[Frontiers in Bioscience 5, d108-120, January 1, 2000]

THE DEVELOPMENT OF AUDITORY ATTENTION IN CHILDREN

Hilary Gomes [1,2], Sophie Molholm [1,3], Christopher Christodoulou [4], Walter Ritter [3] and Nelson Cowan [5]

[1]Department of Psychology, City College of the City University of New York, NY, NY, [2]Department of Neurology, Albert Einstein College of Medicine, Bronx, NY, [3]Department of Neuroscience, Albert Einstein College of Medicine, Bronx, NY, [4]Neuropsychology and Neuroscience Laboratory, Kessler Medical Rehabilitation Research and Education Corporation, West Orange, NJ and Department of Physical Medicine and Rehabilitation, UMDNJ-New Jersey Medical School, Newark, NJ, [5]Department of Psychology, University of Missouri, Columbia, MO

TABLE OF CONTENTS

1. ABSTRACT

In this paper we review the development of four components of auditory attention: arousal, orienting, selective attention and sustained attention. We focus especially on the processes responsible for the selection of specific stimuli for further processing because these are essential for learning and development. Although much work still needs to be done, there is evidence of developmental change in some of the components of attention, especially early in infancy. Later developmental improvements seem to be primarily attributable to higher cognitive processes, such as motivation, strategy development and implementation, and voluntary direction and regulation of attention.

2. INTRODUCTION

Attention is important for most, if not all, information processing. Attentional processes are involved in determining which internal and external stimuli are singled out for further processing and, consequently, which stimuli warrant a response. This process of selecting stimuli from an extremely complex, ever changing, multisensory environment is determined not only by the physical characteristics of the stimuli themselves, but also by the individual interests, motives, and cognitive strategies of the person perceiving the stimuli. Because attention is involved in the process of selection, it plays an important role in the establishment of flexible, adaptive behavior. The distribution of attention is critical for learning and development. Identifying and attending to the important aspects of the environment are essential for the acquisition of new skills. For example, investigators have shown that infants attend to the stress patterns of language and have argued that this facilitates language acquisition (1). The selection of stimuli for further processing also has implications for what information is stored in memory and the level of detail associated with particular memory traces.

Central to our conception of attention are the processes responsible for the selection of specific stimuli for further processing. This selection can be automatic, as in the orienting elicited by a novel stimulus, or active, as in the search for a designated target in a set of stimuli during a selective attention task. In addition to selection, individuals must be alert (or exhibit at least some minimal level of arousal) and must be able to sustain an attentional focus for effective information processing and optimal learning. These four components of attention: arousal, orienting, selective attention, and sustained attention, are important to most models of attention (for example, 2-5) and will be used to organize our discussion of the development of attention.

Attention has been studied extensively in infants and adults, as evidenced by the number of recent books on the subject (for example, 2, 5-12). However, attention research has tended to focus on visual attention, despite the importance of auditory attention for language acquisition and processing (13-14).

Although some aspects of attentional processes are probably similar across the auditory and visual modalities, preferential processing of some stimuli over others based on their physical characteristics may be modality dependent. For example, the mechanisms responsible for the infant's preferential attending to human faces (15) may be qualitatively different from the mechanisms responsible for the preferential attending to pulsed as opposed to continuous auditory stimuli (16). Posner (17) likewise suggested some modality specific and some general attentional processes, proposing that attentional selectivity requires a multilevel hierarchical system with a lower level dedicated to each particular cognitive system and higher levels that are general across different cognitive systems. The mechanisms responsible for these early preferences are probably closely linked to specific sensory systems and may be sensitive to the physical differences in the types of information processed by these modalities. Information in the auditory channel is primarily temporally sequenced and of short duration, in contrast to visual information, which is richer in spatial organization and often stable for a longer duration. Consequently, study of the development of auditory attention cannot be predicated on knowledge of visual attentional mechanisms, and is important for general models of attention as well as for our understanding of auditory attention's role in development. For a comprehensive review of the development of visual attention, see Ruff and Rothbart (5).

