead et al., 1987; Berg and Smith, 1983; Olsho, 1984; Olsho, 1985; Olsho, Koch, and Halpin, 1987; Sinnott, Pisoni and Aslin, 1983). With the adaptive method one does not need to select the stimulus levels to be tested ahead of time. Rather, the selection process occurs as part of the testing session, and depends on the subject's performance. In other words, the stimulus levels are tailored to the individual perceptual limitations and capabilities of every subject. As a result, adaptive methods minimize the number of trials per subject while still assessing individual thresholds.

The most commonly used adaptive procedures are the up-down staircase methods (e.g., Cornsweet, 1962; Levitt, 1971), and a modified version of them, in which the step size is changed as well (Taylor and Creelman, 1967). Different staircase algorithms vary in the rules used to determine when and by how much the stimulus level changes, when to terminate the session and how to estimate threshold. Up-down staircase methods in which every response leads to a change in stimulus level, place threshold observations in the 50 percentile range of performance. However they do not track subjects' performance at a high level, which could make the task much more difficult (Levitt, 1971). This makes simple staircase methods inappropriate for testing young children, as testing must be carried out at levels of performance significantly above chance in order to maintain the subject's interest in the task (Trehub, Bull, Schneider, and Morrongiello, 1986).

The transformed up-down procedure is an alternative method for estimating thresholds at other levels of performance (Levitt, 1971; Taylor & Creelman, 1967; Trehub et al., 1986). Sequences of observations are categorized into two mutually exclusive groups, termed the up and the down groups. The method used to group observations depends on the level of performance to be estimated. In controlling the stimulus level or size, changes occur only after a sequence of observations belonging either to the up or down groups has occurred. The probability-ratio rule used in the mathematical algorithm of up-down testing tracks a subject's performance at a given probability range. This rule results in an increase of the stimulus level (such as sound level, delay or angle) whenever the probability of a positive response lies below the lower bound of the range. Similarly, the stimulus level is decreased whenever the probability of a positive response lies above the upper bound of the range. This type of an up-down procedure converged fairly rapidly on a subject's threshold region and concentrate most of the observations within that region (for further discussion see Levitt, 1971; Taylor and Creelman, 1967).

One of the most critical factors in testing children is to insure that they are not presented with too many trials. Loss of attention and fussiness towards the end of a session could lead to results which underestimate child's perceptual thresholds. In limiting the number of trials however, one is faced with sacrificing other aspects of the data, such as low variability and better estimates of thresholds. It has been suggested however that as long as at least 6-7 reversals of direction are obtained before testing is terminated, one can gain a reasonably good measure of threshold (Wetherill and Levitt, 1965). In addition, it is recommended that for developmental psychophysics, testing be conducted at a level of performance of 70% or higher. Thus, the algorithm of choice with young children are either the

2-down/1-up or 3-down/1-up procedures, which yield performance levels of 70.7% and 79%, respectively (Levitt, 1971).

E. Psychophysical algorithm

The algorithm was calculated in an on-line fashion by a personal computer (IBM PC, model AT). A printed copy of the computer program is included in Appendix G. For all age groups, the psychophysical algorithm was a 2-down/1-up staircase procedure. The threshold estimates derived from this algorithm predict the 71% point on a psychometric function (Levitt, 1971). The algorithm is computed for every trial based on the history of each subject's responses during the session. The initial positions for the side loudspeakers as selected for relative ease of detection in angular shift. Based on results from pilot testing these initial positions were set as follows: SS and LEAD stimuli for 18-month-old children and all stimuli for 5-year-old children = 55°; LAG stimulus for 18-month-olds = 75°; all stimuli for adults = 30°.

Once the initial angle was selected, the PEST rules (Taylor & Creelman, 1967) rules were administered and are listed below:

(1) The size of change in angle position, regardless of direction, was halved every time that a change in direction, i.e. a reversal occurred; the smallest step size was 1°.

(2) After two consecutive correct responses, the angle was decreased. If the resulting angle was smaller than 1°, the step size was halved[1], unless the last angle had been 1°, in which case, the speakers were placed at 0°, and were moved following one failure[2].

(3) A change in the same direction as the last used the same step size as previously. However, a third step in the same direction called for a doubled step, and each successive step in the same direction was also doubled until the next reversal. This was true except when a reversal

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[1] For the 18-month-olds' LAG condition, the computer program treated 75° as any angle above 55°. When an increase in angle resulted in a speaker position above 55°, an angle of 75° was automatically chosen. However, the step size was mistakenly not adjusted to reflect the true step size. Hence, changes in step size followed the rules as per the reversals, but did not take into account the fact that the loudspeaker positions were altered between 55-75°. Consequently, the program did not consider 75° as a probe trial, and entered it into the calculation for reducing the step size. In contrast, probe trials did not enter into the calculation for all other groups. In addition, some of the subjects' algorithm changed in smaller step sizes than they should have been. Although this error may have led to an underestimation of LAG thresholds, the possibility remains that it did not. If subjects thresholds were indeed lower, they would have had the opportunity to require smaller angles had their responses been correct on a regular basis. For a subject who should have been lower, the step size would have eventually increased at angles below 55°.

[2] It should be noted that conceivablly an angle of 0° may have underestimated some subjects' thresholds, especially if they were below 1°.

followed a doubling of step size. In that case, an extra same-size step was taken before doubling, after the original two, and a maximum step was specified.

(4) After a single failure, the angle was increased.

(5) After two consecutive failures a "probe" trial (Aslin, et al., 1981) was presented, where the loudspeakers were placed at the initial angle position. This trial type was repeated until a correct response was made.

(6) Following a probe trial, once a correct response was made, testing resumes at the angle position of the last failure.

(7) When non-response (NR) trials occur they were not considered in the calculation as either correct or incorrect responses. If one NR trial occurred, the same angle position was maintained. If two NR trials occurred in a row, a probe trial was presented and repeated until a correct response was made.

(8) Every time that the shift in angle position changed direction constituted a reversal. This could result from an increase in angle followed by a decrease, or a decrease followed by an increase. The testing session terminated once 7 reversals were reached.

(9) Threshold was calculated as the mean of the angle positions at the last 5 reversals. Subjects who did not reach 7 reversals were excluded from the final sample.

The values chosen for both number of reversals to reach criterion, and number of trials on which a subject had to be correct before the angle was decreased, were based on extensive pilot testing with using the method of constant stimuli. This testing revealed an upper limit in the number of trials on which individual children could be tested during the session. This upper limit restricted some specifications in the psychophysical algorithm in order to insure that subjects' attention span was maintained throughout the session.

F. Procedure

The session consisted of an initial training period to accustom the subjects to the task, and insure that they could meet a required criterion before proceeding with testing. Subsequently threshold testing took place for one or three stimulus condition, depending on the age group. From trial to trial, the sound shifted randomly to the right or left loudspeaker, with the restriction that no more than a certain number of consecutive trials be to one side, depending on age group: 18-month-olds = 3 trials, 5-year-olds = 4 trials, adults = 5 trials. This was done in order to prevent any side bias, especially on the part of 18-month-olds.

1. Practice trials Subjects in all age groups were trained to perform on the task using single source stimuli, with the loudspeakers positioned at 55° away from midline on both right and left. An angular shift from midline to 55° is one which all age groups have previously been found to detect quite easily and reliably. Subjects had to meet the criterion of correct head turns on 4/5 trials, and were allowed a maximum of 10 trials to reach criterion. All subjects met the criterion without difficulty.

2. Testing trials These trials ensued immediately following practice trials. There were three types of testing trials, although in obtaining individual thresholds only one trial type was used at a time. For adults, testing began with the trial types assigned to their condition, and continued until threshold was obtained. Once threshold was measured, testing began again using a new trial type.

a. SS trials The auditory stimulus was pre-recorded on the tape such that it was attenuated to 0 dBA on channel A for an initial 1.5 sec, and on channel B for the 11 sec that followed. Channel B was always connected to the center loudspeaker which was stationary, whereas channel A could transmit signals to either the left or right loudspeakers. When the stimulus was presented, it was initially delivered to the center loudspeaker for 1.5 sec (4 noise bursts), and subsequently switched to either the L or R loudspeaker, where it played for an additional 5 sec (11 noise bursts).

b. PE trials Both types of PE trials (Lead and Lag) were pre-recorded on tape such that, for the initial 1.5 sec the signal on channel A was attenuated to 0 dBA. During the subsequent 11 sec both channels were set to the same dB level; the signal which remained at midline was recorded on channel B, and the signal which was due to shift away from midline was recorded on channel A. Channel B was therefore connected to the center loudspeaker, whereas channel A was connected to either the left or right loudspeakers. Trials began with a SS stimulus presented at midline for 1.5 sec (4 noise bursts) to center the subject's attention. Subsequently, two loudspeakers emitted identical signals, with one leading the other by 25 msec; this stimulus continued for 5 sec (11 noise bursts) or until a response was made, whichever came first.

3. Roles of experimenters

Two experimenters participated in each testing session. The experimenter inside the testing chamber wore earphones to mask information concerning which delay trial type was being presented. She was responsible for centering the infant's attention prior to the onset of each trial, positioning the loudspeakers at the appropriate angles for each trial, and controlling a button box which determines whether the sound shifted to the left or right.

At the beginning of the training session, the inside investigator typed into the computer the initial angle position for the loudspeakers, which was a pre-determined variable in the testing protocol. Based on this initial position the computer calculated the appropriate loudspeaker position for all subsequent trials during the testing session. Prior to each trial the loudspeaker angular position and left or right loudspeaker was displayed on the computer screen. The investigator followed these instructions, and the trial ensued. Following the trial, the experimenter indicated using the y/n buttons on the computer keyboard whether the subject's response was correct. This was determined by whether the reinforcers were activated or not. If a reinforcer is activated, the answer is "y", and if none were activated by the end of 5 sec, then the appropriate answer is "n". If no response was made, an answer of "0" was entered. Based on this response the computer calculated the angle position for the next trial.

The experimenter in the outer room controlled the tape-recorder which delivered the stimulus to the loudspeakers. This person, who did not know which loudspeaker the sound shifted to, was responsible for making judgments about the subjects' behavior. These judgments resulted in activation of the reinforcers for 5 sec following correct responses. If the response was incorrect, no reinforcer was activated and a time-out period of 5 sec ensued. Three independent observers were trained on judging head turning responses, and observer A served as the main experimenter in the control room for the majority of subjects. Percent agreement for the three observers were: A-B = 95 %; A-C = 96%; B-C = 94%.

4. Protocol for testing 18-month-olds

At the onset of each trial, the inside investigator insured that the loudspeakers were at their appropriate positions, and that the correct hemifield to which the sound will shift has been selected. She then held a small toy at midline position above the curtain, and called out the child's name until the child looked straight with the head centered. At that point, the outside investigator, who was monitoring the child's behavior on video, activated the tape-recorder to deliver the stimulus. The inside investigator ceased to call the child's name, but kept the toy in position to maintain the child's attention centered while the sound was emitted from the center loudspeakers. After 1.5 sec, the sound shifted to either the left or right loudspeakers, at which point the toy was withdrawn. The outside investigator observed the child's behavior in preparation for making a judgment about a head turn in either direction. It has been observed during piloting that infants and children develop behavioral contingencies with reinforcement fairly quickly, and that if not reinforced immediately, the contingencies may develop for behaviors other than head turning. In order to avoid reinforcement of other behaviors the first change in the child's head position was used to judge a choice about right or left. A head turn was therefore defined as the first observable change in the infant's head orientation from midline, toward either the left or right side. There was no required, predetermined minimum shift in head orientation, although pilot testing has revealed that a change of at least 10° was usually needed before the behavior could be reliably detected by most trained observers.

The outside observer made her decision by pressing either the right or left reinforcer buttons, corresponding respectively, to a right or left head turn. Two different toy reinforcers were presented alternatively in order to maintain the child's attention for as long as possible. If no head turn was made during the 5 sec after the shift in loudspeaker position, the trial was considered a non-response trial. On these trials, no reinforcement was delivered, but a natural 5-sec time-out period ensued, due to the fact that no response occurred. The selection box for the reinforcers (in the control room) was connected to the loudspeaker-selection box (in the testing room) through a voltage meter and a power supply box. The power supply delivered voltage to a reinforcer only if it was on the same side as the one selected on the loudspeaker selection box. This connection ensured that the reinforcer was activated only if the side chosen matched the side to which the sound had shifted. Thus for psychophysical purposes a subject was correct on a trial only if a reinforcer is activated.

5. Protocol for testing 5-year-old children and adults

At the onset of each trial the subject was asked to center the head and look straight ahead. The stimulus was then presented, and subjects were instructed to point their hand toward the right or left hemifield once the sound shifted. Subjects were told that on some trials they might perceive no change in the position of the sound, and on such trials they should guess as to whether the sound shifted to the right or left. Subjects were also told that following a correct response they would see a toy animal activated. No direct information was provided concerning an incorrect response. During testing the experimenter in the outer room observed the subject's behavior through the video monitor, and pressed the reinforcer button corresponding to the side chosen by the subject. This feedback was especially important for children. Although they were not trained to respond on the task using reinforcement techniques, children attended to the task for a longer time period. The experimenter in the inside room involved the children in a game, in order to maintain their interest in the task. Each child was told that if he/she knew which direction the sound had moved in, they would acquire a point, as indicated by the activation of a toy animal. If the toy was not activated following their decision, the experimenter received a point. Children were told that if at the end of the game they had more points than the experimenter, they would receive a prize. Since the psychophysical algorithm maintained performance at 70% correct, all children "won the game" and received a prize.

CHAPTER III

RESULTS

A. Threshold calculation

The present study utilized an adaptive mathematical algorithm during testing, which determined the angular positions at which the stimuli should be presented based on the subject's performance throughout the session (see Method chapter, section E for set of rules). Correct responding on two consecutive trials resulted in a decreased angle, and incorrect responding on one trial resulted in an increased angle. This rule, conventionally known as the 2-down/1-up rule, converges on a performance level of approximately 71% correct (Levitt, 1971). Whenever a change in angular position was in a direction opposite to the one that preceded it, e.g. an increase followed by a decrease, this change constituted a reversal. Testing terminated following 7 reversals. Each subject's minimum audible angle (MAA) threshold was calculated based on the mean of the last 5 reversals. The initial 2 reversals were dropped from the calculation to minimize variability in the data, since those trials are associated with targeting the vicinity of psychophysical threshold. An example of an 18-month-old subject's threshold estimate for the SS stimulus condition is plotted in Figure 2. The angular shift in the position of the sound is plotted as a function of trial number. Note

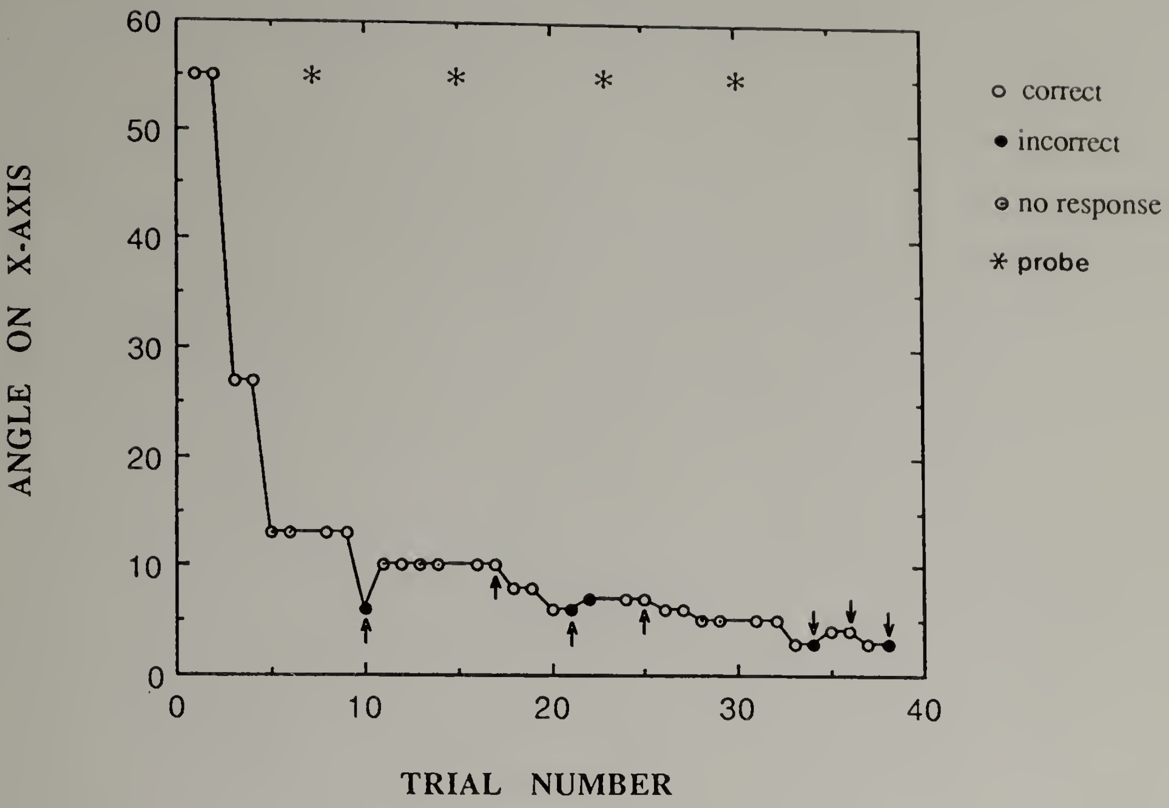

Figure 2. Sample threshold estimation for an 18-month-old subject tested with the SS stimulus. Plotted on the x-axis are trials, and on the y-axis are the corresponding angles. The asterisk marks denote probe trials at 55°, which follow 2 consecutive no-response or incorrect trials. The arrow marks denote reversals in the direction of change in angular position.

that every so often the angle was increased to 55°, which occurred following 2 consecutive incorrect or no-response trials. These so called "probe" trials do not enter into the calculation of MAA threshold. Their purpose is merely to reinstate the subject's attention. As depicted in Figure 2, the initial decrease in angular position represents the largest change in angular displacement of the loudspeakers (55 down to 6); the first reversal is often relatively large as well (6 up to 10 in this case). Subsequent changes are much smaller (2° initially, and 1° towards the end of the session), as the listener converges on her psychophysical threshold. The mean number of trials required to achieve threshold were: 18-month-olds = 28.69 (range=14-50), 5-year-olds = 27.09 (range=21-40), adults = 26.47 (range=19-36). Samples of individual subjects' threshold estimates (SS, LEAD, LAG for each age group) are included in Appendix H. LAG data for 18-month-olds are in Appendix I (see below for discussion of this group of subjects).

The results of this study were initially analyzed in order to elucidate within-age and between-age differences in localization precision for sounds with and without simulated echoes. All data with children were analyzed using between-subjects tests, since each child was tested on one condition only. Adults had three separate threshold estimates, one for each stimulus condition, hence a within-subjects design. MAA threshold estimates are listed for each subject: Table 5 for

18-month-olds, Table 6 for 5-year-olds and Table 7 for adults. Mean thresholds for the SS stimulus were 1.02°, 1.78°, and 6.15°, for adults, 5-year-olds and 18-month-olds, respectively. Mean MAA thresholds for the LEAD stimulus were 1.7°, 5.13°, and 26.08°, for adult, 5-year-olds, and 18-month-olds, respectively. Finally, for the LAG stimulus, mean MAA thresholds were 3.7°, 20.68°, and 52.37°, for the adult (25 msec group), 5-year-olds, and 18-month-olds, respectively. These means are plotted in Figure 3. Results of the analyses are summarized in Tables 8-11. When post-hoc tests and groups of t-tests were conducted, Scheffe's adjustment for multiple comparisons was applied. The adjustment demands that the desired p-value be divided by the number of contrasts being conducted in the analysis. For a definition of a group of analyses which make up a family of contrasts see Myers & Well (1991).