Studying the development of attentional processes, however, is complicated by the fact that it is often difficult to separate attention from encoding, memory, decision making, and response systems in the information processing stream (18). This difficulty has two primary implications for the developmental study of attention. First, it is often difficult to identify which aspect of information processing is responsible for a developmental change in behavior (19-20). Second, if infants or children are unable to perform a task accurately, it can be difficult to identify where in the information-processing stream the failure occurred (21).

Behavioral studies, primarily recent studies of visual attention, have attempted to overcome this difficulty by carefully and creatively designing tasks that manipulate the attention variable of interest while maintaining equivalence across all other parameters (22). Further, recent neuropsychological studies have used factor analysis to separate visual attention from other aspects of information processing (23). Event related potentials (ERPs) offer another methodology for separating components of information processing since they provide information about the temporal dynamics of processing between the stimulus and behavioral response. Molholm, Gomes and Ritter (21) recently demonstrated that children can evidence the ability to discriminate tones at an automatic, preattentive level and yet perform poorly on a behavioral discrimination task with the same stimuli. This finding shows that the inability to perform a behavioral task does not provide definitive information about where in processing the difficulty has occurred and suggests that the stages of information processing may develop at different rates (also see 24). Although, there are currently only a few ERP studies which have examined the development of auditory attention in normal children (25), the methodology has advanced models of adult selective attention (10, 26) and holds potential for furthering our understanding of the development of auditory attention.

3. DEVELOPMENT OF FOUR COMPONENTS OF ATTENTION

3.1. Arousal

Arousal refers to the physiological readiness to perceive and process stimuli. States of arousal can vary from deep sleep to extreme distress or excitation. One's state of arousal is closely associated with level of fatigue. However, it can also be affected by factors such as emotional and cognitive state, bodily comfort and processing of external stimuli. Some arousal is clearly necessary for information processing to occur, although the optimal level varies from task to task and is usually inversely related to task difficulty (27). Lower and higher levels of arousal than considered optimal, lead to less efficient stimulus processing (16, 28-30). Further, there are reciprocal effects such that engagement in information processing can modulate level of arousal (31-32).

During the first few months of life, the infant's level of arousal changes frequently and fluidly (33). Development is evidenced by the increased time spent in an awake, alert state and by more differentiated transitions between states. General levels of arousal are most frequently included in developmental studies of attention as baseline conditions or exclusionary criteria (29).

Adult theories of arousal have suggested that there is a dual-level control mechanism, consisting of a passive, low-level, physiological arousal system, mediated by the reticular formation, and a higher-level, cognitive arousal system (34-35). The higher-level system can modulate the lower-level system to establish or maintain an optimal level of arousal for performance of a particular task. The reticular arousal system is established early in development. The cognitive arousal system develops later as the child gains control over self-regulatory functions. This second system is especially important for maintaining attentional focus and consequently is critical for sustained attention.

3.2. Orienting

Orienting refers to the physiological and behavioral changes associated with detection of a novel stimulus (36). Orienting alerts the individual to the presence of potentially important stimuli in the environment and facilitates attention to and further processing of the stimulus (37). Such processing is necessary if the individual is to understand and react appropriately to the stimulus. Further, failure to attend to such information could threaten the survival of the organism. In addition to novel stimuli, salient and primed signals may also elicit orienting responses (38).

The characteristics of a stimulus which lead it to be regarded as "novel" or "salient" can vary with context and the experience of individual subjects. As a stimulus loses its novelty with repeated presentations, the size of the orienting response decreases unless the stimulus has immediate value. This process is referred to as habituation of the orienting response. If a stimulus perceived as different is presented after the response to the initial stimulus has habituated, the new stimulus will elicit an orienting response, a phenomenon called recovery of the orienting response. Higher cognitive processes also have been shown to affect the orienting response. If a stimulus is expected, the orienting response is smaller than if it is unexpected (15). In addition, the subject's degree of involvement in some other activity can influence the size of the orienting response (5, 39-40). The more that this other activity engages the attention of the subject, the smaller the orienting response to the novel stimulus.