B. Threshold comparisons between children

Threshold estimates for the two younger age groups, both of which had a within-subjects design, were analyzed in a 2-way ANOVA of Age (18-mo, 5-year) x Stimulus type (SS, LEAD, LAG). Results revealed significant main effects for Age [$F(1,67) = 14.28$, $p<.001$] and Stimulus type [$F(2,67) = 14.35$, $p<.001$], but no significant interaction of Age x Stimulus type. Post-hoc t-tests revealed that 5-year olds

Table 5: MAA Thresholds for 18-month-olds

	SS	LEAD	LAG
	4.8	21.8	57.8
	7.0	22.6	54.4
	9.6	18.4	48.6
	6.4	28.0	62.6
	6.6	28.6	42.2
	6.4	36.2	62.8
	3.8	13.2	62.8
	4.8	37.0	62.4
	2.6	28.0	30.8
	4.2	22.2	63.0
	5.8	36.0	63.0
	11.8	21.0	18.0
MEAN	6.15	26.08	52.37
SD	2.53	7.57	14.91

had significantly lower thresholds than 18-month olds for all three stimulus conditions: SS, [*t*(22) = 5.62, *p*<.0001]; LEAD, [*t*(22) = 9.08, *p*<.0001]; LAG, [*t*(22) = 5.41, *p*<.0001]. In addition, within each age group there were significant differences between all three stimulus conditions. MAA thresholds were smallest for SS, larger for LEAD, and largest for LAG. Results of the post-hoc t-tests for the 18-month-olds were: SS vs. LEAD [*t*(22)= 8.65, *p*<.0001]; SS vs. LAG [*t*(22) = 10.583, *p*<.0001; LEAD vs. LAG [*t*(22)= 5.45, *p*<.0001]. Results for the 5-year-olds were: SS vs. LEAD [*t*(22)= 4.24, *p*<.0001]; SS vs. LAG [*t*(22) = 4.743, *p*<.0001; LEAD vs. LAG [*t*(22)= 3.84, *p*<.001]. These results suggest

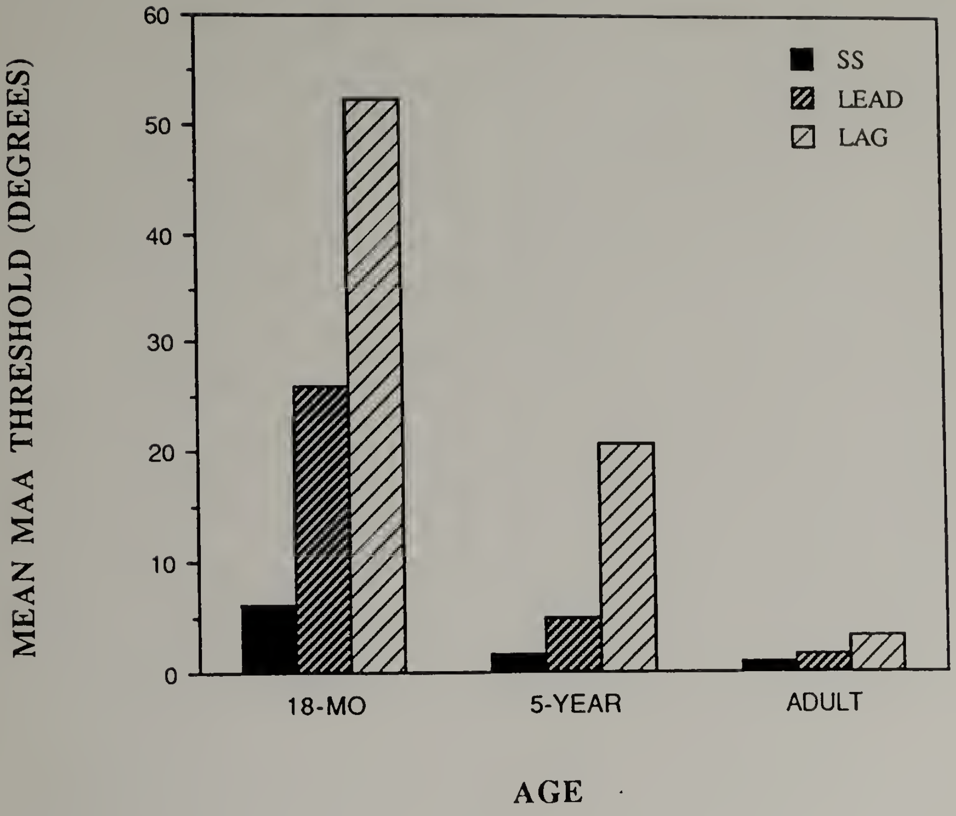

Figure 3. Mean values of minimum-audible-angle (MAA) thresholds are plotted for the three stimulus conditions at each age group.

that between the ages of 18-months and 5-years, children's performance on the localization precision tasks improved significantly. This improvement is evident both under single-source conditions, and under conditions of the precedence effect.

Table 6: MAA Thresholds for 5-year olds

	SS	LEAD	LAG
	1.2	11.2	33.8
	3.2	5.2	52.6
	1.2	6.2	14.2
	2.2	2.2	14.4
	2.6	2.6	19.2
	1.2	8.2	12.0
	3.0	4.6	24.2
	0.4	3.5	6.2
	1.8	5.6	35.4
	0.8	2.8	8.0
	1.2	3.2	19.2
	2.6	5.4	9.0
MEAN	1.78	5.13	20.68
SD	.92	2.57	13.78

Table 7: Results of analyses comparing children groups

18-month-olds vs. 5-year-olds MAA thresholds
Between-subjects 2-way ANOVA (age x stimulus type)

Effect	F-value	DF	p<
Age	14.28	1,22	.0001 *
Stimulus	14.35	2,44	.0001 *
A x S	2.45	2,67	.09

Post-hoc t-tests: (22 degrees of freedom)

Effect	t-value	p<
a) 5-year vs 18-months:		
SS	5.616	.0001 *
LEAD	9.081	.0001 *
LAG	5.400	.0001 *
b) Stimulus between groups of 18-months		
SS-LEAD	-8.653	.0001 *
SS-LAG	-10.583	.0001 *
LEAD-LAG	-5.453	.0001 *
c) Stimulus between groups of 5-years		
SS-LEAD	-4.241	.0001 *
SS-LAG	-4.741	.0001 *
LEAD-LAG	-3.844	.001 *

* Scheffe's: critical p value = .005 for family of 9 contrasts

C. Adult threshold data

MAA thresholds were compared in order to assess the effects of stimulus duration and stimulus type on localization precision. A 2-way ANOVA of Group (25 msec and 4 msec duration) x Stimulus type (SS, LEAD, LAG) yielded significant effects of Group [$F(1,22) = 15.95$, $p<.001$] and Stimulus type [$F(2,44) = 34.15$, $p<.0001$], and a significant interaction [$F(2,44) = 18.28$, $p<.0001$]. Post-hoc t-tests revealed that for group A (the 25-msec stimuli) thresholds were significantly lower for the SS than the LEAD condition [$t(11) = 3.71$, $p<.003$]. The LEAD condition was not significantly lower than the LAG condition ($p=.05$). The SS condition is marginally significant ($p=.046$), however, once corrected for family-wise contrasts, the p value necessary for significance = .016. This lack of significance is puzzling since the lag condition had the highest threshold, triple that of SS and more than double that of lead. In fact, these mean differences are greater than the one between SS and LEAD, which did produce significant findings.

The most likely explanation for lack of significance of SS and LEAD vs. LAG was the high variance (SD = 3.62) on LAG thresholds, which was larger than the mean (mean = 3.37). A closer examination of the data reveals that LAG thresholds were higher than those of SS for 11 out of 12 subjects, and higher than the LEAD for 8 out of the 12 subjects.

Table 8: Results of analyses comparing adults with children

MAA thresholds compared between adults and children; independent t-tests (22 degrees of freedom):

	18-Month-olds vs. adults		5-year-olds vs. adults	
SS:	t= 6.965	p = .0001 *	t= -2.736	p < .012
LEAD:	t= 11.114	p = .0001 *	t= -4.452	p < .0001 *
LAG:	t= 11.06	p = .0001 *	t= -4.211	p < .0001 *

* Scheffe's: critical p value = .008 for family of 6 contrasts

A Wilcoxon signed ranks test revealed significant differences for SS-LAG (*p*<.003). The LEAD-LAG comparison (*p*<.037) was not significant once the p-value was adjusted for multiple comparisons which require significance at *p*<.025. Thus, adult subjects' performance was hindered with PE stimuli, regardless of whether the leading or lagging signal was shifting from midline.

Additional post-hoc tests on the initial ANOVA were conducted, comparing thresholds for the 4-msec subjects (group B) vs. the 25-msec subjects (group A). Results revealed significantly higher MAA thresholds for group B on the LAG stimulus [*t*(22) = 4.205, *p*<.0001], but no significant differences (*p*'s>.05) on the SS or LEAD stimuli. A shorter duration stimulus has the effect of degrading localization precision for the condition in which the echo is shifting location. This could signify a decreased

Table 9: Results of analyses comparing adult groups

1) MAA thresholds compared between adult groups A-B
2-way ANOVA (group x stimulus type)

Effect	F-value	DF	p<
Group	15.95	1,22	.001 *
Stimulus	34.148	2,44	.0001 *
G x S	18.277	2,44	.0001 *

Post-hoc t-tests: (22 degrees of freedom)

Effect	t-value	p<
a) stimulus conditions within group A		
SS-LEAD	-3.71	.003 *
SS-LAG	-2.248	.046
LEAD-LAG	-1.169	.119
b) stimulus conditions within group B		
SS-LEAD	.549	.594
SS-LAG	-5.530	.0001 *
LEAD-LAG	-5.528	.0001 *
c) group A vs. B for each stimulus condition		
SS	-1.38	.182
LEAD	2.145	.043
LAG	-4.205	.0001 *

* Scheffe's: critical p value = .005 for family of 9 contrasts

2) Adults group A non-parametric tests on
MAA thresholds;
Wilcoxon signed ranks test:

Effect	Z-value	p<
SS-LAG	2.944	.003 *
LEAD-LAG	2.091	.037

* Scheffe's: critical p value = .025 for family of 2 contrasts

Table 10: MAA Thresholds for adults

Group 3-A - 25 ms duration

	SS	LEAD	LAG
	0.6	0.4	0.8
	1.2	1.2	2.4
	0.8	1.6	13.2
	1.0	1.8	1.8
	0.8	2.0	1.0
	1.4	1.4	1.2
	0.8	2.4	3.2
	0.8	1.4	1.6
	1.0	2.2	5.0
	1.2	1.2	1.4
	1.6	3.2	7.2
	1.2	1.4	1.6
MEAN	1.0	1.7	3.367
SD	.31	.7	3.62

Group 3-B - 4 ms duration

	SS	LEAD	LAG
	0.8	1.2	8.2
	0.4	1.2	13.0
	1.4	1.2	5.8
	0.8	1.2	21.2
	0.8	1.2	23.6
	2.2	1.6	16.8
	3.4	1.4	19.6
	1.2	1.4	25.4
	1.2	1.2	1.6
	1.2	0.8	16.6
	1.0	1.2	1.8
	2.0	1.4	16.8
MEAN	1.37	1.25	14.2
SD	.82	.19	8.16

influence of the echo on the perceived location of the fused PE stimulus, which would require that the lag be placed at further angular displacements from midline in order for the shift to be discriminable.

D. Threshold comparisons between adults and children

Since adult and children groups were tested using different designs, statistical comparisons were based on independent t-tests of each stimulus type. MAA thresholds on all three stimulus conditions were significantly lower for adults than for 18-month-olds [SS: $t(22) = 6.96$, $p<.0001$; LEAD: $t(22) = 11.11$, $p<.0001$; LAG $t(22) = 11.06$, $p<.0001$]. Comparisons of adults vs. 5-year-olds yielded significant differences for LEAD [$t(22) = 4.45$, $p<.0001$] and LAG [$t(22) = 4.21$, $p<.0001$]. The SS comparison [$t(22) = 2.736$, $p<.012$] was not significant following Scheffe's adjustment for multiple comparisons, which demands significance at the .008 level.

These results indicate that by 5-years of age children's precision for detecting a change in the position of a single-source sound may have reached adult level performance[3]. However, their performance with more complex

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[3] Despite the fact that 5-year-olds' thresholds were statistically lower than adults', they nonetheless differed by 67%, which requires some caution in claiming that children have reached full adult-level maturity.

precedence-effect stimuli is significantly worse than that of adults. This is true for both PE conditions, regardless of whether they were detecting a shift due to movement of the LEAD or LAG stimulus. In combination with the analyses between the 18-month olds and 5-year olds, these results indicate that localization precision, as measured with an MAA task, improves significantly between the second and fifth years of life for both SS and PE tasks, and continues to improve between 5-years of age and adulthood, only for PE tasks.

E. Psychometric functions

MAA thresholds were estimated adaptively, which is not easily conducive to reanalysis of psychometric functions. It is useful however, to present some examples of subjects' individual psychometric functions in order to describe which angles were visited during the runs, and the individual differences within each condition.

Presentation of the data in terms of psychometric functions is thus merely an alternative to presenting MAA thresholds. Psychometric functions represent the proportions of trials at which responses were correct at each stimulus level. This method, common to psychoacoustics, provides a second way of assessing thresholds, by finding the point on the function corresponding to the desired level of performance (71% in the present study).

Data from all subjects' testing session were individually re-computed in order to generate psychometric functions. For each subject, the proportion of correct responses are plotted at each angle that the subject was presented with. Data from three of the most systematic subjects in each age group and at every condition are plotted: Data for 18-month-olds in Figures 4a (SS), 4b (LEAD) and 4c (LAG), Data for 5-year-olds in Figures 5a (SS), 5b (LEAD), and 5c (LAG). Since adults were tested on all stimulus conditions, each subject's data for SS, LEAD and LAG are plotted together. Figures 6a, 6b and 6c contain adult psychometric functions.

Response functions were fairly steep for individual subjects, and are somewhat non-monotonic for some subjects, primarily due to the fact that each point is based on very few trials. The only functions that do not asymptote at 100% correct are the 18-month-olds LAG functions, because that stimulus condition was the most difficult. In addition, the point at which each function meets the 71% criterion (indicated by an asterisk) is fairly well matched to the MAA thresholds (calculated by averaging the angles at the last 5 reversals). For example, 18-month-old LEAD subjects #15, #17 and #26 had mean MAA thresholds of 28.6, 36.2, and 13.2, respectively. The angles matching their psychometric functions at 71% are approximately: 28, 36, and 13, respectively.

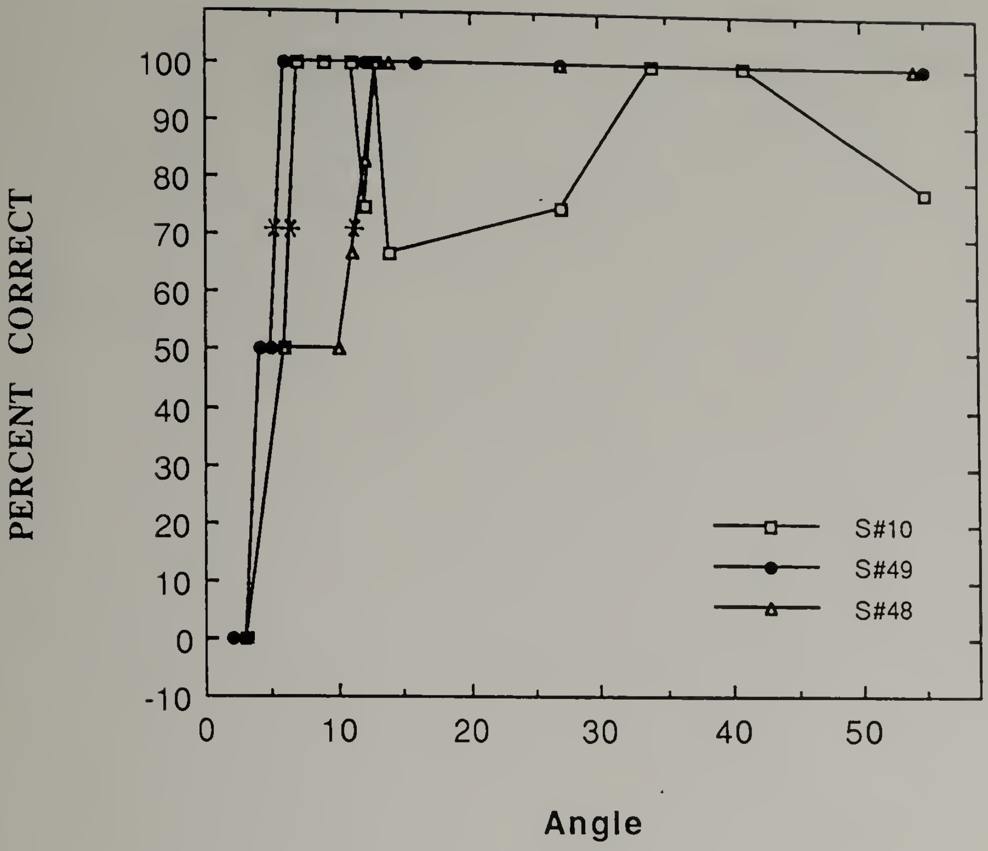

Figure 4. Psychometric functions for 18-month-olds. Plotted on the x-axis are the angular positions at which trials were presented. Plotted on the y-axis are the percent of trials correct at each position. The asterisk marks indicate the 71% point on each psychometric function. 4a page 90 = SS condition, 4b page 91 = LEAD condition, 4c page 92 = LAG condition.

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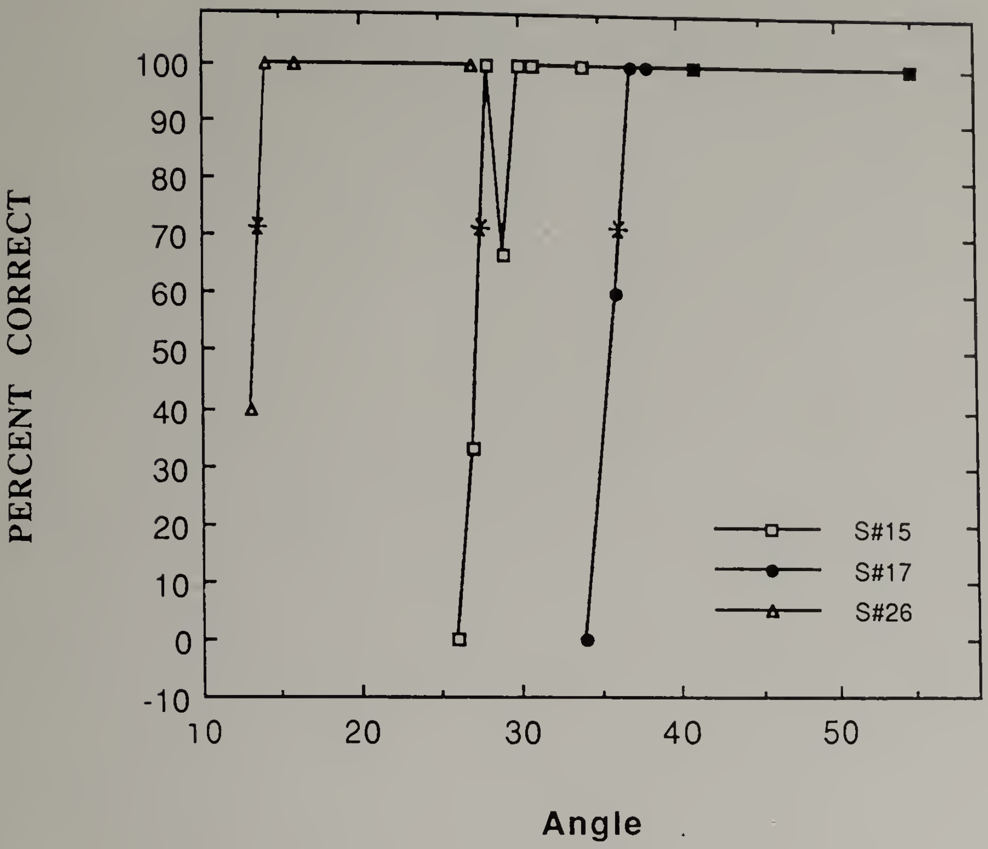

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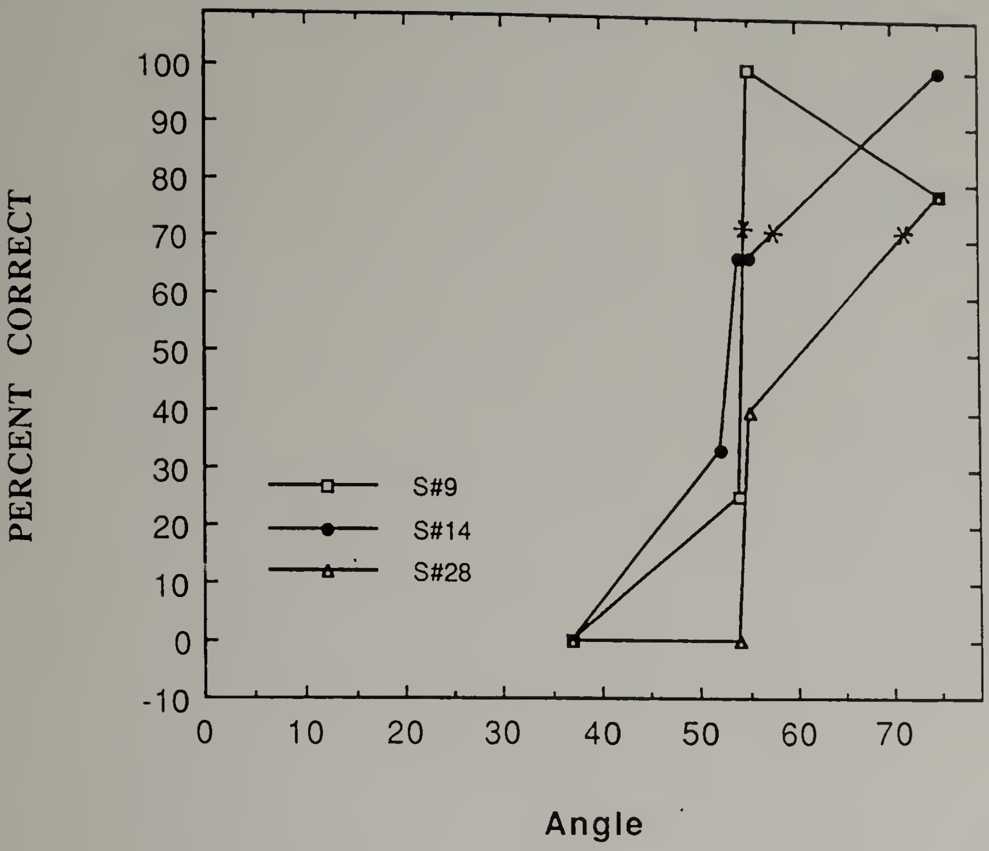

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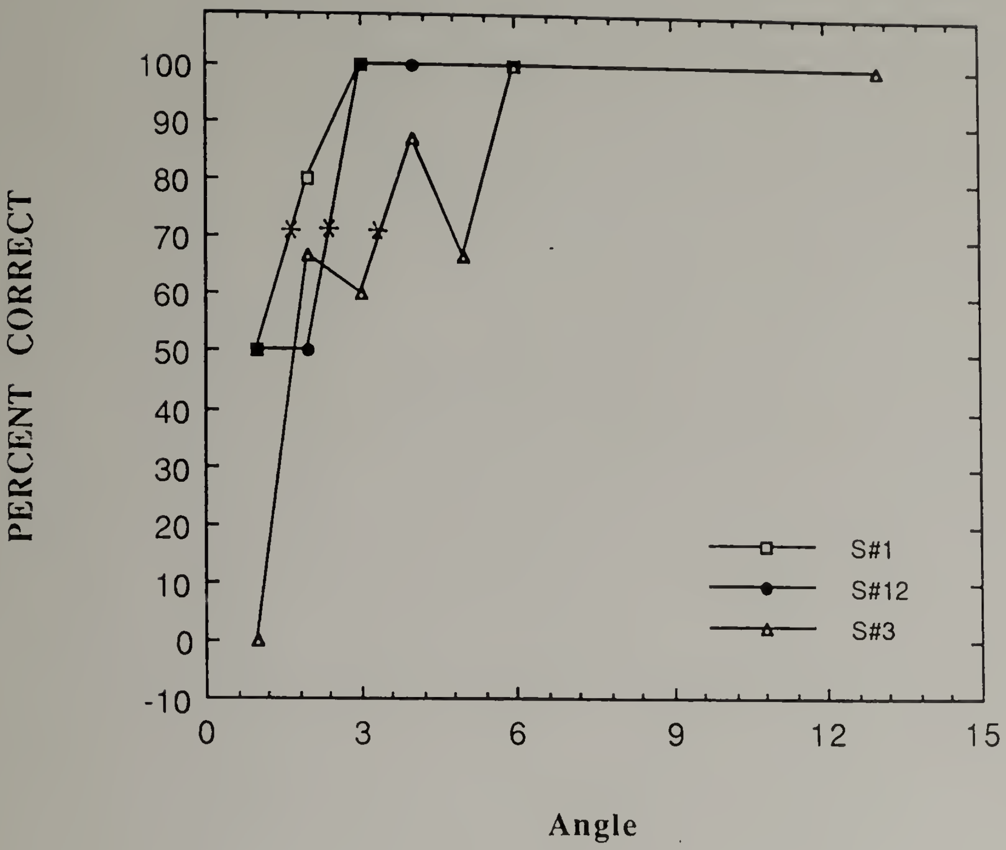

Figure 5. Psychometric functions for three 5-year-olds. Plotted on the x-axis are the angular positions at which trials were presented. Plotted on the y-axis are the percent of trials correct at each position. The asterisk marks indicate the 71% point on each psychometric function. 5a page 93 = SS condition, 4b page 94 = LEAD condition, 5c page 95 = LAG condition.

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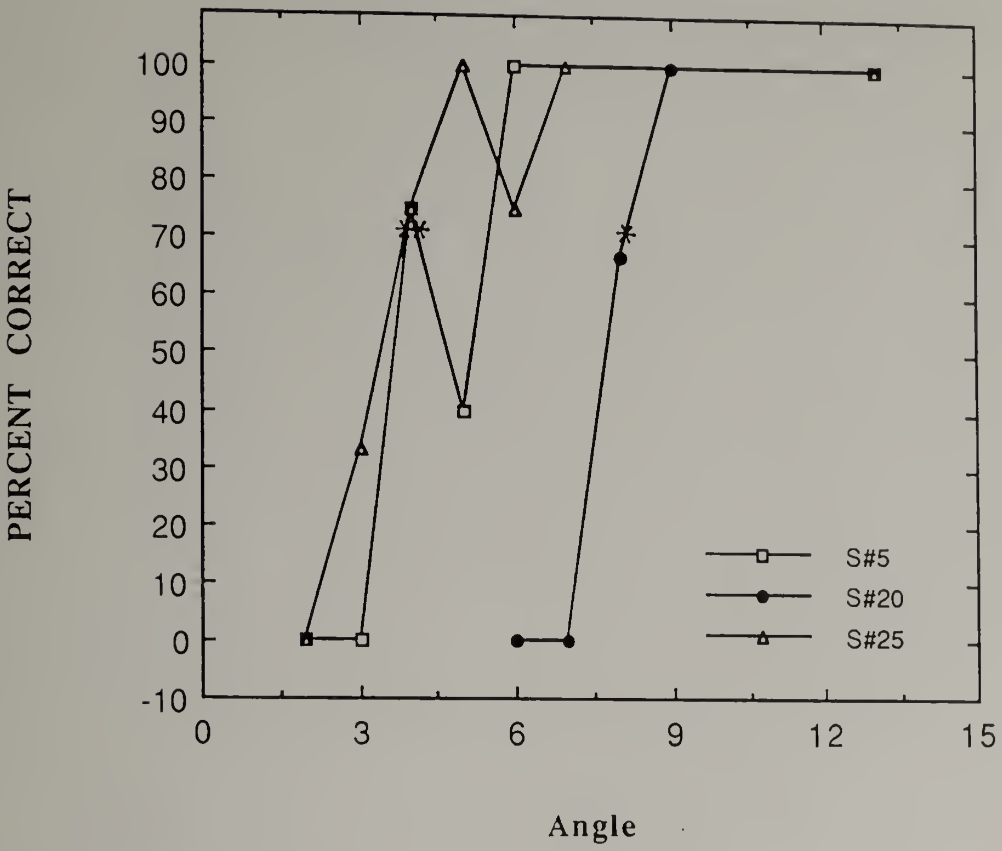

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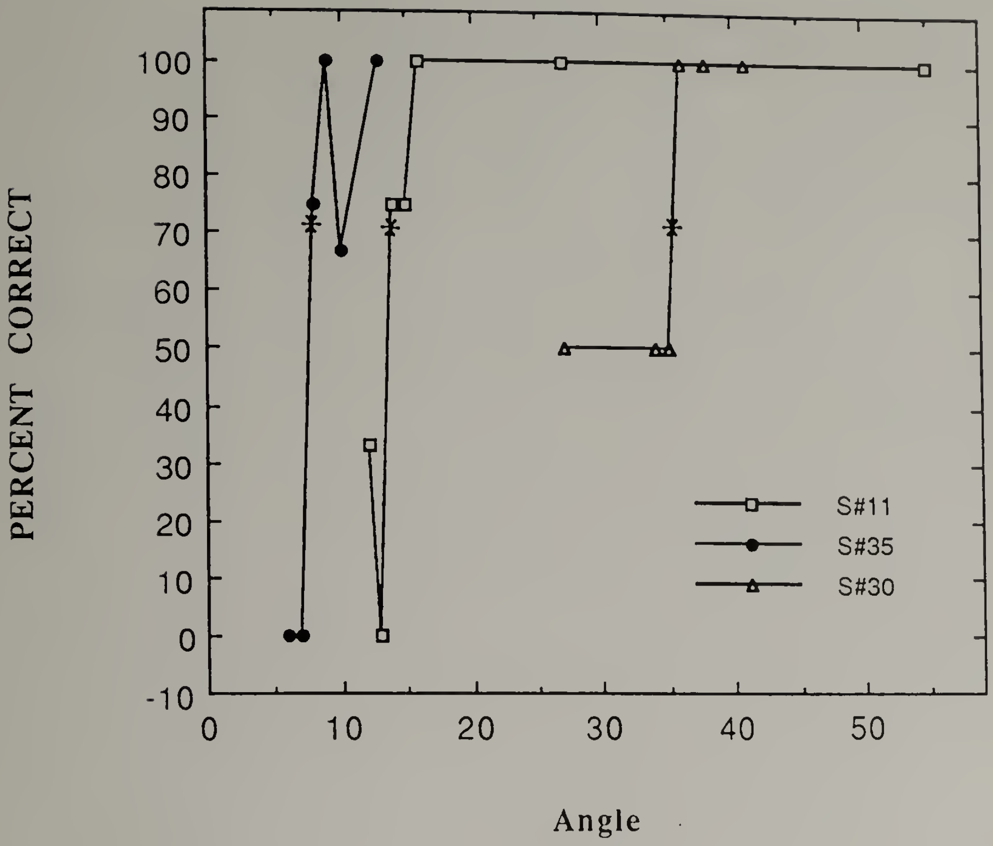

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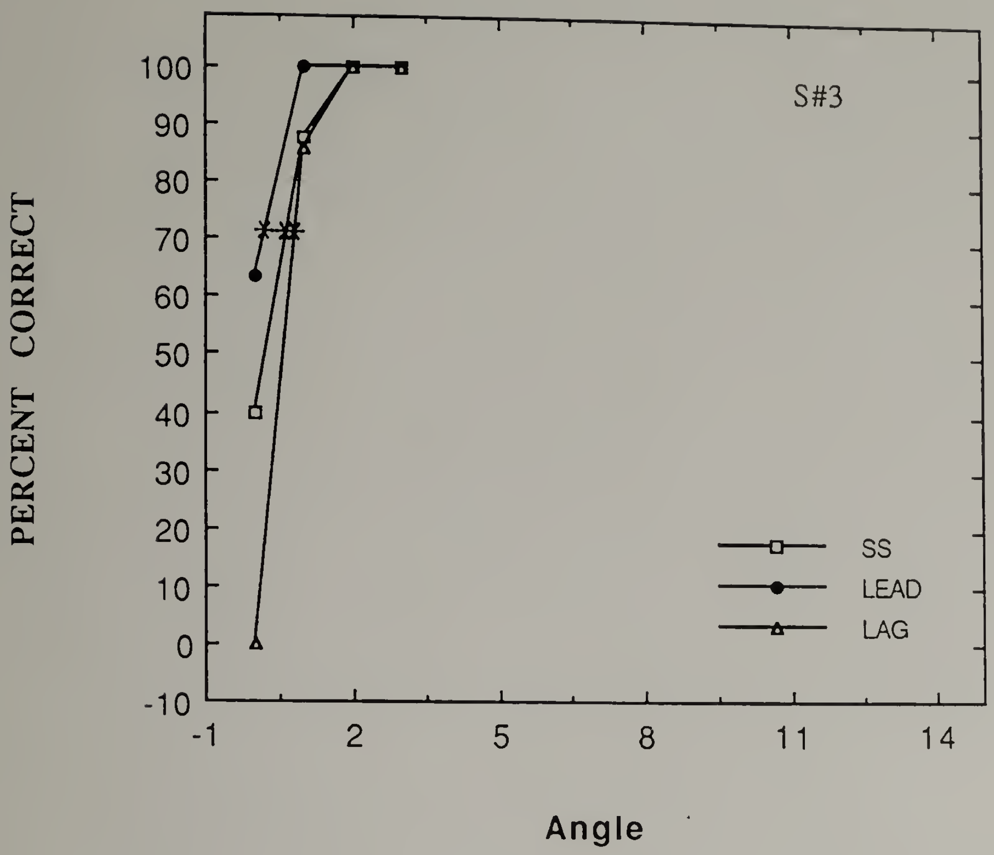

Figure 6. Psychometric functions for adult subjects, comparing SS, LEAD and LAG stimulus conditions. Plotted on the x-axis are the angular positions at which trials were presented. Plotted on the y-axis are the percent of trials correct at each position. The asterisk marks indicate the 71% point on each psychometric function. 6a page 96 = Subject#3, 6b page 97 = S#10, 6c page 98 = S#16.

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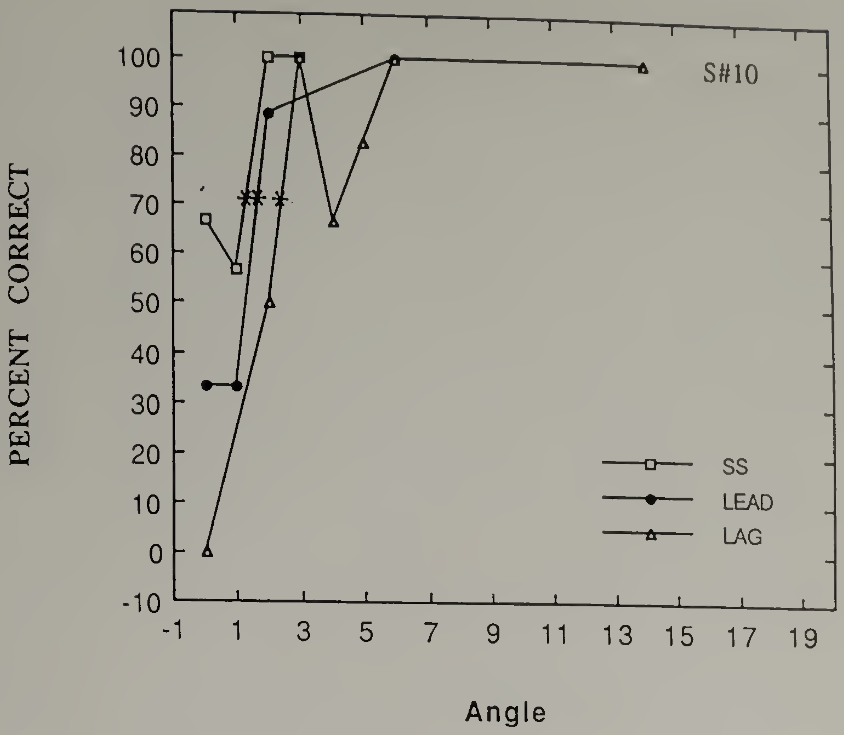

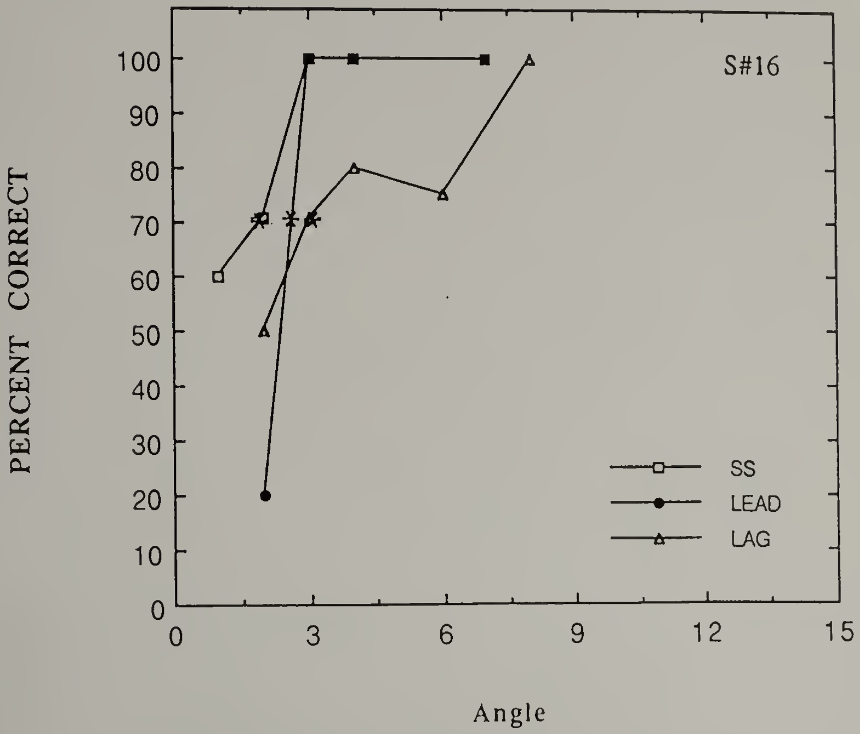

Figure 6 continued

F. A reanalysis of MAA thresholds

The fact that the SS MAA thresholds were significantly lower for the 18-month-olds than for the two older age groups rendered interpretation of developmental changes in performance on PE stimuli difficult. In order to allow comparisons for the age differences that were observed, the data were transformed in a number of ways.

Table 11: Ratios of lead and lag stimuli

	LEAD/SS	LAG/LEAD
ADULTS	1.67	1.98
5-YEAR	2.88	4.03
18-MON	4.24	2.00

Mean MAA threshold data were initially examined with the purpose of describing the influence that the lagging sound exerts on sound localization precision. If the lag has no effect on angular discrimination, then subjects should be able to ignore it and the ratio of LEAD/SS thresholds should equal 1. The extent to which the ratio is greater than 1 represents the influence of the lag on localization precision for the auditory stimulus. The LEAD/SS ratios, which are represented in Table 11, decrease with increasing age, indicating that at older ages the presence of the echo has less influence than at younger ages.

The MAA data were also examined in order to compare the relative influence that leading and lagging signals each exert on sound localization precision. If the lead and lag have equal effects, then the ratio of LAG/LEAD thresholds should equal 1. If the ratio is greater than 1, then LAG thresholds must be higher, indicating that the lead has more weight than the lag ($W_{lead} > W_{lag}$). The centered leading signal dominates the fused auditory image, increasing LAG MAA thresholds.

The ratios from Table 11 indicate that the relationship, $W_{lead} > W_{lag}$, holds for all three age groups. For adults and 18-month-olds the ratio is close to 2.0, and for the 5-year-olds the ratio is close to 4.0. Regardless of age, the leading sound exerts greater weight on the perceived location of the auditory image than the lagging sound. What remains unclear from these lead-lag ratios is _where_ the auditory image is perceived to be. That is, the auditory image is itself somewhere on the horizontal axis. Conceivably, the position in space that a subject would point to when describing where the image is located is the _centroid_, or center point, of the auditory image. The weights obtained for lead and lag at each age group can be applied towards calculation of the position of the assumed centroid. Out of a total weight of 1.0, W_{lead}=(p) and W_{lag}-(1-p). The perceived position of the centroid is calculated by taking into account (p) and (1-p) for the speaker positions of the lead and lag (S_{lead} and S_{lag}, respectively). This calculation can be described as follows:

$$P_{centroid} = S_{lead}\ (p) + S_{lag}\ (1-p)$$

For a given MAA threshold with the LEAD stimulus, the lag loudspeaker is always at 0°, and for an MAA of the LAG stimulus, the lead loudspeaker is at 0°. Thus, only one of the two components of the equation is greater than 0 for a given stimulus condition. In addition, calculation of a centroid is the same regardless of whether it was derived from the LEAD or LAG condition. Let us assume that MAA threshold for LEAD = J and for LAG = K. If W_{lead} is twice that of W_{lag}, then W_{lead}=.67 and W_{lag}=.33. The centroid is at J(.67) for the LEAD stimulus, and at K(.33) for the LAG condition. And, J(.67) equals K(.33). For example, if MAA threshold for LEAD = 15° and for LAG = 30°, then LAG/LEAD=2 and $W_{lead} = 2 \times W_{lag}$, or (p)=.67 and (1-p)=.33.