Orienting in infants has most commonly been measured by using localized head turning, heart rate deceleration, and motor quieting. Using these measures, infants have shown the ability to orient to sounds in the first days of life (41), and there is increasing evidence that near-term fetuses also evidence orienting to some sounds (42). Orienting in infants has been elicited by a wide variety of signals, including tone bursts (43), rattle sounds (44), and male and female voices (42).

Infants have also been found to evidence some selectivity in orienting which is probably related to the salience of the physical characteristics of the stimuli. For example, orienting responses are larger and more reliable for high frequency than low frequency noise (filtered rattle sounds; 41; although see 45), for sounds with prolonged rise times than short (46), and for tones of longer duration than shorter (47). In a number of studies, orienting has been shown to be more pronounced to pulsed than to continuous signals by about 12 weeks of age, with 6-week-old infants orienting to pulsed, but not to continuous stimuli at all (for review see 16, 48). These data have been used to argue that temporal transitions play an important role in determining the stimuli to which infants attend. This hypothesis is particularly interesting because temporal transitions are important for discriminating speech sounds. The optimal characteristics for inducing an orienting response from newborns and infants still need to be determined. Further, the reasons for the preferences need to be explored; do they reflect differences in the infant's ability to process the stimuli (i.e., sensitivity) or responsiveness to adequately processed stimuli (49)?

Finally, some aspects of stimulus change are more likely to capture the subject's attention than others, suggesting that infants may differentially weight stimulus features. Recovery of the orienting response in infants has been elicited by a variety of stimulus changes, including a change in the intensity of a tone burst (43), an altered rattle sound (50), a new pulsed synthetic vowel (48), a change in the initial consonant of a syllable (51), and a new two syllable nonsense word (52). One study (53) presented 6-month-old infants with a pair of tones (400 Hz – 1000 Hz) as habituating stimuli. Recovery of the orienting response was elicited when the first tone in the pair differed from the habituating stimulus but not when only the second tone differed, suggesting that information presented early in a signal may be preferentially attended and processed (53). Additional research is needed in order to determine which aspects of the stimulus are preferentially attended by the infant and how precise a representation is formed (see 52).

Based primarily on visual attention studies, it has been argued that, for newborns, physical features of the stimuli (intensity, pitch, etc…) initially mediate stimulus preference (54). But between 2 and 4 months of age, selectivity is influenced by the previous experience of the infant, and orienting is most associated with novelty. Around 9 months of age, there is evidence for a reduction in the orienting response to novel visual stimuli. It has been suggested that this decrease in the orienting response may be important for the development of directed attention as it may help reduce distraction by irrelevant stimuli (5).

Orienting in childhood has not been extensively explored (but see 55). However, because novelty seems to be the primary factor controlling orienting in older infants and adults, development in orienting through childhood might be expected to be primarily due to the child's increasing knowledge base influencing what is perceived as novel, and advances in higher cognitive processes, such as expectancy.

3.3. Selective Allocation of Attention

Selective attention is the process whereby the individual focuses on a specific stimulus or stimulus stream for the purpose of processing the information more fully while ignoring other, potentially distracting, stimuli. Many models of selective attention assume that the amount of information that can be focused on at any specific moment is limited. Novel or unfamiliar situations usually require controlled or effortful processing which is attentionally demanding. However, with experience and practice, processing of certain materials can become automatic, freeing attentional resources and enlarging apparent capacity (56-59).

Divided attention, in which the subject is required to attend to two or more stimulus streams simultaneously, is another aspect of active attention allocation. Given that there are limited attentional resources, the ability to process two stimulus streams simultaneously depends upon the amount of effortful processing required to attend to the information in each channel. As processing becomes more automatic, the individual is able to effectively handle additional material. Alternatively, it has been suggested that processing in divided attention tasks is not simultaneous but successive and that attention is actually shifted back and forth between the channels (60-61).