If calculated from the LEAD data:

$$P_{centroid} = 15\ (.67) + 0\ (.33) = 10$$

If calculated from the LAG data, results are the same:

$$P_{centroid} = 0\ (.67) + 30\ (.33) = 10$$

Using this equation, a *centroid* position was calculated for each age group based on the mean MAA thresholds for the LEAD and LAG conditions. Table 12 includes these values, as well as MAA thresholds and weights for LEAD and LAG. *Centroid* values are largest for 18-month-old (17.375), smaller for 5-year-olds (4.14) and smallest for adults. Between the two adult groups the centroid values are smaller for the 25 msec group (1.125) than the 4 msec group (1.15).

During performance on an MAA task with PE stimuli, the *centroid* of the auditory image must be perceptually pulled at least to the point of a subject's SS MAA threshold. A subject certainly would not be expected to detect angular shifts in PE stimuli whose *centroid* is less than their MAA threshold for SS sounds. Once the *centroid* has been pulled to the position of SS threshold, one would expect subjects to lateralize the PE stimulus accurately. Unless other variables influenced the perceived position of the *centroid*. The difference between the calculated *centroid* and SS MAA threshold indicates the extent to which factors other than perceptual pulling affect the position of the auditory image. These differences are largest for 18-month-olds, and decrease with age, as well as stimulus duration:

18-month-olds: 17.373 - 6.15 = 11.225

5-year-olds: 4.144 - 1.78 = 2.360

Adults (25msec): 1.125 - 1.02 = .015

Adults (4msec): 1.15 - 1.37 = -.220

Table 12: Estimations of <u>CENTROID</u> for three age groups

	18-M	5-YEARS	A(25ms)	A(4ms)
$LEAD_{maa}$	26.08	5.19	1.70	1.25
LAG_{maa}	52.37	20.68	3.37	14.2
W_{lead}	0.67	0.80	0.67	0.92
W_{lag}	0.33	0.20	0.33	0.08
$P_{centroid}$	17.37	4.14	1.13	1.15

An additional transformation was conducted on the data in order to standardize the scores across the three ages. This transformation applied to the MAA thresholds was aimed at treating the SS MAA thresholds at each age as a baseline localization precision for that age. Under this scenario, sound localization precision at any given age is measured as a <u>function</u> of precision for SS stimuli. To test this hypothesis, MAA thresholds for each subject were divided by the mean SS MAA threshold for that age. For adults the transformation did not yield values radically different from the untransformed values, since the SS mean MAA threshold was 1.02 (very close to 1.0). The children's data are plotted in Figure 7 and were analyzed with a 2-way ANOVA of Age (18-months vs. 5-years) x Stimulus type (SS, LEAD, LAG). Results revealed a significant main effect of Stimulus type [F(2,66)= 42.29, p<.0001], but no main effect of Age [p<.852] and no significant interaction. Post-hoc t-tests revealed that the SS values were lower than the LEAD [t(23)= 7.71, p<.0001], and LAG [t(23)= 7.8, p<.0001], and the LEAD values were lower than the LAG [t(23)= 5.5, p<.0001]. Children's data on the two PE conditions were also compared with those of adults with independent t-tests. The SS data were not compared since they served as the baseline level and were standardized to equal 1 for all ages. Adults' "units" thresholds were significantly lower than 18-month-olds' LEAD [t(22)=2.627, p<.015], and LAG [t(22)=3.381, p<.003], as well as the 5-year-olds' LEAD [t(22)=6.354, p<.001] and LAG [t(22)=4.233, p<.001] thresholds (for summary of results, see Table 13).

It is possible that the computational process involved in determining the position of a PE stimulus in space is function of the process involved in the presence of a SS stimulus. In the presence of an echo, precision is degraded by a multiple of the SS performance precision. One should be able to directly predict localization precision for PE stimuli from performance on SS stimuli. In addition, localization precision can be compared directly across ages by taking SS level performance into account.

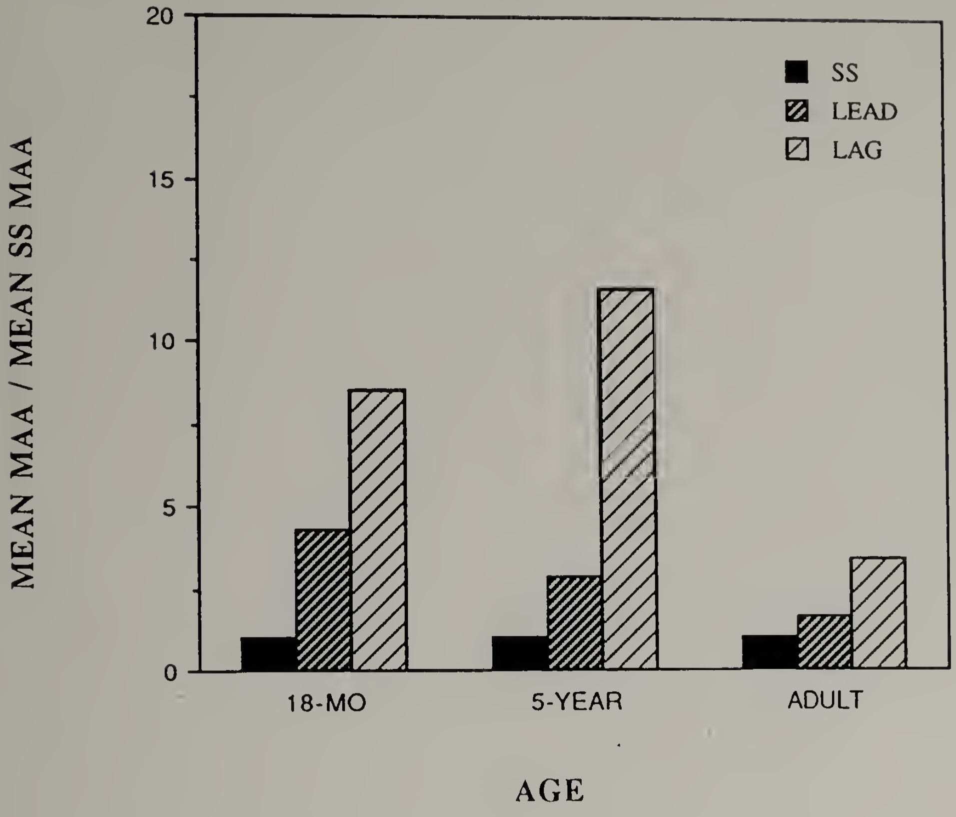

Figure 7. The mean values of minimum-audible-angle (MAA) thresholds for each stimulus type are divided by the mean SS-MAA value of that age group. Each ratio is considered a "unit" of MAA threshold, plotted for three stimulus conditions at each age group.

Table 13: Results of analyses comparing "units" of MAA

18-month-olds versus 5-yr. PE MAA / SS MAA
Between-subjects 2-way ANOVA (age x stimulus type)

Effect	F-value	DF	p<
Age:	.035	(1,66)	.852
Stim:	42.295	(2,66)	.0001 *
A x S:	1.319	(2,66)	.274

Post-hoc t-tests: (22 degrees of freedom)

Effect	t-value	p<
SS-LEAD	-7.708	.0001 *
SS-LAG	-5.428	.0001 *
LEAD-LAG	-7.796	.0001 *

* Scheffe's: critical p value = .016 for family of 3 contrasts

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Adults versus children PE MAA / SS MAA
independent t-tests (22 degrees of freedom):

	18-Month-olds vs. adults		5-Year-olds vs. adults	
LEAD:	t= 2.62	p=.015	t= 6.35	p<.001 *
LAG:	t= 3.38	p<.003 *	t= 4.23	p<.001 *

* Scheffe's: critical p value = .0125 for family of 4 contrasts

In the present study, when PE thresholds were divided by SS thresholds, children's performance on PE conditions had virtually identical ratios at the two ages.

CHAPTER IV

DISCUSSION

The purpose of the present study was to investigate developmental differences in sound localization precision, under both single source (SS), and precedence effect (PE) conditions. Precision was measured with MAA thresholds on the horizontal axis. In the present section, each analysis or measure presented in the Results will be considered. In addition, the implications for the development of the precedence effect and directions for future research will be discussed.

A. Threshold estimation

The present study utilized an up-down transformed response method with a 2-down/1-up rule which predicts p(correct responses)=.71. It has been suggested by Green (1990) that in a 2AFC procedure the optimal stimulus placement level should be between 84% to 94%, and that standard deviation of threshold estimates is larger when the stimulus level corresponds to 71% versus 94%. This point was made specifically with adult subjects, although Green's assertion may be generalized to all human listeners regardless of age. In fact, it is always ideal to keep childrens' and infants' performance at a high level, for it provides them with positive reinforcement on most trials, and may increase their interest in the task. However, this issue has not been confirmed experimentally. Furthermore, increasing performance level may have the disadvantage of lengthening the test session. Pilot testing with young children suggested that their attention span sets an upper limit on a test session to approximately 30 trials. It was therefore necessary to implement a method which would generate a complete adaptive procedure in less than 30 trials. Simulations conducted using the 2-down-1-up method with 7 reversals to criterion predicted that sessions would last between 28-30 trials. Indeed, average number of trials to completion of an adaptive run was 29.8 for 18-month-olds and 27.09 for 5-year-olds.

Other compromises could have been made in the adaptive algorithm rules to minimize the number of trials while keeping performance at a higher level. For instance, a 3-down/1-up rule predicts p(correct responses)=.79, which, according to Green, would decrease variability in threshold estimation. Since the 3-down/1-up rule requires additional trials, the testing session would have been limited by decreasing the number of reversals required for threshold estimation. However, a decreased number of reversals is also likely to increase variability. The rule was employed essentially because it is commonly used in developmental psychophysics work, and since thus far no better method for threshold estimation with young children exists (Ashmead et al., 1987; Aslin & Pisoni, 1980; Olsho, 1984; 1985; Olsho et al., 1987; 1988)

B. Age effects for SS stimuli

MAA thresholds were lowest for adults, slightly higher for 5-year-olds and much higher for the 18-month-olds. The adult data are consistent with previous findings of thresholds between 1-2° on the horizontal axis for broad-band stimuli similar to those used in the present study (Gardner, 1968; Mills, 1958; Perrott, et al., 1989; Perrott & Pacheco, 1989; Perrott & Saberi, 1990). MAA represents the angle formed at the center of the head by imaginary lines projecting to two sources of sound, whose exact positions are just noticeably different when sounded in succession. It can also be expressed in terms of discriminability of changes at the subject's ears in cues which are known to be important for localization, such as ITD and ILD. The present results confirm that adult subjects are capable of discriminating extremely fine changes in the position of a sound located in the horizontal azimuth dimension.

MAA thresholds for 5-year-old children were not significantly different from adults, indicating that by the late pre-school years children have developed adult-like localization precision. In fact, their level of performance is quite impressive. When one considers the types of localization precision tasks which are required in the real world, discrimination of 1° does not emerge as a capacity that might be essential to the survival of the organism, and which should have developed by this age. People and certainly children are rarely, if ever, faced with the task of discriminating such small changes in the position of a sound. A measurement of MAA may however reflect the lower limits of the perceptual system associated with localization precision, and perhaps with other temporal tasks.

These findings with young children have not been previously reported in the literature. The only closely related work has been conducted on children's discrimination of temporal cues, which are also relied on in auditory localization. There appear to be significant maturational changes in auditory temporal acuity between the pre-school and teen-age years (Irwin et al., 1980; Wightman et al., 1989). In addition, measures of auditory fusion (the ability to detect short time intervals between stimuli) improve rapidly and in an orderly fashion from 3-8 years of age, stabilizing between 9 and 12 years of age (Davis & McCroskey, 1980). The fact that children's MAA thresholds were at adult level suggests that localization precision for SS stimuli does not depend heavily on temporal acuity, otherwise children's thresholds should have been higher than adults'.

It is interesting to note that there was a larger variance in performance among children than among adults. Developmental findings in temporal acuity may account for the higher thresholds observed in some children in the present study, who have clearly not reached adult level. For the children with higher thresholds it is also possible that their perceptual mechanism for MAA discrimination has reached adult levels, but that attentional decrements were responsible for worse performance. A second possibility is that 5 years of age is a transitional stage, during which some children have acquired adult capacities for localization precision and others have not. All children may have been capable of obtaining adult-level thresholds, but the ones who did not may have done so for attentional and motivational reasons as opposed to sensory ones.

The next question concerns findings with children at 18-months of age. MAA thresholds with the SS condition yielded a mean of 6.15°, which compares fairly well with previously reported MAA thresholds of 4.0° (Morrongiello, 1988). There is however a difference of 2.15°, or 53% (2.15/4.0=53%) between Morrongiello's (1988) results and the present study. This difference cannot be attributed to differences in target proportions, since like the present study, Morrongiello used approximately 70%. A major difference between the two studies is that Morrongiello used a method of constant stimuli, in which each subject received a few trials at each of four positions, ranging from 4-16°. It is not clear why the method of constant stimuli yielded lower thresholds than the adaptive method, although it should be noted that a similar difference has been previously observed with 6-month-old infants as well. Ashmead et al. (1987) reported MAA thresholds of 19° with adaptive methods, whereas infants in Morrongiello's study (1988) had thresholds of approximately 12°. In any case, it is clear that between 6- and 18-months there is a considerable change in localization precision, reflecting increasing resolution of auditory space with increased age.

A great deal of improvement also occurs between 18 months and 5 years, reflected in a significant difference between thresholds at these two ages. This difference is most likely not due to changes underlying sensitivity to interaural differences, since discrimination of interaural cues is substantially better than would be predicted from MAA thresholds (Ashmead, Davis, Whalen & Odom, in press). What factors may contribute to age differences? One possibility is that the auditory cortex undergoes considerable maturation during early childhood, with extensive myelination, dendritic arborization and neuronal growth extending into late childhood (Yakovlev & Lecours, 1967). These changes may be especially important for integration of the multiple cues involved in localization precision in free field.

A second possibility concerns the need for recalibration of interaural time differences as the head circumference increases between 18-month, 5-years and adulthood. Proportion of children's head circumference is 85% that of adults' at 18-months and 93% at 5-years (Eichorn & Bayley, 1962). Sound travelling in free field results in interaural time differences that change with age. A constant updating of the association between the origin of the sound source and the interaural cues associated with it is required (Clifton et al., 1988). In fact, studies on owls have indicated that there is a very dramatic recalibration during early development (for review see Knudsen, 1988), and in human adults some capacity for recalibration is retained much after the head has reached its full adult size (Held, 1955).

The age difference may also be partially attributed to non-sensory factors. Children at 5-years may have been better than 18-month-olds at learning the task, especially since they could be verbally instructed regarding when and how to respond to a shift in the position of the sound. A non-sensory explanation may also account for the proportion of 15% no-response trials at 18-months compared with less than 1% at 5-years. Younger children were conditioned to turn their heads in the correct direction. Although many of the children were easily conditioned, and yielded MAA thresholds of 1-4°, a number of them were more restless, and consequently were hard to condition. This difficulty in maintaining the 18-month-olds' attention is generally true for this age, which may account for the sparsity of auditory data at this stage in development.

C. Effects of stimulus conditions

1. General findings

For all age groups, MAA thresholds were highest for LAG, lower for LEAD, and lowest for SS. Changes in the location of PE sounds, which provide a more complex array of binaural stimulation compared with a SS sound, were heard only with greater angular shifts. If the presence of an echo had no influence on the perceived location of the auditory event, one would expect no difference between MAA thresholds on the LEAD and SS conditions. However, the fact that MAA thresholds for LEAD were higher than for SS indicates a decreased acuity in the presence of an echo. When two identical signals are presented with a delay between them, the number of binaural temporal cues that must be compared is multiplied, and may create some difficulty in completely ignoring the later arriving signal. In the current situation, the lead-lag delay was short enough so that the two sounds were fused for all ages, with the lagging sound not audible as a separate sound. Adult subjects reported anecdotally that they heard only one auditory image whose position was heavily dominated by the leading signal.

It seems that the auditory system treats the lagging sound as a component of the same auditory percept associated with the leading sound, and uses both signals to calculate the position of the auditory percept. In the LEAD condition the echo (at midline) perceptually pulls the position of the auditory event in its direction. A similar "pulling" phenomenon has been previously described in free-field (Hartmann & Rakerd, 1985; Leaky & Cherry, 1957; Wallach et al., 1949) and under earphone conditions (Yost & Soderquist, 1984; Zurek, 1980). In the free-field situations, the lead and lag signals were always on opposite hemifields, rather than one being at 0° and the other off-midline. It is conceivable that in such a paradigm the lagging sound exerts less influence on the auditory image due to its distance from the lead.

The MAA under conditions of the PE is the closest measure for directly observing the influence of the lag on the auditory image. Amount of pulling can be quantified by measuring the difference in threshold between SS and LEAD conditions. In the present study, LEAD MAA thresholds were 1.7 times those of SS for adults in the 25 msec duration condition. If the binaural system functions on a linear scale, then this measure would describe the exact amount of pulling, that is .7°.

These results closely match the findings of Perrott et al. (1989), who reported average MAA thresholds of 0.8° for the SS condition, and between 2.5-4.0° for the LAG condition, depending on the delay employed. For a delay of 4.5 msec, which is close to the 5.0 msec used in the present study, MAA thresholds were approximately 3.4°, which is similar to the value of 3.37° found here. This similarity is especially striking since Perrott et al. (1989) employed a stimulus of much shorter duration (5 msec) than the one I used for adults group A (25 msec). Based on their findings, Perrott et al. (1989) asserted that the lagging sound was essentially not suppressed, since listeners could detect relatively small changes in its angular displacement. However, this assertion cannot be deduced from their data without also measuring the MAA for a LEAD condition. A true test of echo suppression requires a direct measure of the influence that the lag exerts on the lead. The present study included that essential third condition. Effects of stimulus types were compared in order to assess localization precision for the LEAD and LAG conditions. If the signals from the two speakers are treated the same by the nervous system, and as Perrott et al. claim, there is no echo suppression, one would expect no difference in MAA thresholds between LEAD and LAG. Results of the present study show that, regardless of age, MAA thresholds for LAG were higher than for LEAD.

In the present study, the extent to which the position of the auditory image was dominated by the lead and lag signals was described by their relative weights. For all age groups, W_{lead} was greater than W_{lag} by at least a factor of 2, indicating that the lead exerts more influence in spatial perception. The fact that the lag has any weight at all, and tha LAG MAA thresholds are not infinitely greater than the LEAD thresholds indicates that, although the leading signal dominates the auditory image, the lagging sound also contributes to the perceived location. Similar weighting effects have been reported in studies conducted under earphones (Wallach et al., 1949; Yost & Soderquist, 1984; Zurek, 1980).

In a free-field situation, most similar to the one in the present study, Perrott et al. (1989) tested subjects' thresholds for SS and LAG conditions. From their data it is possible to assess relative influence of leading and lagging sounds to compare with results in the present study. Perrott et al.'s LAG/SS ratios are approximately 5:1, and in the present study, LAG/SS ratios are 3.37:1, which are fairly comparable, but still lower in Perrott et al.'s data. The difference between the two studies may be due to the difference in stimulus duration, which was longer in the present study than in Perrott et al.'s.

Using earphone paradigms, Wallach et al. (1949) presented subjects with PE stimuli which varied in interaural time delay to each ear. They presented a 4-click array with two clicks presented to each ear, simulating a PE stimulus in space. Using earphones, they were able to manipulate the time delay to each ear from the simulated right and left speakers, as well as the time delay between the two ears. Wallach et al. (1949) measured the necessary increase in time delay in the lagging pair necessary to match the effectiveness of the leading pair. The first pair was about 6 times as effective as the second pair in determining lateralization for a 400 usec click pair. That is $W_{lead} = .86$ and $W_{lag} = .15$. An increase in the interaural delay of the first pair decreased the weight of the second even more, down to $W_{lag} = .05$. Using a similar paradigm, Yost & Soderquist (1984) replicated the results of Wallach et al. (1949), finding W_{lead} between .86 and .88, versus W_{lag} between .12-.14. Yost & Soderquist (1984) also demonstrated that detection threshold for the binaural 4-click stimulus is lower when the leading click pair is presented with an interaural delay than if the lagging click pair is presented with a delay.

Compared with the results of the earphone studies, adult subjects in Group B of the present study has similar LEAD / LAG ratios. The ratio of LAG/LEAD thresholds increases significantly in the present study when adults are presented with 4 msec stimuli. For subjects in this condition $W_{lead} = .92$ and $W_{lag} = .08$. Thus, stimulus duration has a direct effect on influence that the lagging sound exerts on the perceive position of the auditory image. It is further possible that the amount of temporal overlap that exists between the leading and lagging signal influences their relative weights. For the 25 msec duration stimulus, the lagging sound was activated 5 msec after the leading one is, and the two sounds overlapped for a total of 20 msec, until the leading one was deactivated. In contrast, for the 4 msec duration stimulus, there was a 4 msec delay between lead and lag, hence there was no overlapping of the two stimuli. Other researchers who used short duration stimuli reported similar LEAD / LAG ratios to mine. Yost & Soderquist (1984) used 100 usec clicks, and Wallach et al. (1949) used 1 msec noise bursts.

Perrott et al. (1989) did use 5-msec noise bursts, which are comparable to the 4 msec ones that I used. But there was an additional difference between Perrott et al.'s (1989) procedure and the one in this study. Perrott et al. varied lead-lag delays by physically moving the loudspeakers further back from the lead loudspeaker, but they did not compensate for the intensity differences resulting from this situation. Thus, their echoes were not just delayed in time, but were also reduced in sound pressure level relative to the leading sound. A decrease in sound pressure level may have certainly given greater weight to the lead over the lag, resulting in LAG/SS ratios closer to 5, compared with 3.37 in this study.

Compared with earphone studies, the MAA thresholds of Perrott et al. are still closest to my results, which could be due to the procedure that we both used. In both studies, a SS sound was first presented as a "standard" from the center loudspeaker, and was followed by a PE stimulus presented from both the center loudspeaker and a second loudspeaker on the right or left. Freyman, Clifton & Litovsky (in press) have found that if a PE stimulus is preceded by a SS stimulus, subjects experience a perceptual enhancement of the echo, whereby the echo's audibility is increased. They speculated that in Perrott et al.'s (1989) study the presence of the SS stimulus prior to the PE stimulus in the LAG condition enhanced the influence of the lag on sound localization, and decreased MAA thresholds for that condition. Given my replication of Perrott et al.'s (1989) findings, I would tend to agree with that hypothesis, relating it to the findings of the present study as well. An enhancement of the echo would naturally decrease the difference between LEAD and LAG thresholds, and produce a relatively smaller weighting value for the LEAD. The SS standard might also account for the weighting differences between Perrott et al.'s and my data. They presented subjects with only one SS noise burst at midline prior to the PE stimulus, whereas I presented subjects with a train of 4 SS noise bursts prior to the PE stimulus. A longer train may have resulted in a greater enhancement of the echo than a single noise burst.

It seems that the auditory system gives greater perceptual weight to the lead signal than to the lag, not just in terms of suppressing audibility of the lag, but in terms of how much each signal influences sound localization. This finding is consistent with Zurek's (1980) hypothesis, that the precedence effect acts as an inhibitory mechanism which blocks interaural information for a short time period after the onset of a stimulus. According to this hypothesis, the leading sound which signals the onset of an auditory event is assigned perceptual dominance, which diminishes the nervous system's interaural sensitivity for the later-arriving echo.

2. Developmental effects

Past research has shown that the PE is first observed in human infants around 5 month of age (Clifton et al., 1984; Muir et al., 1989; for review, see Clifton, 1985). At this stage in development, infants have higher echo thresholds than both adults and 5-year-old children (Clifton, 1985). That is, greater delays between lead and lag are needed in order for the infants to turn their heads towards the hemifield containing the lag. What remained unclear from this previous work was whether at short delays, when the lag is inaudible it still influences children's localization accuracy. One might suppose that higher echo threshold in children may reflect stronger echo suppression, which is not necessarily true. It depends on how one chooses to define the term "strength of echo suppression".

Measurement of echo threshold is one approach, which describes the strength of echo suppression in terms of the delay necessary for the lead and lag to be heard as two separate sounds. The longer the delay, the stronger the echo suppression. A second approach is to measure the amount of influence that the lag has on the perceived location of the auditory image. For developmental comparisons this is best measured under conditions of the PE at very short delays, when the lag is not heard by any listeners regardless of age. If the lag has no influence at all, then it can be thought of as having no influence on localization accuracy. However, if it does influence localization precision, there is evidence that the echo is only partially suppressed. In fact, the amount of influence that the lag exerts may be used as an index of the strength of echo suppression.

Results of the present study are similar to previous developmental work on the PE in that regardless of methodology, younger infants have a more difficult time identifying the lagging sound. In the case of echo thresholds, greater lead-lag delays are necessary in order for them to turn their heads towards to lagging sound. In case of MAA thresholds, the lag has to be placed at greater distances from midline in order for the auditory image to shift and for reliable discrimination to be observed.

Clifton and colleagues found that 5-year-olds had similar echo thresholds to adults for short-duration 3 msec clicks. However, the children's echo thresholds were higher than adults for a longer-duration rattle stimulus (Clifton et al., 1984). The auditory stimulus used in the present study was also a long-duration stimulus (25 msec), although qualitatively different from the rattle stimulus. In either case, a stimulus of long duration produces significant age differences in processing of echoes.

One difficulty in drawing conclusions about age differences in the LAG stimulus stems from a procedural complication. Due to the physical size of the apparatus, presentation of auditory stimuli between 56-74° was not possible, a difficulty only relevant to the LAG condition for 18-month-olds. For this age group, an incorrect response at 55° resulted in an automatic increase of angular position to 75°, and vice versa. Individual subjects' data (included in Appendix I) reveals the fact that even at 75° the 18-month-olds had difficulty choosing the correct hemifield, and often gave either incorrect or no responses on these trials. It is quite possible that if given the LAG condition at greater angles the children would have performed better, and that their thresholds were under-estimated with the current procedure. The problem is not serious however, since these children's mean threshold of 52° was indisputably larger than any other thresholds obtained for this or other ages. An incorrect threshold estimation may over-estimate some inter-stimulus and inter-age ratios, but if anything, the ratios would be increased beyond their current values. Further studies may be necessary to obtain more accurate LAG threshold estimates for subjects whose do not perform well at 75° and whose thresholds may have been under-estimated.

Another difficulty inherent in this study, which is common to much of developmental research, can be referred to as a scaling problem. In order to draw conclusions regarding developmental changes in LEAD and LAG thresholds one needs a baseline comparison which is equal across all ages. Unfortunately, the SS condition which serves as the baseline in the present study is significantly different for 18-month-olds versus the two older age groups. Although it can certainly be stated that there are significant differences in LEAD and LAG thresholds across age groups, it is difficult to ascertain whether these differences are a function of performance on the SS condition, or whether they are on a different order of magnitude, and a more complicated computational process in the central auditory system. The problem does not exist for comparisons between 5-year-olds and adults.

One way of addressing this scaling problem was to treat the SS threshold as the basic unit of localization precision. If MAA thresholds for PE conditions are multiple units of SS MAA, then an analysis of the data should yield no significant age effects, although there should still be a difference between SS, LEAD and LAG. These predictions were confirmed when the data were analyzed in terms of "units" of SS MAA for the 18-month-olds and 5-year-olds. There are no theoretical reasons for claiming that localization precision during childhood functions in terms of units of SS MAA. However, the results do suggest that binaural analysis of interaural cues may include a multiplicative process.

A second approach used to handle the scaling problem was to calculate relative weights of lead and lag stimuli at each age. This method essentially ignores performance on the SS task, and compares performance on the two PE tasks. Results of these ratio comparisons indicated that for all ages, there was an element of perceptual "pulling" of the auditory image by the lagging sound. Otherwise, LEAD thresholds should have equalled SS thresholds.

In the PE conditions, which consisted of both a leading and lagging sound, the auditory image had to be perceptually pulled <u>at least</u> to the position of the subject's threshold for SS stimuli. If the auditory image was perceived as being between 0° and that subject's SS threshold, the subject would not be able to determine accurately the lateral position of the sound. For instance, if a subject's SS MAA threshold was 5.0°, the loudspeakers had to be placed at a distance from midline which would be sufficient for pulling the auditory image to 5.0° or beyond. It is not clear how much of the auditory image must be pulled, but certainly enough of it to allow reliable estimation of the correct hemifield. It is likely that the central part of the broad auditory image, or <u>centroid</u>, had to be pulled beyond the SS MAA to result in reliable MAA discrimination of the PE stimuli.

For each age group, a perceptual <u>centroid</u> was calculated, which represents the mean physical position of a PE auditory image for that age group. If the position of the <u>centroid</u> is at a larger angle on the horizontal plane than the mean SS MAA threshold for that age, then other variables must be influencing the perceived position of the <u>centroid</u>. The difference between the <u>centroid</u> and SS MAA thresholds was calculated for each age group. The differences were largest for 18-month-olds, smaller for 5-year-olds and smallest for adults. What might this difference reflect?

Adult subjects provided anecdotal reports that the auditory image was perceptually expanded or "broadened" in the presence of an echo, compared with the SS condition. Hence, the influence of the lag, in combination with that of the lead resulted in an ambiguous lateral position due to "spreading" of the auditory image in the space between the two loudspeakers. I propose that the difference between the calculated centroid and SS MAA thresholds directly reflects the amount of perceptual "broadening" of the auditory image. For adults this effect is fairly small, or they are able to ignore the broadening. For children the effect increases, creating more difficulty for them in discriminating the lateral position of the image.

A "broadened" auditory image under conditions of the precedence effect has been previously reported by numerous investigators (Blauert, 1982; Wallach et al., 1949; Yost & Soderquist, 1984; Zurek, 1980). Blauert's (1982) subjects reported hearing a diffuse auditory event, which filled large parts of the spatial area between the lead and lag loudspeakers (although most of the diffuse image was still perceived as being closer to the lead loudspeaker). Zurek (1980) has suggested that ambiguity in the lateral position may result directly from the fact that the lag is not entirely suppressed and exerts some influence on the auditory image.

Performance on an MAA task, regardless of the expanse of the auditory image, can be described as a decision making process. If the auditory image being detected is physically diffuse, there may be an increased variability in its perceived location. This could be especially true for variability between individual subjects, which might account for the large standard deviations in the children's LEAD and

LAG conditions and in adults' LAG conditions. Increased variability in the data of a complex PE stimulus was also reported by Yost & Soderquist (1984), who found considerable spread of the data both within subjects and between subjects.

Variability in data for a decision making process can also be obtained from the distribution of individual subjects' psychometric functions. These functions were plotted for every stimulus condition, at each age (see Figures 4a-6c). As was discussed above (see section on psychophysical algorithms), developmental auditory studies often employ a method of constant stimuli. Such an approach requires data collection at numerous stimulus levels, which is necessary in order to describe the relationship between perceptual sensitivity and stimulus level, referred to as a psychometric function.

This method does however demand that a large number of subjects be tested in order to obtain a sufficient number of data points at each level. In the case of infants and children, who can usually only be tested on a limited number of trials, each subject receives a few trial types at each stimulus level. In the present study an alternative, more efficient adaptive method was used in which threshold estimates were obtained for individual subjects. Despite the fact that this adaptive procedure did not present each subject with trials at every angular position, sensitivity measures were obtained over some range, and psychometric functions were derived from the adaptive procedure data, but they were based on relatively few data points at each stimulus level. When plotting psychometric functions thresholds are established by finding the stimulus level at which subjects were correct on a certain proportion of trials, e.g. 71%. For most of the Figures (4a-6c), threshold estimation with the functions is fairly close to estimation using the mean of angle reversals. The most notable effect within each age is the large variability in where the function lies on the abscissa. Slopes for individuals are quite steep, although they are spread over a large range of stimulus levels, reflecting the variability in subjects' performance at these stimulus levels. For this reason it is suggested that psychometric functions not be plotted as group data, since the resulting functions would be much shallower in slope than the original data.

3. Hypotheses about developmental aspects of the PE

Clifton et al's (1984) findings of higher echo thresholds for children than for adults may suggest that echo suppression is fairly strong in young children, and becomes more moderate with age. Under this scenario, one would expect that the 18-month-olds in the present study would have displayed fairly low LEAD MAA's, and very high

LAG MAA's. The former did not happen but the latter did. If on the other hand, young children have weak echo suppression, 18-month-olds should have displayed high LEAD MAA's, and slightly higher LAG MAA's. The data in the present study do not point directly to either scenario, since the 18-month-olds' LEAD thresholds were high, but their LAG thresholds were twice as high. This pattern of results suggests that processes other than mere echo suppression are involved in processing PE stimuli during localization tasks.

There should be at least two different levels of neuronal functioning related to binaural sound localization under conditions of the PE. One level operates on all sounds that impinge upon the nervous system. It acts as an all-or-none filter which, by eliminating the audibility of reverberations at a certain range of delays, prevents the auditory system from treating echoes as unique auditory events. At this level listeners' delay thresholds for hearing the echo are determined. It may be that in young children and infants, the filter is highly selective, allowing only echoes with very long delays to be heard. This filter mechanism may explain why young infants have much higher echo thresholds than adults.

The second level is primarily related to sound localization accuracy in reverberant environments. Once reverberations have been filtered out and treated as echoes, the extent to which those echoes influence the perceived locations of the original sound source is determined. It is not clear whether functioning at these two levels develops in parallel, or whether one precedes the other. However, if this hypothesis is correct, then the PE should not serve just as a means of preventing localization errors by inhibiting later-arriving signals. Rather it may act as a more fundamental decision making process which involves familiarity with the auditory signal and experience in the environment.

Rakerd & Hartmann (1985) offer a similar interpretation of the PE, suggesting that listeners treat echoes according to how plausible they may be as a sound that deserves to be assigned weight in localization. It is possible that young children do not have this level of decision making about an echo, which is why they cannot suppress its influence in localization precision.

In addition to echo suppression, there is an added factor associated with sound localization in the presence of two sounds. For children, the existence of two sounds, even if one of them is inaudible, might be largely distracting. Their nervous system generates a perceptually broad auditory image, which greatly diminshes their localization precision. With age, children may learn to select out unwanted signals and concentrate on the original signal. This ability, however it is acquired, may help listeners to perceive a punctate stimulus which is more easily localizable.

D. Limitations of the present study and future directions

The present study examined developmental changes in localization precision under conditions of the precedence effect, as measured with the minimal audible angle (MAA). MAA thresholds are a good measure of the limits of the auditory system, however, they are not a direct measure of localization accuracy in free-field. In the real world listeners rarely have to detect small changes in the position of a sound. However, they are often faced with the need to localize the absolute locations of sounds in space. Unfortunately, the methodologies for testing localization accuracy in young children are not well developed. Children require constant reinforcement, contingent on their performance in a task. The reinforcement serves both to maintain interest in the task and provide children with feedback.

Reinforcement procedures in pure localization tasks are difficult for two reasons. First, young children do not possess a behavior which clearly and accurately reflects <u>where</u> they perceive an object to be located. Although some measures have been attempted such as head turning (Morrongiello, 1988), they are limited in that such a behavior may not be well developed by this age, and errors on the task could reflect errors in motoric coordination as oppposed to sound localization. It is infinitely easier to teach children to discriminate between two positions, and to train them to associate a correct response with a reinforcer. Second, a general problem of studying localization is that perceptually there is no correct or incorrect response. There is only a perceived location, which may deviate from the actual location, but reinforcers cannot be used in this case to teach children to respond. If an appropriate measure for localization accuracy can be found, it may provide a great deal of information about the direct influence of a PE sound on localization accuracy in free-field.

A second limitation to the present study is rooted in the "scaling" problem which was discussed above. Essentially, each age group had a different level of performance for the baseline condition (SS), which limits the interpretations of developmental differences in localization of PE stimuli. It is not clear whether these differences reflect sensory processes, or whether the 18-month-olds' thresholds are elevated for lack of a better measuring technique. As a result, the questions remain whether performance on PE tasks develops as a function of improvement on SS tasks, and whether there are actual age differences in the strength of echo suppression. These issues may be addressed by comparing echo thresholds for the three age groups, and especially for 18-month-olds whose thresholds have never been measured. Development of strength of echo suppression can be further measured by obtaining MAA thresholds at different lead-lag delays. In the present study a short delay was used, at which the PE was assumed to be operational for all age groups. However, that delay may have been closer to some subjects' echo thresholds than others, which may have affected the extent to which the lag influenced the perceived location of the auditory image.

E. Conclusions

The present study explored developmental changes in localization precision during late infancy, early childhood and adulthood. For all age groups, precision was best for single-source sounds (SS), and diminished for PE sounds. The 18-month-olds' thresholds were significantly larger than those of either 5-year-olds or adults. Five-year-olds' performance was close to adults for SS sounds but much worse for PE sounds. Regardless of age, when multiple arrays of the same signal are presented, the number of binaural temporal cues that must be compared multiplies, thereby decreasing the accuracy for sound localization. In the presence of an inaudible echo, the auditory system treats the echo as a component of auditory percept of the original sound. The presence of an echo hinders localization precision, as indicated by higher thresholds for the LEAD than for the SS condition. However, the extent to which this is true may depend on the age of the listener. Adults may be fairly accurate at detecting changes in sound location, perhaps due to experience, and perhaps due to their fully matured brain. It is not clear when children's auditory system reaches adult level maturity, although it is clearly after the age of 5 years. It is possible that auditory localization is subserved in the central auditory system by at least two separate mechanisms, one of which is involved in processing of single-source sounds, and the other which is involved in negotiating the role that echoes may play. If this is true, then by 5 years of age children have reached full development on the first level of localization processing, but not of the second level. Further research is necessary to determine how many mechanisms are involved in sound localization, in which situations they are each operational, and at what ages each one reaches full adult maturity.

APPENDIX A

SAMPLE LETTER TO PARENTS OF 18-MONTH-OLDS

Dear Parents:

As part of an ongoing project in infant perception, we are studying how young toddlers respond to sounds they hear around them. We learned about the birth of your child from the birth announcements in the newspaper at the time. We are now writing to you to describe our project and invite you and your child to participate.

In this study we are interested in how well children can localize sound around them. They will be hearing an attractive sound coming from one of many locations in the room, and we will be observing their head orientation during that time. As part of the experiment we will also present them with colorful and interesting toys on a number of occasions. Many of you have been kind enough to participate in previous projects in our laboratory when your child was a young infant, for which we are very grateful. Although this study is similar to some of our previous ones in that it involves auditory perception, it is a new and separate project, which we hope will teach us a lot about perception in young toddlers.

Throughout the test session your child's behavior will be videotaped for later scoring of head turning toward the sound. During the entire session, your child will be seated on your lap. There are no discomforts or risks involved in this study. In fact, we hope that the visit will be very pleasant for both you and your child. We will be happy to show you the videotape after the session and to discuss with you the findings of this study as well as other studies on the development of perception.

Participation in this study involves one visit of approximately 30 minutes, to Tobin Hall, room 651 at University of Massachusetts in Amherst. We are including a map for your convenience, showing you where on the campus you can park nearby our building. If you should decide to come, we will be happy to meet you by your car and escort you into our laboratory.

Our study depends mostly on parents' help and participation, and we will be extremely grateful if you will be able to help us out. We will be calling you by phone over the next few days, to answer any questions and ask if you would like to schedule an appointment. However, if you have received this letter and would like to contact us, to learn more about our study or to arrange an appointment quickly, please feel free to do so. You can call Ruth at 545-4774 or 256-0076.

Thank you very much for your consideration of our project.

Ruth Litovsky — Rachel Clifton

Graduate Researcher — Professor

APPENDIX B

SAMPLE LETTER TO PARENTS OF 5-YEAR-OLDS

Dear Parents:

As part of an ongoing project in perception, we are studying how young children respond to sounds they hear around them. We we were granted permission by the Mark's Meadow Governance Board's Research Committee to send this letter home to you. We would like to describe our project and invite you and your child to participate.

In this study we are interested in the types of cues that children use to localize sound around them. They will be hearing a sound coming from one location in the room, which will then shift to a second location. We will be asking your child to point in the direction that the sound moved to. As part of the experiment we will also present them with colorful and interesting mechanical toys on most of the trials, to maintain their interest in tracking the movement of the sound.

During the testing session, your child will be seated on a chair inside the testing room, and if you would like to, you will be able to sit behind your child in the room. Otherwise, we can invite you to observe your child's behavior on a video monitor in the adjacent room. There are no discomforts or risks involved in this study. In fact, we hope that the visit will be very pleasant for both you and your child. We will be happy to show you the results after the session, and to discuss with you the findings of this study as well as other studies on the development of perception.

Participation in this study involves one visit of approximately 45 minutes to Tobin Hall, room 651 at University of Massachusetts in Amherst. Our testing hours are very flexible, as we try to accommodate the schedules of all parents who wish to have their child participate in our study. We are including a self-addressed, postcard. If you would like to participate in our study, we would ask you to please fill out the information on the postcard, and mail back to us as soon as possible, or to call Ruth at the telephone numbers listed below, so that we can make an appointment. We are interested in testing children who are between the ages of 4-1/2 and 6 years. If you are very busy at this time of year but would like to be contacted at a later date, we can arrange to do so if indicated on the postcard.