It is much easier to examine selective attention in children and adults than in infants given the limitations imposed by the inability to use verbal instructions to direct the attention of infants. Consequently, much of what is known about the role of selective processing in infants has been a byproduct of investigations directed at other issues, primarily speech and language perception and discrimination. In these studies, it is usually difficult to differentiate processes associated with attending, encoding, remembering, comparing, and responding to a stimulus. If the infant responds to a specific stimulus, all of the processes from selectively attending through responding are assumed to be functioning.

If the infant fails to respond, it is difficult to know where in the processing stream the difficulty occurred. Keeping these limitations in mind, we consider selective allocation of attention in infants, followed by a discussion of selective allocation in children.

3.3.1. Selective Allocation of Attention in Infants

Most of the studies that have required selective processing in infants have used conditioned response paradigms, usually high amplitude sucking or head turning paradigms (for a review, see 49, 62-63). In these paradigms, infants evidence a stimulus preference by more frequently displaying one of two conditioned behaviors that, in turn, elicit a desired stimulus. Preferences have been found for mother's voice over female stranger's voice (64), prosody of native language over prosody of a foreign language (65), and infant-directed speech over adult-directed speech (66). In contrast, infants have not shown evidence of a preference for frequency modulated sweeps that mimic adult-to-infant intonation patterns over those that mimic adult-to-adult intonation patterns. The infants' failure to exhibit a preference was not due to the discriminability of the sweeps, as the infants were able to differentiate the two signals (67).

Infants also are able to selectively attend to a voice in the context of a competing distractor voice when the target voice is louder than the distractor. Newman and Jusczyk (68) presented infants with two competing stimulus streams during a familiarization phase. One stream was in a female voice and consisted of single words spoken in a lively animated manner, "as if speaking to a small child" (p.1148). The other was in a male voice and consisted of the text from the methods section of a journal article. When the female voice was 5 or 10 dB higher than the male voice during familiarization, infants listened longer to the previously heard words than to novel words during a later test phase. Familiar words were not recognized during the test phase when the two voices were equally intense during familiarization.

In these paradigms, as in the discussed studies of the recovery of the orienting response, infants have demonstrated the ability to attend to critical stimulus features and to discriminate a variety of auditory signals. They can discriminate syllables that differ minimally along phonetic dimensions (e.g., [b] vs. [d]) and multisyllabic stimuli that differ in location of syllable stress (for review see 14). Further, infants have demonstrated the ability to attend to one aspect of a stimulus steam and to disregard another. Infants can discriminate tone sequences with contrasting temporal structures (for example, X-XX vs. XX-X) even when presentation rate and frequency (pitch) are varied (69). They can discriminate syllables, even when the tokens of a particular stimulus come from different talkers. This generalization is not based on an inability to differentiate talkers; infants can also discriminate talkers when the syllable remains constant (14,70). Further, infants can attend to a critical phonemic contrast (e.g., [ba] vs. [du]) and discriminate that contrast even when it is embedded with redundant (e.g., [ko ba ko] vs. [ko du ko]) and mixed context syllables ([ko ba ti] vs. [ko du ti]) that change from block to block (71). In addition, 7-month-olds can discriminate sentences with different structures in an artificial language, even when the nonsense words in the test sentences are novel (72). These studies demonstrate multiple instances of young infants selectively attending to specific aspects of stimuli or stimulus streams in contexts in which other aspects of the signal must be disregarded.