Also included is a map for your convenience, showing you where on the campus you can park nearby our building. If you should decide to make an appointment, we will meet you by your car and escort you into our laboratory.

Our study depends mostly on parents' help and participation, and we will be extremely grateful if you will be able to help us out. If you would like to contact us by telephone, to learn more about our study or to arrange an appointment, please feel free to do so. You can call Ruth at 545-5965 or 256-0076 (days or evenings). Please feel free to leave a message on the answering machine if she is not there.

Thank you very much for your consideration of our project.

Ruth Litovsky Rachel Clifton

Project Director Professor

APPENDIX C

BIOGRAPHICAL INFORMATION SHEET FOR CHILDREN

Infant's Last Name ____________________ First Name ____________

Sex _________ Birth Date __________________

Date Tested ________________ Age (yr/mo) ________________

Birth-weight (toddlers) ______________

Fullterm (toddlers) _____________

Frequent ear infections since birth?

____

Any suspicion of hearing impairment?

____

Is the child on any medication this week/today?

____

____

Time of day ______________ Condition ______________________

Video Tape # _________________ Locations _________________

Experimenters: 1(inside) ___________ 2(outside) ___________

Was session completed? _____________

If no, give reason ____

APPENDIX D

CONSENT FORM FOR CHILDREN

Consent Form For Participation of Children in a Study on the Development of Auditory Localization

Investigators: Ruth Y. Litovsky and Rachel K. Clifton

We are studying how young children respond to sounds that they hear at various locations in space. We are interested in understanding what sort of information children use in order to localize sound, and what type of developmental changes can be observed at different ages.

In this procedure the child sits on a chair in the testing room, facing a curtain about 2 meters away. You will be able to observe the test on a video monitor in the adjacent room. An investigator will be standing behind the curtain and calling out the child's name from time to time, to get the child's attention. We will be presenting sounds from behind the curtain. These sounds will consist of trains of noise bursts, at an intensity level of about 50 decibels (equivalent to average speaking voice level). The sounds will begin at midline, will remain there for 1.5 seconds, and will subsequently shift to either the right or left, where it will be played for 5 seconds. We will ask your child to indicate with their hand which direction the sound was shifting to. Intermittently during the session, mechanical toys will also be activated for the child's entertainment.

Although the length of the testing session varies with each child, it usually lasts about 45 minutes. We may decide to take a short break during the session, to let the child play with some toys in the adjacent room. Throughout the session we will be video-taping your child's behavior for scoring at a later date.

We make every effort to insure that you and your child are comfortable. There is no discomfort or danger in this study, to either you or your child. Although there are no direct benefits either, this study will increase our knowledge of perceptual and cognitive development.

Participation in this study is completely voluntary, and if at any point during the experiment you wish to terminate the session please let us know. This research project has been reviewed and approved by the University of Massachusetts Human Subjects Committee.

We thank you and your child for your participation and would be very glad to answer any questions you may have now, or following the testing session.

I understand the procedure and agree to allow my child to participate

____

Child's Name

____________________________________ __________________

Parent's Signature Date

APPENDIX E

MAILING LOG

	18-month-olds	5-year-olds
Number of letters sent:	147	109
Number of subjects scheduled:	49	46
Number of no contacts:	32	23
Number of not interested:	60	36
Number of cancellations:	6	4

APPENDIX F

CONSENT FORM FOR ADULT SUBJECTS

Consent Form for Adult Subjects' Participation in a Study on Auditory Localization

Investigators: Ruth Y. Litovsky and Rachel K. Clifton

This study focuses on people's responses to sounds that they hear in various locations in space. We are interested in studying what type of information is used in order to localize sounds in the environment.

We will be playing sounds, consisting of trains of noise bursts, at an intensity level of about 50 dBA, and a rate of 2 per second. These sounds will be played through small loudspeakers, located behind a curtained enclosure. They will begin at a position directly in front of you, will be played there for 1.5 seconds, and will subsequently shift either to the right or left, where they will remain for an additional 5 seconds. We will ask that you to point your hand to either the left or right, depending on which direction you think that the sound had shifted to. If you are not sure, we will ask you to guess. Following your response, if your answer was correct you will see a small light flash on the side of the apparatus corresponding to your response. If your answer was incorrect, we will proceed to the next trial.

The entire testing session will last approximately 45-60 minutes. There is no discomfort or danger in this study. There are no direct benefits to subjects. However, the results of this study will increase our knowledge of perceptual and cognitive processes. All records are kept confidential and subjects are only identified by number, not by name.

Participation in this study is completely voluntary, and if at any point during the experiment you wish to terminate the session please let us know.

This research project has been reviewed and approved by the University of Massachusetts Human Subjects Committee. We thank you for your participation and would be glad to answer any questions you may have, now or following the session.

I understand the procedure and agree to participate in this study. I also understand that I will receive 1 (one) experimental credit in return for my participation, to be used toward my grade in an approved psychology course.

Subject's Signature	Date

APPENDIX G

PSYCHOPHYSICAL ALGORITHM COMPUTER PROGRAM

This program is written in computer language C for operating an adaptive psychophysical algorithm. It can be run using any IBM - compatible personal computer.

Instructions for operating the program:

A) Load the program into any disk drive on your computer, or copy it onto the hard drive.

B) At the c:\> prompt type "baby" and press the Enter button. The program is set to operate a 2-down/1-up rule, with 7 reversals to end the session and with a minimum step size = 2.

C) If you would like to change any of these parameters you need to do the following: After typing "baby" you add an extention to the executable command, which includes a dash (-), a letter, and the number corresponding to the value that you wish to change. Each parameter has a fixed corresponding letter:

Step size = m

reversals = r

correct trials to decrease the angle = s

For instance if you would like to have a total of 5 reversals, a minimum step size of 2 and a 3-down/1-up rule, type the follwing: "baby -r 5 -m 2 -s 3" and press Enter.

Threshold is calculated based on the mean of all the reversals minus the first two. The program automatically drops the first two reversal.

Note: all entries much be in alphanumerical form. Do not use decimal point. The program expects integers.

D) Once you have chosen your executable command, the program will bring up a table on the screen which will request the following information:

Subject's name
Birth Date
Age Group
Today's Date
Delay (of stimulus)
Output File

(You will be able to start the program without some of the information. The program does however require an output file name. Without it, you will not be able to run the program because there is no designated place for the data to be saved you provide the information on this line)

E) When you have filled in the information, press the Esc button. The program will ask you the name of the condition that you are running. Type in that name (e.g. SS, LEAD, LAG) and press Enter.

F) Next, you will be asked for the initial angle position. This is the very first positions that you would like to present the sound at. It is also the position which will be repeated for probe trials. Type in the number and press enter.

G) The program will start with a series of Practice trials. You will enter information regarding the subject's response. There are 4 options; use only one of these keys on the pad; the computer will not respond to any other entry:

<u>Subject's response</u>	<u>Entry on key pad</u>
correct	Y
incorrect	N
no response	0
If you want to quit	Esc

If you chose the Esc button, the computer will ask you if you want to continue with another condition. Type Y or N. If you type Y it will take you back to the point of entering the name of the condition (part E). If you type N, you will be back at the c:\> prompt.

H) <u>Retreiving the data</u>:

Data are saved in ASCII code. You can either type them to the screen or print them onto a printer. At the c:\> prompt:

To read data on screen type: "type filename"

To print out data type: "print filename"

If you need to edit the file, you can also read it into your word processor. For example, in Wordperfect version 5.0 use the Cntr-F5 key to read in a DOS file. WP will convert the file into the proper format and you can then save it back either as a DOS file or as a file on a word processor.

```
/* PROGRAM BABY */

/* The following include commands and bring in tools that you
will need in order to operate the program */

#include <stdio.h>
#include <stdlib.h>
#include <conio.h>
#include <time.h>
#include "window.h"
#include "keys.h"
#include "cursor.h"
#include "entry.h"

#define    NAME_LEN   30  /* subject's name */
#define    LEFT 0          /* left speaker */
#define    RIGHT      1          /* right speaker */
#define    INC   1         /* increase position */
#define    DEC   2         /* decrease position */

PROMPT prompts[] = {
     { 2, 20, "--- Test Record ---"},
     { 4, 8, "Subject Name:"},
     { 6, 8, "Birth Date:"},
     { 8, 8, "Age Group:"},
     { 10, 8, "Today's Date:"},
     { 12, 8, "Delay:"},
     { 14, 8, "Output File:"},
     { 16, 20, "Press ESC to start"},
     { 0, 0, NULL}
};

struct nad {
     char name[NAME_LEN+1];
     char dob[21];
     char agegroup[11];
     char today[21];
     char delay[11];
     char output[21];
} nd;

FIELD template[] = {
     { 4, 22, NAME_LEN, nd.name  },
     { 6, 22, 20, nd.dob },
     { 8, 22, 10, nd.agegroup },
     { 10, 22, 20, nd.today },
     { 12, 22, 10, nd.delay },
     { 14, 22, 20, nd.output },
     { 0, 0, 0, NULL}
};

extern int    optind;
```

```
extern int      opterr;
extern char     *optarg;

FILE *fp;
int   ma = 1; /* minimum angle */
int   tr = 7; /* total reversals */
int   ss = 2; /* step size, 2 downs 1 up */
int   xa = 55; /* if initial angle larger than xa, no angle
is
                                  is allowed to fall between
these two angles */
int   init_angle;

void
main(argc, argv)
int   argc;
char **argv;
{
     char  in_buff[40];
     FIELD      temp;
     int   i;
     int   c;
     int   err = 0;

     opterr = 0;
     while ((c = getopt(argc, argv, "s:r:m:")) != -1) {
               switch(c) {
               case 'r':
                         tr = atoi(optarg);
                         break;
               case 's':
                         ss = atoi(optarg);
                         break;
               case 'm':
                         ma = atoi(optarg);
                         break;
               case '?':
                         err = 1;
                         break;
               }
     }
     if (err == 1) {
               fprintf(stderr,    "Useage:    baby    -r
total_reversals -s step_size -m min angle\n");
               exit(1);
     }
     if (tr <= 2 || ss <= 0 || ma <= 0 ) {
               fprintf(stderr, "Invalid arguments.\n");
               exit(1);
     }

     randomize();
```

```
	clrscr();
	open_window(10,4,70,22,ENTRYFG,ENTRYBG,2,0);
	clear_template(template, prompts);
	data_entry(template, prompts);

	/*
	 * Open the output file
	 */
	while ((fp = fopen(nd.output, "w")) == (FILE *)0) {
		error_message(" Can't open output file");
		nd.output[0] = '\0';
		data_entry(template, prompts);
	/*	get_field(&template[4]); */
	}

	/*
	 * Write test record into output file
	 */
	fprintf(fp,  "\n\n\t\tDevelopmental  Precedence  Effect
Study\n\n\n");
	fprintf(fp, "Name:\t%s\n", nd.name);
	fprintf(fp, "Birth Date:\t%s", nd.dob);
	fprintf(fp, "\t\tAge Group:\t%s\n", nd.agegroup);
	fprintf(fp, "Test Date:\t%s", nd.today);
	fprintf(fp, "\t\tDelay:\t\t%s\n\n", nd.delay);

	/*
	 * Start the dialogue
	 */
	close_window();
restart:
	i = 1;
	clrscr();
	gotoxy(1,1);
	cputs("Enter the CONDITION: ");
	temp.frow = wherey();
	temp.fcol = wherex();
	temp.flen = 10;
	temp.fbuff = in_buff;
	in_buff[0] = '\0';
	while (get_field(&temp) != '\r') {
		error_message(" Must end your input with RETURN");
		in_buff[0] = '\0';
		blank_field(&temp);
	}
	cputs("\r\n");
	fprintf(fp, "Condition:\t%s\n\n",in_buff);

	textcolor(WHITE);
	textbackground(BLACK);
	cputs("Enter the initial speaker position: ");
	temp.frow = wherey();
```

```
        temp.fcol = wherex();
        temp.flen = 2;
        in_buff[0] = '\0';
next:
        while (get_field(&temp) != '\r') {
                error_message(" Must end your input with RETURN");
                in_buff[0] = '\0';
                blank_field(&temp);
        }
        textcolor(WHITE);
        textbackground(BLACK);
        init_angle = atoi(in_buff);
        if (init_angle <= ma || init_angle >= 91) {
                error_message(" Invalid angle");
                in_buff[0] = '\0';
                blank_field(&temp);
                goto next;
        }
        cputs("\r\n\n\n");
        cputs("Practice Phase:\r\n");
        fprintf(fp, "\tPractice Phase:\n");
        if (do_practice(init_angle, &i) == -1) {
                cputs("\r\n\nExperment aborted!\r\n");
                fprintf(fp, "\n\tExperiment aborted!\n\n");
                goto abort;
        }

        /*
         * Test Phase
         */
        cputs("Test Phase:\r\n");
        fprintf(fp, "\n\tTest Phase:\n");
        if (do_test(init_angle) == -1) {
                fprintf(fp, "\n\tExperiment aborted!\n\n");
                cputs("\r\n\nExperment aborted!\r\n");
        } else {
                sprintf(in_buff,"\n\n%d    reversals    have    been
reached.\r\n", tr);
                cputs(in_buff);
        }
abort:
        cputs("Continue with another condition (Y/N)? ");
        temp.frow = wherey();
        temp.fcol = wherex();
        temp.flen = 1;
        temp.fbuff = in_buff;
        in_buff[0] = '\0';
next2:
        while (get_field(&temp) != '\r') {
                error_message(" Must end your input with RETURN");
                in_buff[0] = '\0';
                blank_field(&temp);
```

```
        }
        cputs("\r\n");
        textcolor(WHITE);
        textbackground(BLACK);
        if (tolower(in_buff[0]) != 'y' && tolower(in_buff[0]) !=
'n') {
                        error_message("  Must  enter  either  Y(y)  or
N(n)");
                        in_buff[0] = '\0';
                        blank_field(&temp);
                        goto next2;
        }
        cputs("\r\n");
        if (tolower(in_buff[0]) == 'y') goto restart;

        normalcursor();
        close_window();
        fclose(fp);
        clrscr();
}

int
get_spkr(void)
{
        static int      last = LEFT;
        static int      llast = LEFT;
        int     cur;

        cur = random(2);
#if 0
        if (last == llast && last == cur) {
                cur = 1 - cur;
        }
#endif
        llast = last;
        last = cur;
        return cur;
}

int
trial(ang, i)
int     ang;
int     i;
{
        FIELD       temp;
        char buff[80];
        char in_buff[10];
        int     retval;
        char spkr[5];

        sprintf(buff,"     Trial #%d:  ", i);
        if (get_spkr() == LEFT) {
```

```
               strcat(buff, "LEFT  Speaker\r\n");
               strcpy(spkr, "Left");
     } else {
               strcpy(spkr, "Right");
               strcat(buff, "RIGHT Speaker\r\n");
     }
     cputs(buff);
     cputs("                           Was subject correct (Y/N/0/Esc)?
");
     temp.frow = wherey();
     temp.fcol = wherex();
     temp.flen = 1;
     temp.fbuff = in_buff;
     in_buff[0] = '\0';
next1:
     while (1) {
               retval = get_field(&temp);
               if (retval == '\r')  break;
               else if (retval == ESC) return -1;

               error_message(" Must end your input with
RETURN");
               in_buff[0] = '\0';
               blank_field(&temp);
     }
     textcolor(WHITE);
     textbackground(BLACK);
     in_buff[0] = toupper(in_buff[0]);
     if (in_buff[0] != 'Y' && in_buff[0] != 'N' && in_buff[0]
!= '0') {
               error_message(" Must enter Y(y), N(n), or 0");
               in_buff[0] = '\0';
               blank_field(&temp);
               goto next1;
     }
     cputs("\r\n");

fprintf(fp,"\t\t%2d\t\t%s\t\t%2d\t\t%s\n",i,spkr,ang,in_buff);

     if (in_buff[0] == '0') return 2;
     return(in_buff[0] == 'Y');
}

int
do_practice(ang, ip)
int   ang;
int   *ip;
{
     int  record[5] = {0, 0, 0, 0, 0};
     int  i = *ip;
     int  here = 0;
     int  retval;
```

```
        fprintf(fp, "\t   Trial #           Speaker        Angle
        Response\n");
        fprintf(fp,
"\t------------------------------------------------------------
-\n");
        while(1) {
                        retval = trial(ang, i++);
                        if (retval == -1) return -1;
                        else if (retval == 2) continue; /* no response
*/
                        record[here] = retval;
                        here = (here+1) % 5;
                        if (i>= 5) {
                                int  j;
                                int  k = 0;
                                for (j=0; j<5; j++) {
                                        k += record[j];
                                }
                                if (k >= 4) {
                                        break;
                                }
                        }
        }
        *ip = i;
        return(0);
}

int
do_test(init_angle)
int  init_angle;
{
        int  i = 1;
        int  err;
        int  cur_angle = init_angle;
        int  step;
        int  bound;
        char val_buff[5];
        int  reversal = 0;
        int  direction = DEC;
        int  init = 1;
        int  angs[7];
        int  retval;
        float     mang;
        int  cnt = 0;

        extern void    get_legal_angle();

        step = round2(init_angle);
        cputs("\n\n     ***  Place speaker at angle ");
        itoa(cur_angle, val_buff, 10);
        cputs(val_buff);
```

```
	cputs(" ***\r\n\n\n");

/*
	do_probe(cur_angle, &i);
	bound = i+ 2;
	cur_angle = round2(cur_angle);
	step = round2(step);
*/
	fprintf(fp, "\t  Trial #              Speaker         Angle
	Response\n");
	f    p    r    i    n    t    f    (    f    p    ,
"\t--------------------------------------------------------------
-\n");
	bound = i+ss;
again:
	err = 0;
	while ( i< bound) {
		retval = trial(cur_angle, i++);
		if (retval == -1) return -1;
		else if (retval == 2) { /* no response */
				retval = trial(cur_angle, i);
				if (retval == -1) return -1;
				else if (retval == 2) {
					cputs("\n\n    *** Place speaker at
angle ");
					itoa(init_angle, val_buff, 10);
					cputs(val_buff);
					cputs(" ***\r\n\n\n");

					if (do_probe(init_angle, &i) == -1)
return -1;
					bound = i+ ss;
					cputs("\n\n    *** Place speaker at
angle ");
					itoa(cur_angle, val_buff, 10);
					cputs(val_buff);
					cputs(" ***\r\n\n\n");
					goto again;
				}
		}
		if (retval == 0) {
			err = 1;
			break;
		}
	}
	if (err == 1 && init == 1) {
		bound = i+ ss;
		goto again;
	}
	if (err == 1) {
		if (direction == DEC) {
			cnt = 0;
```

```
               direction = INC;
               angs[reversal] = cur_angle;
               reversal++;
               if (reversal == tr) goto leave;
               step = round2(step);
          }
          cnt++;
          get_legal_angle(&cur_angle, &step, &cnt, direction);

          cputs("\n\n     *** Place speaker at angle ");
          itoa(cur_angle, val_buff, 10);
          cputs(val_buff);
          cputs(" ***\r\n\n\n");
          retval = trial(cur_angle, i++);
          if (retval == -1) return -1;

          else if (retval == 2) { /* no response */
                    retval = trial(cur_angle, i);
                    if (retval == -1) return -1;
                    else if (retval == 2) {
                         cputs("\n\n     *** Place speaker at
angle ");
                         itoa(init_angle, val_buff, 10);
                         cputs(val_buff);
                         cputs(" ***\r\n\n\n");

                         if (do_probe(init_angle, &i) == -1)
return -1;
                         bound = i+ ss;
                         cputs("\n\n     *** Place speaker at
angle ");
                         itoa(cur_angle, val_buff, 10);
                         cputs(val_buff);
                         cputs(" ***\r\n\n\n");
                         goto again;
                    }
          }

          if (retval == 0) {
               cputs("\n\n     *** Place speaker at angle ");
               itoa(init_angle, val_buff, 10);
               cputs(val_buff);
               cputs(" ***\r\n\n\n");

               if (do_probe(init_angle, &i) == -1) return -1;

               /*
                * Always count one reversal?
               reversal++;
               if (reversal == tr) goto leave;
               direction = DEC;
                */
```

```
               bound = i+ ss;
               cputs("\n\n    *** Place speaker at angle ");
               itoa(cur_angle, val_buff, 10);
               cputs(val_buff);
               cputs(" ***\r\n\n\n");
               goto again;
          } else {

               bound = i+ ss - 1;
               goto again;
          }
     } else {
          init = 0;
          if (direction == INC) {
               cnt = 0;
               direction = DEC;
               angs[reversal] = cur_angle;
               reversal++;
               if (reversal == tr) goto leave;
               step = round2(step);
          }
          cnt++;
          get_legal_angle(&cur_angle, &step, &cnt, direction);

          bound = i+ ss;
          cputs("\n\n    *** Place speaker at angle ");
          itoa(cur_angle, val_buff, 10);
          cputs(val_buff);
          cputs(" ***\r\n\n\n");
          goto again;
     }
leave:
     mang = 0.0;
     while(--reversal >= 2) mang += (float)angs[reversal];
     fprintf(fp,
"\t------------------------------------------------------------
-\n");
     fprintf(fp, "\tThe mean of the last %d reversals =
%5.2f\n\n", tr-2, mang/(tr-2));
     return 0;
}

int
round2(ang)
int  ang;
{
           int  retval;

           retval = ang % 2?   (ang / 2 + 1) : (ang / 2);
           if (retval <= ma) retval = ma;
           return (retval);
}
```

```
int
do_probe(ang, ip)
int  ang;
int  *ip;
{
     int  i = *ip;
     int  retval;

     while(1) {
          retval = trial(ang, i++);
          if (retval == -1) return -1;
          else if (retval == 1) break;
     }
     *ip = i;
     return 0;
}

void
get_legal_angle(cur_angle, cur_step, count, dir)
int  *cur_angle;
int  *cur_step;
int  *count;
int   dir;
{
          int  ang = *cur_angle;
          int  stp = *cur_step;

          if (*count > 2) {
                    stp *= 2;
                    *count = 0;
          }
          ang += ((dir == INC)? 1: -1) * stp;
          if (ang < ma || ang > init_angle) {
                    stp = *cur_step;
          }

 next_step:
          ang = *cur_angle;
          if (dir == INC && ang == init_angle && stp == 1)
 goto abort;
          if (dir == DEC && ang == ma && stp == 1) goto abort;

          ang += ((dir == INC)? 1: -1) * stp;
          if (ang < ma || ang > init_angle) {
                    stp = round2(stp);
                    goto next_step;
          }

          /* now ang is a new legal angle and stp is a new
 step size */
          if (init_angle > xa && ang > xa) {
```

```
                        if (dir == INC) ang = init_angle;
                        else ang = xa;
            }
abort:
            *cur_angle = ang;
            *cur_step = stp;
}
```

APPENDIX XX

Program written in computer language C for operating an adaptive psychophysical algorithm. This program can be run using any IBM - compatible personal computer. Ther are no specific memory requriements.

Instructions for operating the program:
Load the program into any disk drive on your computer, or copy it onto the hard drive.

At the c:\> prompt type "baby" and press the Enter button. The program is set to operate a 2-down/1-up rule, with 7 reversals to end the session and with a minimum step size = 2. If you would like to change any of these parameters you need to do the following:

After typing "baby" you add an extention to the executable command, which includes a dash (-), a letter and the number corresponding to the value that you wish to change. Each parameter has a fixed corresponding letter:

Step size = m
reversals = r
correct trials necessary in order to decrease the angle = s

For instance if you would like

```
#include <stdio.h>
#include <stdlib.h>
#include <conio.h>
#include <time.h>
#include "window.h"
#include "keys.h"
#include "cursor.h"
#include "entry.h"

#define   NAME_LEN  30
```

```
#define   LEFT 0
#define   RIGHT     1
#define   INC  1
#define   DEC  2

PROMPT prompts[] = {
     { 2, 20, "--- Test Record ---"},
     { 4, 8, "Subject Name:"},
     { 6, 8, "Birth Date:"},
     { 8, 8, "Age Group:"},
     { 10, 8, "Today's Date:"},
     { 12, 8, "Delay:"},
     { 14, 8, "Output File:"},
     { 16, 20, "Press ESC to start"},
     { 0, 0, NULL}
};

struct nad {
     char name[NAME_LEN+1];
     char dob[21];
     char agegroup[11];
     char today[21];
     char delay[11];
     char output[21];
} nd;

FIELD template[] = {
     { 4, 22, NAME_LEN, nd.name  },
     { 6, 22, 20, nd.dob },
     { 8, 22, 10, nd.agegroup },
     { 10, 22, 20, nd.today },
     { 12, 22, 10, nd.delay },
     { 14, 22, 20, nd.output },
     { 0, 0, 0, NULL}
};

extern int     optind;
extern int     opterr;
extern char    *optarg;

FILE *fp;
int   ma = 1; /* minimum angle */
int   tr = 7; /* total reversals */
int   ss = 2; /* step size, 2 downs 1 up */
int   xa = 55; /* if initial angle larger than xa, no angle
is
                                    is allowed to fall between

these two angles */
int   init_angle;

void
main(argc, argv)
```

```
int   argc;
char **argv;
{
        char   in_buff[40];
        FIELD       temp;
        int    i;
        int    c;
        int    err = 0;

        opterr = 0;
        while ((c = getopt(argc, argv, "s:r:m:")) != -1) {
                switch(c) {
                case 'r':
                        tr = atoi(optarg);
                        break;
                case 's':
                        ss = atoi(optarg);
                        break;
                case 'm':
                        ma = atoi(optarg);
                        break;
                case '?':
                        err = 1;
                        break;
                }
        }
        if (err == 1) {
                fprintf(stderr,   "Useage:   baby   -r
total_reversals -s step_size -m min angle\n");
                exit(1);
        }
        if (tr <= 2 || ss <= 0 || ma <= 0 ) {
                fprintf(stderr, "Invalid arguments.\n");
                exit(1);
        }

        randomize();
        clrscr();
        open_window(10,4,70,22,ENTRYFG,ENTRYBG,2,0);
        clear_template(template, prompts);
        data_entry(template, prompts);

        /*
         * Open the output file
         */
        while ((fp = fopen(nd.output, "w")) == (FILE *)0) {
            error_message(" Can't open output file");
            nd.output[0] = '\0';
            data_entry(template, prompts);
        /*  get_field(&template[4]); */
        }
```

```
        /*
         * Write test record into output file
         */
        fprintf(fp,  "\n\n\t\tDevelopmental  Precedence  Effect
Study\n\n\n");
        fprintf(fp, "Name:\t%s\n", nd.name);
        fprintf(fp, "Birth Date:\t%s", nd.dob);
        fprintf(fp, "\t\tAge Group:\t%s\n", nd.agegroup);
        fprintf(fp, "Test Date:\t%s", nd.today);
        fprintf(fp, "\t\tDelay:\t\t%s\n\n", nd.delay);

        /*
         * Start the dialogue
         */
        close_window();
restart:
        i = 1;
        clrscr();
        gotoxy(1,1);
        cputs("Enter the CONDITION: ");
        temp.frow = wherey();
        temp.fcol = wherex();
        temp.flen = 10;
        temp.fbuff = in_buff;
        in_buff[0] = '\0';
        while (get_field(&temp) != '\r') {
                error_message(" Must end your input with RETURN");
                in_buff[0] = '\0';
                blank_field(&temp);
        }
        cputs("\r\n");
        fprintf(fp, "Condition:\t%s\n\n",in_buff);

        textcolor(WHITE);
        textbackground(BLACK);
        cputs("Enter the initial speaker position: ");
        temp.frow = wherey();
        temp.fcol = wherex();
        temp.flen = 2;
        in_buff[0] = '\0';
next:
        while (get_field(&temp) != '\r') {
                error_message(" Must end your input with RETURN");
                in_buff[0] = '\0';
                blank_field(&temp);
        }
        textcolor(WHITE);
        textbackground(BLACK);
        init_angle = atoi(in_buff);
        if (init_angle <= ma || init_angle >= 91) {
                error_message(" Invalid angle");
                in_buff[0] = '\0';
```

```
            blank_field(&temp);
            goto next;
        }
        cputs("\r\n\n\n");
        cputs("Practice Phase:\r\n");
        fprintf(fp, "\tPractice Phase:\n");
        if (do_practice(init_angle, &i) == -1) {
             cputs("\r\n\nExperment aborted!\r\n");
             fprintf(fp, "\n\tExperiment aborted!\n\n");
             goto abort;
        }

        /*
         * Test Phase
         */
        cputs("Test Phase:\r\n");
        fprintf(fp, "\n\tTest Phase:\n");
        if (do_test(init_angle) == -1) {
             fprintf(fp, "\n\tExperiment aborted!\n\n");
             cputs("\r\n\nExperment aborted!\r\n");
        } else {
             sprintf(in_buff,"\n\n%d   reversals   have   been
reached.\r\n", tr);
             cputs(in_buff);
        }
abort:
        cputs("Continue with another condition (Y/N)? ");
        temp.frow = wherey();
        temp.fcol = wherex();
        temp.flen = 1;
        temp.fbuff = in_buff;
        in_buff[0] = '\0';
next2:
        while (get_field(&temp) != '\r') {
             error_message(" Must end your input with RETURN");
             in_buff[0] = '\0';
             blank_field(&temp);
        }
        cputs("\r\n");
        textcolor(WHITE);
        textbackground(BLACK);
        if (tolower(in_buff[0]) != 'y' && tolower(in_buff[0]) !=
'n') {
                  error_message("  Must  enter  either  Y(y)  or
N(n)");
                  in_buff[0] = '\0';
                  blank_field(&temp);
                  goto next2;
        }
        cputs("\r\n");
        if (tolower(in_buff[0]) == 'y') goto restart;
```

```
     normalcursor();
     close_window();
     fclose(fp);
     clrscr();
}

int
get_spkr(void)
{
     static int     last = LEFT;
     static int     llast = LEFT;
     int  cur;

     cur = random(2);
#if 0
     if (last == llast && last == cur) {
          cur = 1 - cur;
     }
#endif
     llast = last;
     last = cur;
     return cur;
}

int
trial(ang, i)
int  ang;
int  i;
{
     FIELD     temp;
     char buff[80];
     char in_buff[10];
     int  retval;
     char spkr[5];

     sprintf(buff,"     Trial #%d: ", i);
     if (get_spkr() == LEFT) {
               strcat(buff, "LEFT  Speaker\r\n");
               strcpy(spkr, "Left");
     } else {
               strcpy(spkr, "Right");
               strcat(buff, "RIGHT Speaker\r\n");
     }
     cputs(buff);
     cputs("                Was subject correct (Y/N/0/Esc)?
");
     temp.frow = wherey();
     temp.fcol = wherex();
     temp.flen = 1;
     temp.fbuff = in_buff;
     in_buff[0] = '\0';
next1:
```

```
    while (1) {
                retval = get_field(&temp);
                if (retval == '\r')  break;
                else if (retval == ESC) return -1;

                error_message("  Must  end  your  input  with
RETURN");
                in_buff[0] = '\0';
                blank_field(&temp);
    }
    textcolor(WHITE);
    textbackground(BLACK);
    in_buff[0] = toupper(in_buff[0]);
    if (in_buff[0] != 'Y' && in_buff[0] != 'N' && in_buff[0]
!= '0') {
                error_message(" Must enter Y(y), N(n), or 0");
                in_buff[0] = '\0';
                blank_field(&temp);
                goto next1;
    }
    cputs("\r\n");

fprintf(fp,"\t\t%2d\t\t%s\t\t%2d\t\t%s\n",i,spkr,ang,in_buff);

    if (in_buff[0] == '0') return 2;
    return(in_buff[0] == 'Y');
}

int
do_practice(ang, ip)
int   ang;
int  *ip;
{
    int  record[5] = {0, 0, 0, 0, 0};
    int  i = *ip;
    int  here = 0;
    int  retval;

    fprintf(fp, "\t   Trial #            Speaker          Angle
    Response\n");
    fprintf(fp,
"\t-----------------------------------------------------
-\n");
    while(1) {
                retval = trial(ang, i++);
                if (retval == -1) return -1;
                else if (retval == 2) continue; /* no response
*/
                record[here] = retval;
                here = (here+1) % 5;
                if (i>= 5) {
                        int  j;
```

```
                        int  k = 0;
                        for (j=0; j<5; j++) {
                                k += record[j];
                        }
                        if (k >= 4) {
                                break;
                        }
                }
        }
        *ip = i;
        return(0);
}

int
do_test(init_angle)
int  init_angle;
{
        int  i = 1;
        int  err;
        int  cur_angle = init_angle;
        int  step;
        int  bound;
        char val_buff[5];
        int  reversal = 0;
        int  direction = DEC;
        int  init = 1;
        int  angs[7];
        int  retval;
        float     mang;
        int  cnt = 0;

        extern void     get_legal_angle();

        step = round2(init_angle);
        cputs("\n\n     ***  Place speaker at angle ");
        itoa(cur_angle, val_buff, 10);
        cputs(val_buff);
        cputs(" ***\r\n\n\n");

/*
        do_probe(cur_angle, &i);
        bound = i+ 2;
        cur_angle = round2(cur_angle);
        step = round2(step);
*/
        fprintf(fp, "\t  Trial #            Speaker        Angle
        Response\n");
        fprintf(fp,
"\t------------------------------------------------------------
-\n");
        bound = i+ss;
again:
```

```
     err = 0;
     while ( i< bound) {
          retval = trial(cur_angle, i++);
          if (retval == -1) return -1;
          else if (retval == 2) { /* no response */
                         retval = trial(cur_angle, i);
                         if (retval == -1) return -1;
                         else if (retval == 2) {
                                   cputs("\n\n     *** Place speaker at
angle ");

                                   itoa(init_angle, val_buff, 10);
                                   cputs(val_buff);
                                   cputs(" ***\r\n\n\n");

                                   if (do_probe(init_angle, &i) == -1)
return -1;

                                   bound = i+ ss;
                                   cputs("\n\n     *** Place speaker at
angle ");

                                   itoa(cur_angle, val_buff, 10);
                                   cputs(val_buff);
                                   cputs(" ***\r\n\n\n");
                                   goto again;
                         }
          }
          if (retval == 0) {
               err = 1;
               break;
          }
     }
     if (err == 1 && init == 1) {
          bound = i+ ss;
          goto again;
     }
     if (err == 1) {
          if (direction == DEC) {
               cnt = 0;
               direction = INC;
               angs[reversal] = cur_angle;
               reversal++;
               if (reversal == tr) goto leave;
               step = round2(step);
          }
          cnt++;
          get_legal_angle(&cur_angle, &step, &cnt, direction);

          cputs("\n\n     *** Place speaker at angle ");
          itoa(cur_angle, val_buff, 10);
          cputs(val_buff);
          cputs(" ***\r\n\n\n");
          retval = trial(cur_angle, i++);
          if (retval == -1) return -1;
```

```
          else if (retval == 2) { /* no response */
                    retval = trial(cur_angle, i);
                    if (retval == -1) return -1;
                    else if (retval == 2) {
                         cputs("\n\n    *** Place speaker at
angle ");
                         itoa(init_angle, val_buff, 10);
                         cputs(val_buff);
                         cputs(" ***\r\n\n\n");

                         if (do_probe(init_angle, &i) == -1)
return -1;
                         bound = i+ ss;
                         cputs("\n\n    *** Place speaker at
angle ");
                         itoa(cur_angle, val_buff, 10);
                         cputs(val_buff);
                         cputs(" ***\r\n\n\n");
                         goto again;
                    }
          }

          if (retval == 0) {
               cputs("\n\n    *** Place speaker at angle ");
               itoa(init_angle, val_buff, 10);
               cputs(val_buff);
               cputs(" ***\r\n\n\n");

               if (do_probe(init_angle, &i) == -1) return -1;

               /*
                * Always count one reversal?
               reversal++;
               if (reversal == tr) goto leave;
               direction = DEC;
                */
               bound = i+ ss;
               cputs("\n\n    *** Place speaker at angle ");
               itoa(cur_angle, val_buff, 10);
               cputs(val_buff);
               cputs(" ***\r\n\n\n");
               goto again;
          } else {

               bound = i+ ss - 1;
               goto again;
          }
     } else {
          init = 0;
          if (direction == INC) {
               cnt = 0;
```

```
                direction = DEC;
                angs[reversal] = cur_angle;
                reversal++;
                if (reversal == tr) goto leave;
                step = round2(step);
            }
            cnt++;
            get_legal_angle(&cur_angle, &step, &cnt, direction);

            bound = i+ ss;
            cputs("\n\n     *** Place speaker at angle ");
            itoa(cur_angle, val_buff, 10);
            cputs(val_buff);
            cputs(" ***\r\n\n\n");
            goto again;
        }
leave:
        mang = 0.0;
        while(--reversal >= 2) mang += (float)angs[reversal];
        f     p     r     i     n     t     f     (     f     p     ,
"\t-------------------------------------------------------------
-\n");
        fprintf(fp, "\tThe mean of the last %d reversals =
%5.2f\n\n", tr-2, mang/(tr-2));
        return 0;
}

int
round2(ang)
int  ang;
{
            int  retval;

            retval = ang % 2?   (ang / 2 + 1) : (ang / 2);
            if (retval <= ma) retval = ma;
            return (retval);
}

int
do_probe(ang, ip)
int  ang;
int  *ip;
{
        int  i = *ip;
        int  retval;

        while(1) {
            retval = trial(ang, i++);
            if (retval == -1) return -1;
            else if (retval == 1) break;
        }
        *ip = i;
```

```
1
     return 0;
}

void
get_legal_angle(cur_angle, cur_step, count, dir)
int  *cur_angle;
int  *cur_step;
int  *count;
int   dir;
{
          int  ang = *cur_angle;
          int  stp = *cur_step;

          if (*count > 2) {
                    stp *= 2;
                    *count = 0;
          }
          ang += ((dir == INC)? 1: -1) * stp;
          if (ang < ma || ang > init_angle) {
                    stp = *cur_step;
          }

next_step:
          ang = *cur_angle;
          if (dir == INC && ang == init_angle && stp == 1)
goto abort;
          if (dir == DEC && ang == ma && stp == 1) goto abort;

          ang += ((dir == INC)? 1: -1) * stp;
          if (ang < ma || ang > init_angle) {
                    stp = round2(stp);
                    goto next_step;
          }

          /* now ang is a new legal angle and stp is a new
step size */
          if (init_angle > xa && ang > xa) {
                    if (dir == INC) ang = init_angle;
                    else ang = xa;
          }
abort:
          *cur_angle = ang;
          *cur_step = stp;
}
```

APPENDIX H

SAMPLE DATA FROM INDIVIDUAL SUBJECTS

Subject Number: 49
Birth Date: 5/25/89 Age Group: 18-months
Test Date: 12/5/90 Delay: 5 ms

Condition: ss

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	Y
4	27	Y
5	13	N
6	20	Y
7	20	Y
8	16	Y
9	16	Y
10	12	Y
11	12	Y
12	4	Y
13	4	Y
14	2	N
15	3	N
16	55	Y
17	3	N
18	4	N
19	55	Y
20	4	N
21	6	Y
22	6	0
23	6	Y
23	5	Y
24	5	N
25	6	Y
26	6	Y
27	5	Y
28	5	N

The mean of the last 5 reversals = 4.80

Subject Number: 47
Birth Date: 5/24/89 Age Group: 18-months
Test Date: 12/4/90 Delay: 5 ms

Condition: ss

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	N
3	55	Y
4	55	Y
5	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	Y
4	27	Y
5	13	Y
6	13	Y
7	6	N
8	10	Y
9	10	Y
10	8	Y
11	8	Y
12	6	Y
13	6	N
14	7	Y
15	7	N
16	8	N
17	55	Y
18	8	Y
19	8	Y
20	7	Y
21	7	Y
22	6	N
23	7	Y
24	7	Y
25	6	N

The mean of the last 5 reversals = 6.60

Subject Number: 48
Birth Date: 4/16/89
Test Date: 12/4/90

Age Group: 18-months
Delay: 5 ms

Condition: ss

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	Y
4	27	Y
5	13	Y
6	13	Y
7	6	Y
8	6	N
9	10	Y
10	10	N
11	14	Y
12	14	Y
13	12	Y
14	12	0
15	12	N
15	13	Y
16	13	0
17	13	0
17	55	Y
18	13	Y
19	13	Y
20	12	Y
21	12	0
22	12	Y
22	11	0
23	11	Y
23	11	N
24	12	0
25	12	Y
25	12	0
26	12	Y
26	11	N