Although most of the studies examining discrimination in infants are behavioral in nature, researchers have begun to use electrophysiological measures, especially mismatch negativity (MMN) (73). MMN does not require active discrimination or overt motor responses by the subject and provides an objective measure of the brain's automatic, sensory discriminative capability. Virtually all of the studies examining the MMN have used auditory stimuli (10) and the principal source of the MMN has been determined to be located within the supratemporal plane in or near primary auditory cortex (for a review of the evidence see 74). MMN studies usually present two auditory stimuli in an "oddball" paradigm where one stimulus is presented frequently (termed "standard") and another is presented infrequently (termed "deviant"). The infant is not required to attend or respond to the stimuli. A comparison of the ERPs elicited by the standards and deviants in these studies reveals a potential that is larger for the deviant tones, and is negative at the midline and often positive at the mastoids when the nose is used as the reference. MMN in infants generally peaks between 150 and 450 ms following stimulus onset. Studies with infants have elicited MMNs for tones differing in frequency and syllables differing in place of articulation and voice onset time (75-76).

In a recent study, the amplitude of the MMN was also found to be sensitive to the language environment of the infant. Cheour *et al.* (77) presented 6- and 12-month-old Finnish infants and 12-month-old Estonian infants with native and non-native vowel phonemes in an oddball paradigm. The frequent or standard stimulus was the vowel /e/ which is present in both languages. The deviant stimuli were /õ/, a vowel in Estonian but not in Finnish, and /ö/, a vowel in both languages. The 6-month-old Finnish infants and the 12-month-old Estonian infants exhibited MMNs of similar amplitude for the two deviants, but the 12-month-old Finnish infants exhibited a larger MMN for the phoneme native to their language than for the nonnative phoneme. This developmental change in the amplitude of the MMN elicited from Finnish infants must be a consequence of the infants having attended (either passively, actively or both) to their linguistic environment and extracting information about the structure of their native language (for a review of similar findings in behavioral studies see 78).

Despite the infant's ability to detect regularities in the environment and the alteration of discriminative criteria based on these regularities, studies have shown that infants do not use this information to alter processing strategies during a task. For example, adults and children 6 to 8 years of age (79) can detect a tone at a lower intensity level when it is of an expected frequency than when it is of an unexpected frequency, suggesting that these subjects use the contextual information to listen selectively for specific stimuli. Using a conditioned head turn procedure, however, investigators have found no evidence that 7- to 9-month-old infants detect expected stimuli better than unexpected stimuli despite extensive exposure to the

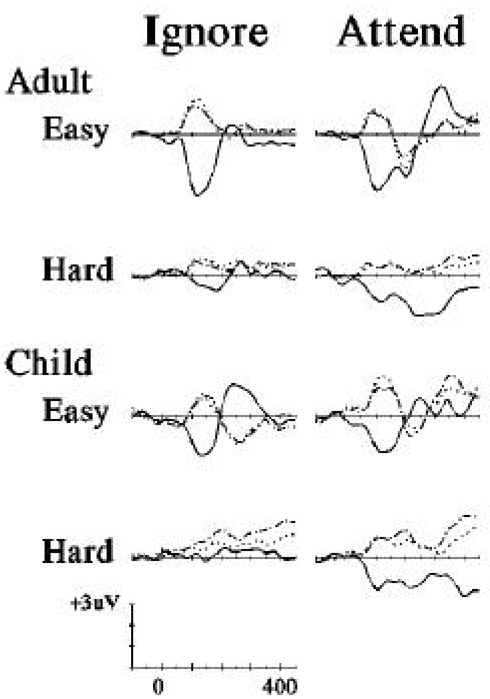

Figure 1. Grand mean difference waveforms elicited from adults and children in the ignore and attend conditions obtained by subtracting the ERPs elicited by the standard frequency tone (1000 Hz) from the ERPs elicited by the easy (1500 Hz) and hard (1050 Hz) frequency deviant tones. The solid lines are the waveforms at Fz and the dashed lines are the waveforms at the mastoids. Stimuli were presented at time zero. (modified from Gomes, *et al.*, submitted)