The mean of the last 5 reversals = 11.80

```
Subject Number:      7
Birth Date:      2/1/89            Age Group:      18-months
Test Date:       12/15/90          Delay:          5 ms

Condition:       lead

      Practice Phase:
         Trial  #                    Angle          Response
-----------------------------------------------------------
              1                  55         Y
              2                  55         Y
              3                  55         Y
              4                  55         Y

      Test Phase:
         Trial  #             Angle         Response
-----------------------------------------------------------
              1                  55         Y
              2                  55         Y
              3                  27         Y
              4                  27         Y
              5                  13         N
              6                  20         Y
              7                  20         Y
              8                  16         N
              9                  18         Y
             10                  18         Y
             11                  17         Y
             12                  17         N
             13                  18         0
             14                  18         0
             14                  55         Y
             15                  18         Y
             16                  18         0
             17                  18         N
             17                  19         0
             18                  19         Y
             18                  19         N
             19                  21         Y
             20                  21         Y
             21                  20         N

-----------------------------------------------------------
     The mean of the last 5 reversals = 18.40
```

Subject Number: 17
Birth Date: 2/28/89 Age Group: 18-months
Test Date: 10/30/90 Delay: 5 ms

Condition: lead

Practice Phase: (ss)

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase: (lead)

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	N
4	41	Y
5	41	Y
6	34	N
7	38	Y
8	38	Y
9	36	Y
10	36	0
11	36	0
11	55	Y
12	36	Y
13	36	0
14	36	0
14	55	Y
15	36	Y
16	36	N
17	37	Y
18	37	Y
19	36	N

The mean of the last 5 reversals = 36.20

Subject Number: 15
Birth Date: 2/27/89 Age Group: 18-months
Test Date: 10/25/90 Delay: 5 ms

Condition: lead

Practice Phase:

Trial #	Angle	Response
1	55	0
2	55	0
3	55	Y
4	55	0
5	55	Y
6	55	Y
7	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	0
4	27	0
4	55	Y
5	27	N
6	41	Y
7	41	Y
8	34	Y
9	34	Y
10	27	Y
11	27	N
12	31	Y
13	31	Y
14	29	N
15	30	0
16	30	Y
16	30	Y
17	29	Y
18	29	Y
19	28	0
20	28	Y
20	28	0
21	28	Y
21	26	N

The mean of the last 5 reversals = 28.60

Subject Number: 1
Birth Date: 10/14/84 Age Group: 5-years
Test Date: 10/19/90 Delay: 5 ms

Condition: ss

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	Y
4	27	Y
5	13	Y
6	13	Y
7	6	Y
8	6	Y
9	2	Y
10	2	Y
11	1	0
12	0	Y
12	1	N
13	2	0
14	2	N
14	55	Y
15	2	N
16	3	Y
17	3	Y
18	2	Y
19	2	Y
20	1	Y
21	1	Y
22	0	Y
23	0	N
24	2	Y
25	2	Y
26	1	N
27	2	Y
28	2	Y
29	1	N

The mean of the last 5 reversals = 1.20

Subject Number: 12
Birth Date: 11/3/84 Age Group: 5-years
Test Date: 11/18/90 Delay: 5 ms

Condition: ss

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	Y
4	27	Y
5	13	Y
6	13	Y
7	6	Y
8	6	Y
9	2	N
10	4	Y
11	4	Y
12	3	Y
13	3	Y
14	2	Y
15	2	N
16	3	Y
17	3	Y
18	2	Y
19	2	Y
20	1	Y
21	1	N
22	2	Y
23	2	N
24	3	Y
25	3	Y
26	2	N

The mean of the last 5 reversals = 2.20

Subject Number: 18
Birth Date: 2-5-86
Test Date: 2-6-91

Age Group: 5-years
Delay: 5 ms

Condition: ss

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	Y
4	27	Y
5	13	Y
6	13	Y
7	6	Y
8	6	Y
9	2	Y
10	2	Y
11	1	Y
12	1	N
13	2	N
14	55	Y
15	2	Y
16	2	Y
17	1	Y
18	1	N
19	2	Y
20	2	Y
21	1	Y
22	1	Y
23	0	Y
24	0	N
25	2	Y
26	2	Y
27	1	Y
28	1	N

The mean of the last 5 reversals = 1.20

Subject Number: 5
Birth Date: 1/19/85 Age Group: 5-years
Test Date: 10/29/90 Delay: 5 ms

Condition: lead

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	N
2	55	N
3	55	Y
4	55	Y
5	27	Y
6	27	Y
7	13	Y
8	13	Y
9	6	Y
10	6	Y
11	2	N
12	4	Y
13	4	Y
14	3	N
15	4	Y
16	4	N
17	5	Y
18	5	N
19	7	Y
20	7	Y
21	6	Y
22	6	Y
23	5	Y
24	5	N
25	6	Y
26	6	Y
27	5	N

The mean of the last 5 reversals = 5.20

Subject Number: 15
Birth Date: 11/8/85 Age Group: 5-years
Test Date: 12/04/90 Delay: 5 ms

Condition: lead

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	N
4	41	Y
5	41	Y
6	34	Y
7	34	Y
8	27	Y
9	27	Y
10	13	Y
11	13	Y
12	6	Y
13	6	Y
14	2	N
15	4	Y
16	4	Y
17	3	Y
18	3	Y
19	2	N
20	3	Y
21	3	Y
22	2	Y
23	2	N

The mean of the last 5 reversals = 2.60

Subject Number: 25
Birth Date: 2/22/85 Age Group: 5-years
Test Date: 2/18/91 Delay: 5 ms

Condition: lead

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	Y
4	27	Y
5	13	Y
6	13	Y
7	6	Y
8	6	Y
9	2	N
10	4	Y
11	4	N
12	6	Y
13	6	N
14	10	Y
15	10	Y
16	8	Y
17	8	Y
18	6	Y
19	6	N
20	7	Y
21	7	Y
22	6	Y
23	6	Y
24	5	Y
25	5	Y
26	3	N
27	4	Y
28	4	Y
29	3	Y
30	3	N

The mean of the last 5 reversals = 4.60

Subject Number: 11
Birth Date: 2/19/85 Age Group: 5-years
Test Date: 11/15/90 Delay: 5 ms

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	N
2	55	Y
3	55	Y
4	27	Y
5	27	Y
6	13	N
7	20	Y
8	20	Y
9	16	Y
10	16	Y
11	12	N
12	14	Y
13	14	N
14	16	Y
15	16	Y
16	15	Y
17	15	N
18	16	Y
19	16	Y
20	15	Y
21	15	Y
22	14	Y
23	14	Y
24	12	Y
25	12	N

The mean of the last 5 reversals = 14.20

Subject Number:26
Birth Date: 11/27/85 Age Group: 5-years
Test Date: 2/8/91 Delay: 5 ms

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	Y
4	27	Y
5	13	0
6	13	N
6	20	N
7	55	Y
8	20	N
9	27	Y
10	27	Y
11	23	N
12	25	N
13	55	Y
14	25	Y
15	25	Y
16	24	N
17	25	Y
18	25	Y
19	24	Y
20	24	N

The mean of the last 5 reversals = 24.20

Subject Number: 28
Birth Date: 3-1-85 Age Group: 5-years
Test Date: 2-22-91 Delay: 5 ms

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	55	Y
2	55	Y
3	27	Y
4	27	Y
5	13	Y
6	13	Y
7	6	N
8	10	Y
9	10	Y
10	8	Y
11	8	Y
12	6	Y
13	6	N
14	7	N
15	55	Y
16	7	Y
17	7	Y
18	6	Y
19	6	Y
20	5	Y
21	5	N
22	6	N
23	55	Y
24	6	N
25	7	Y
26	7	Y
27	6	Y
28	6	N

The mean of the last 5 reversals = 6.20

Subject Number: 3
Birth Date: 12/21/71
Test Date: 10/12/90
Age Group: adults
Delay: 5 ms

Condition: ss

Practice Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	30	Y
4	30	Y

Test Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	15	Y
4	15	Y
5	7	Y
6	7	Y
7	3	Y
8	3	Y
9	1	Y
10	1	Y
11	0	N
12	2	Y
13	2	Y
14	1	Y
15	1	N
16	2	Y
17	2	Y
18	1	Y
19	1	Y
20	0	N
21	2	Y
22	2	Y
23	1	Y
24	1	Y
25	0	Y
26	0	Y
27	0	N

The mean of the last 5 reversals = 0.60

(continue S# 3)

Condition: lead

Practice Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	30	Y
4	30	Y

Test Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	15	Y
4	15	Y
5	7	Y
6	7	Y
7	3	Y
8	3	Y
9	1	Y
10	1	Y
11	0	Y
12	0	Y
13	0	Y
14	0	N
15	2	Y
16	2	Y
17	1	Y
18	1	Y
19	0	Y
20	0	Y
21	0	Y
22	0	Y
23	0	N
24	2	Y
25	2	Y
26	1	Y
27	1	Y
28	0	N
29	2	Y
30	2	Y
31	1	Y
32	1	Y
33	0	N

The mean of the last 5 reversals = 0.40

(continue S# 3)

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	30	Y
4	30	Y

Test Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	15	Y
4	15	Y
5	7	Y
6	7	Y
7	3	Y
8	3	Y
9	1	Y
10	1	Y
11	0	N
12	2	Y
13	2	Y
14	1	Y
15	1	Y
16	0	N
17	2	Y
18	2	Y
19	1	N
20	2	Y
21	2	Y
22	1	Y
23	1	Y
24	0	Y
25	0	Y
26	0	Y
27	0	N

The mean of the last 5 reversals = 0.80

Subject Number: 10
Birth Date: 3/15/71
Test Date: 10/24/90

Age Group: adults
Delay: 5 ms

Condition: ss

Practice Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	30	Y
4	30	Y

Test Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	15	Y
4	15	Y
5	7	Y
6	7	Y
7	3	Y
8	3	Y
9	1	Y
10	1	N
11	2	Y
12	2	Y
13	1	Y
14	1	N
15	2	Y
16	2	Y
17	1	Y
18	1	Y
19	0	Y
20	0	Y
21	0	N
22	2	Y
23	2	Y
24	1	N

The mean of the last 5 reversals = 1.20

(continue S# 10)

Condition: lead

Practice Phase:

Trial #	Angle	Response
1	30	N
2	30	Y
3	30	Y
4	30	Y
5	30	Y

Test Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	15	Y
4	15	Y
5	7	Y
6	7	Y
7	3	Y
8	3	Y
9	1	Y
10	1	N
11	2	N
12	30	Y
13	2	N
14	3	Y
15	3	Y
16	2	N
17	3	Y
18	3	Y
19	2	N
20	3	N
21	30	Y
22	3	Y
23	3	Y
24	2	Y
25	2	Y
26	1	N

The mean of the last 5 reversals = 2.20

(continue S# 10)

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	30	Y
4	30	Y

Test Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	15	Y
4	15	Y
5	7	Y
6	7	Y
7	3	Y
8	3	N
9	5	Y
10	5	N
11	7	Y
12	7	Y
13	6	Y
14	6	N
15	7	Y
16	7	Y
17	6	Y
18	6	Y
19	5	Y
20	5	N
21	6	Y
22	6	Y
23	5	Y
24	5	Y
25	4	Y
26	4	Y
27	2	Y
28	2	Y
29	1	Y
30	1	Y
31	0	N

The mean of the last 5 reversals = 5.00

Subject Number: 16
Birth Date: 2/4/70
Test Date: 11/1/90
Age Group: adults
Delay: 5 ms

Condition: ss

Practice Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	30	Y
4	30	Y

Test Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	15	Y
4	15	Y
5	7	Y
6	7	Y
7	3	Y
8	3	Y
9	1	Y
10	1	Y
11	0	Y
12	0	Y
13	0	N
14	2	N
15	30	Y
16	2	Y
17	2	Y
18	1	N
19	2	Y
20	2	Y
21	1	Y
22	1	N
23	2	Y
24	2	Y
25	1	Y
26	1	Y
27	0	Y
28	0	N

The mean of the last 5 reversals = 1.20

(continue S# 16)

Condition: lead

Practice Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	30	Y
4	30	Y

Test Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	15	Y
4	15	Y
5	7	Y
6	7	Y
7	3	Y
8	3	Y
9	1	N
10	2	Y
11	2	Y
12	1	Y
13	1	N
14	2	Y
15	2	Y
16	1	N
17	2	Y
18	2	Y
19	1	N

The mean of the last 5 reversals = 1.40

(continue S# 16)

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	30	Y
4	30	Y

Test Phase:

Trial #	Angle	Response
1	30	Y
2	30	Y
3	15	Y
4	15	Y
5	7	Y
6	7	Y
7	3	N
8	5	Y
9	5	N
10	7	Y
11	7	Y
12	6	Y
13	6	Y
14	5	Y
15	5	Y
16	3	Y
17	3	Y
18	1	Y
19	1	N
20	2	N
21	30	Y
22	2	Y
23	2	N
24	3	Y
25	3	Y
26	2	Y
27	2	Y
28	1	Y
29	1	N
30	2	Y
31	2	Y
32	1	Y
33	1	N

The mean of the last 5 reversals = 1.60

APPENDIX I

18-MONTH-OLDS LAG DATA

Name: Fabozzi, Maria
Birth Date: 5/11/89 Age Group: toddler
Test Date: 10/17/90 Delay: 5 ms

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	75	Y
4	75	N
5	75	Y

Test Phase:

Trial #	Angle	Response
1	75	0
2	75	Y
2	75	Y
3	37	N
4	75	Y
5	75	0
6	75	N
6	75	Y
7	75	N
8	75	Y
9	75	Y
10	55	Y
11	55	Y
12	54	N
13	55	Y
14	55	Y
15	54	Y
16	54	N
17	55	0
18	55	0
18	75	Y
19	55	Y
20	55	Y
21	54	N

The mean of the last 5 reversals = 54.40

Subject: BLM
Birth Date: 5/31/89 Age Group: 18-months
Test Date: 10/24/90 Delay: 5 ms

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	75	Y
4	75	Y

Test Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	37	N
4	75	Y
5	75	Y
6	55	N
7	75	Y
8	75	Y
9	55	Y
10	55	0
11	55	Y
11	52	0
12	52	Y
12	52	0
13	52	N
13	54	N
14	75	Y
15	54	Y
16	54	Y
17	53	N

The mean of the last 5 reversals = 57.80

Subject: ZB
Birth Date: 2/27/89 Age Group: 18-months
Test Date: 10/29/90 Delay: 5 ms

Condition: lag

Practice Phase: (ss)

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	37	Y
4	37	N
5	75	Y
6	75	Y
7	55	Y
8	55	Y
9	45	N
10	50	Y
11	50	Y
12	47	Y
13	47	N
14	49	N
15	75	Y
16	49	Y
17	49	N
18	51	Y
19	51	Y
20	50	N

The mean of the last 5 reversals = 48.60

Subject: LP
Birth Date: 5/14/89
Test Date: 10/31/90
Age Group: 18-months
Delay: 5 ms

Condition: lag

Practice Phase: (ss)

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	N
4	55	Y
5	55	Y

Test Phase: (lag)

Trial #	Angle	Response
1	75	Y
2	75	Y
3	37	0
4	37	N
4	75	Y
5	75	0
6	75	N
6	75	Y
7	75	Y
8	55	N
9	75	0
10	75	N
10	75	Y
11	75	Y
12	75	N
13	75	Y
14	75	0
15	75	Y
15	55	Y
16	55	0
17	55	0
17	75	0
18	75	0
19	75	Y
20	55	0
21	55	Y
21	55	Y
22	54	N
23	55	Y
24	55	N
25	75	Y
26	75	Y
27	55	Y

```
          28                  55        Y
          29                  54        N

-----------------------------------------------------------
     The mean of the last 5 reversals = 62.60
```

Subject: JC
Birth Date: 3/22/89 Age Group: 18-months
Test Date: 11/5/90 Delay: 5 ms

Condition: lag

Practice Phase: (ss)

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase: (lag)

Trial #	Angle	Response
1	75	Y
2	75	N
3	75	Y
4	75	Y
5	37	N
6	75	0
7	75	Y
7	75	Y
8	55	Y
9	55	Y
10	45	Y
11	45	Y
12	25	N
13	35	N
14	75	N
15	75	0
16	75	0
17	75	Y
18	35	Y
19	35	N
20	45	Y
21	45	Y
22	40	N
23	43	N
24	75	Y
24	43	N
25	46	Y
26	46	N
27	52	Y
28	52	Y
29	49	N

The mean of the last 5 reversals = 42.20

Subject: CG
Birth Date: 3/6/89 Age Group: 18-months
Test Date: 11/7/90 Delay: 5 ms

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	75	Y
4	75	Y

Test Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	37	Y
4	37	Y
5	18	N
6	28	Y
7	28	N
8	38	Y
9	38	N
10	75	N
11	75	Y
12	75	Y
13	75	Y
14	55	N
15	75	Y
16	75	N
17	75	Y
18	75	Y
19	55	N
20	75	Y
21	75	Y
22	55	Y
23	55	0
24	55	Y
24	54	N

The mean of the last 5 reversals = 62.80

Subject: EG
Birth Date: 5/30/89 Age Group: 18-months
Test Date: 11/13/90 Delay: 5 ms

Condition: lag

Practice Phase: (ss)

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	0
4	55	Y
5	55	Y

Test Phase:

Trial #	Angle	Response
1	75	Y
2	75	N
3	75	Y
4	75	Y
5	37	N
6	75	0
7	75	0
7	75	0
8	75	N
9	75	Y
10	75	Y
11	75	0
12	75	0
12	75	0
13	75	0
14	75	Y
15	75	0
16	75	N
16	75	Y
17	75	Y
18	55	N
19	75	Y
20	75	0
21	75	N
21	75	0
22	75	Y
22	75	Y
23	55	0
24	55	Y
24	55	Y
25	54	N
26	55	N
27	75	Y
28	75	Y

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     29                            75         Y
     30                            55         N

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     The mean of the last 5 reversals = 62.8
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Subject: TS
Birth Date: 5/26/89 Age Group: 18-months
Test Date: 11/26/90 Delay: 5 ms

Condition: lag

Practice Phase: (ss)

Trial #	Angle	Response
1	55	Y
2	55	Y
3	55	Y
4	55	Y

Test Phase:

Trial #	Angle	Response
1	75	Y
2	75	N
3	75	N
4	75	Y
5	75	Y
6	37	N
7	75	Y
8	75	Y
9	55	N
10	75	N
11	75	Y
12	75	Y
13	75	Y
14	55	Y
15	55	Y
16	52	0
17	52	N
17	54	0
18	54	Y
18	54	N
19	75	Y
20	75	Y
21	55	N

The mean of the last 5 reversals = 62.40

Subject: GA			
Birth Date:	4-7-89	Age Group:	18-months
Test Date:	11-27-90	Delay:	5 ms

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	75	Y
2	75	N
3	75	Y
4	75	Y
5	75	Y

Test Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	37	N
4	75	N
5	75	Y
6	75	Y
7	75	Y
8	55	Y
9	55	Y
10	45	Y
11	45	Y
12	25	Y
13	25	N
14	35	O
15	35	O
15	75	Y
16	35	Y
17	35	Y
18	30	N
19	33	Y
20	33	Y
21	31	Y
22	31	N

The mean of the last 5 reversals = 30.80

Subject: LM
Birth Date: 5/1/89 Age Group: 18-months
Test Date: 11/28/90 Delay: 5 ms

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	75	N
4	75	Y
5	75	Y

Test Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	37	Y
4	37	Y
5	18	Y
6	18	Y
7	8	Y
8	8	N
9	13	N
10	75	Y
11	13	Y
12	13	Y
13	10	N
14	12	N
15	75	N
16	75	N
17	75	Y
18	12	Y
19	12	N
20	14	Y
21	14	N
22	18	Y
23	18	N
24	22	0
25	22	Y
25	22	Y
26	20	N
27	21	0
28	21	N
28	75	N
29	75	Y
30	21	N

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          31                  22        Y
          32                  22        0
          33                  22        Y
          33                  21        Y
          34                  21        0
          35                  21        Y
          35                  20        0
          36                  20        Y
          36                  20        0
          37                  20        0
          37                  75        Y
          38                  20        Y
          39                  20        Y
          40                  18        Y
          41                  18        Y
          42                  16        N

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     The mean of the last 5 reversals = 18.00
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Subject: AL
Birth Date: 4/24/89 Age Group: 18-months
Test Date: 11/30/90 Delay: 5 ms

Condition: lag

Practice Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	75	Y
4	75	Y

Test Phase:

Trial #	Angle	Response
1	75	Y
2	75	Y
3	37	Y
4	37	N
5	75	Y
6	75	Y
7	55	N
8	75	Y
9	75	Y
10	55	N
11	75	0
12	75	Y
12	75	Y
13	55	N

The mean of the last 5 reversals = 63.00

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