expected stimulus (80). Expectancy in this study was built up in three ways. First, the frequent or "expected" tone was present at a clearly audible level 100% of the time during a training procedure until an accuracy criterion was reached (80% correct responding on signal vs. no signal trials). Second, the "expected" tone was presented at softer intensities 100% of the time during the first test phase until an accuracy criterion was reached (73% correct). Third, the "expected" tone was presented at low intensities 75% of the time during the second test phase. Although extensive familiarization was provided, it is not known whether the infants' inability to detect the expected stimuli at a lower intensity than the unexpected stimuli in the second test phase was because they failed to use expectancy information to modify their listening strategy or because they were unable or slow to develop an expectancy. Infants do exhibit habituation in other paradigms, which indicates that they notice redundancy, but expectancy also requires that the infant anticipate what the next stimulus will be. Both developing expectancies and using listening strategies are probably mediated by higher cognitive processes suggesting that these are not fully developed until sometime after infancy.

In summary, the above studies demonstrate that infants can selectively attend to specific features of a stimulus stream while disregarding others, and can selectively attend to one of two competing stimulus streams in certain circumstances. Further, automatic processing, as evidenced by MMN amplitude, was found to be influenced by attending to the linguistic environment over an extended period of time. However, unlike 6- to 8-year-old children, infants were not able to use information about expectancy to modify their behavior during a task adaptively. It appears that the ability to develop and utilize short-term listening strategies is not mature in infants. In the next section, selective attention in children will be considered.

3.3.2. Selective Allocation of Attention in Children

3.3.2.1. Automatic Processing in Children

Using models of information processing, researchers have argued that, during learning, most tasks require significant attention, but that, with experience and practice, processing of certain materials can become automatic (56-59). Thus one might expect developmental changes in automatic processing of auditory material associated with increased general exposure to auditory stimuli.

MMN, the electrophysiological component introduced above, appears to be elicited by the automatic, preattentive detection of a change in the stimulus stream and thus may be a good measure of automatic processing. In MMN studies with children (and adults), the stimuli are usually presented while the subject is engaged in some other activity, such as reading a book or watching a video with the sound turned down or off. The latency of the MMN in children is shorter than in infants, generally peaking between 150 to 300 ms following stimulus onset (81).

Studies of MMN in children have generally found effects that parallel those described in adults (e.g., 76, 82-85; for a review of adult studies, see 10, 86). However, it has been found that when the stimuli are ignored, larger deviants are required to elicit MMNs from children than from adults (87). To determine whether attention affected the processing associated with the MMN, Gomes *et al.* compared the MMNs elicited by deviant stimuli when they were ignored and when they were attended to. In the attended to condition, subjects were instructed to press a button when they heard a deviant stimulus; all deviant stimuli, even the hardest to discriminate, elicited MMNs from children in contrast to when the stimuli were to be ignored. Adults in this study exhibited MMNs for all attended and ignored deviants (see **figure 1**). These data suggest that the discrimination of relatively hard to detect differences requires that children actively attend to the stimuli, whereas in adults such processing appears to be automatic. It is possible that easy to discriminate stimuli are handled automatically from infancy but that difficult auditory discriminations initially involve controlled processes requiring focused attention. Further, it is possible that many initially difficult discriminations become automatic over time, probably as a consequence of active discrimination and general auditory experience (also see 88).

3.3.2.2. Selective Attention in Children

Many situations require that we attend to a specific stimulus in an environment that contains competing signals. Children are expected to listen to the teacher's voice even when other children are outside playing and a movie is being shown in the adjacent classroom. This ability to selectively attend to some auditory information while ignoring irrelevant auditory information has been studied developmentally using two primary tasks. The first, shadowing, requires the subject to repeat everything heard in the attended channel, and the second, selective monitoring, requires the subject to listen for and respond to a specified target. In general, these studies show that older children perform better and make fewer errors than younger children (for reviews see 18, 20, 89-92).

The process of selectively attending when there are distracting stimuli requires the ability to differentiate the two stimulus streams, select the relevant stream, inhibit processing of the irrelevant stream and sustain focused attention on the wanted stream over some period of time. Based on a review of the literature and a consideration of alternative hypotheses, Maccoby (61) has suggested that there are age-related improvements in the ability to differentiate stimulus streams that are associated with perceptual learning and improvements in automatic processing. Stronger differentiation between the streams earlier in processing would allow the child to better focus on the designated stimuli with less effort.

The ability to ignore or inhibit processing of the irrelevant stimulus stream is also important for efficient selective attending. The finding that younger children make substantially more errors than older children has been interpreted as reflecting younger children's poorer ability to differentiate and block out the irrelevant stimuli (61, 93). Alternatively, it has been suggested that both younger and older children process the irrelevant stimuli but that older children are better able to separate the channels in memory and to selectively report only the target stimuli. Evidence for this view was provided by a study which found that older and younger children remember the same number of irrelevant stimuli on a surprise recognition test (93). However, if performance on this task is represented as a percentage of relevant stimuli recognized, younger children recognized substantially more irrelevant stimuli than older children, supporting the view that younger children are not as good at blocking out irrelevant information.

These studies suggest that older children are better than younger children at differentiating channels, focusing on the relevant stimuli, and inhibiting processing of the distractor stimuli. However, there are a variety of alternative explanations for the older children's superior performance on these tasks. First, as has been suggested in the visual attention literature (20), the difference might be due to better perceptual abilities in the older than in the younger children. Improved performance on auditory sensitivity and auditory discrimination tasks continues through childhood (94-97). Researchers disagree about how much of this developmental change is due to sensory/perceptual factors and how much is due to changes in nonsensory factors, such as attention (98). However, a number of studies have now demonstrated persuasively that improved attention to the task cannot be responsible for all of the observed developmental changes in discrimination performance (99). For example, Jensen and Neff (96) argued that attention alone could not explain their results because discrimination performance for one feature (intensity) had already reached mature levels while performance for two other features (frequency and duration) were still immature. Consequently, improved sensory/perceptual processing maybe partially responsible for the developmental improvement in performance on attentional tasks. Further, many of the tasks that have been used to study attention contain short-term memory requirements. Short-term memory span has been shown to improve with development (for a review see 100).

It has also been suggested that older children understand the tasks demands and rewards better, and are more able to employ appropriate, efficient strategies for completing tasks (19, 101). Gibson and Rader (19) have argued that younger children are less knowledgeable about which information is relevant for a particular task and consequently may not distribute their attention in the manner expected by the experimenter. Further, multiple studies have documented developmental improvements in strategy development, implementation and efficient use and have suggested that older children are better able to allocate attentional resources appropriately (102-104). Both of these positions argue that what may develop is children's ability to direct, control and regulate their attention in an efficient manner appropriate for the current task.

Finally, it may be sustained, and not selective, attention that is being evaluated in these paradigms. Perhaps, young children's selective attention abilities are comparable to older children's but they have difficulty sustaining their attention. An inability to consistently maintain an attentional focus throughout the task in the younger children could also account for these data. Consequently, it is unclear from the behavioral literature whether there are developmental changes in the processes involved in selective attention or whether the performance differences seen in the literature are due to sensory/perceptual, planning and self-regulation functions, or sustained attention.

The results of a recent ERP study, employed to examine the temporal dynamics of selective attention in children, reduces the number of alternative explanations for the developmental improvements in performance. Berman & Friedman (105; also see 106) presented 8-year-olds, 14-year-olds, and 24-year-olds with two binaural stimulus streams, one to be attended and one to be ignored. Embedded in both streams were stimuli that were longer in duration and the subjects' task was always to identify the infrequent duration deviants in the attended stream. The difficulty of this discrimination was controlled by adjusting the target duration for each subject individually so that targets were correctly detected 75% of the time in a practice block. There were two stimulus conditions, one in which the attended and unattended streams were differentiated by pitch (low- and high-pitched) and the other in which they were differentiated by phoneme (ba and da). The component of interest in this study was Nd, the negative difference that results from subtracting the ERP waveform elicited by the unattended standards from that elicited by the attended standards. Based on studies with adult subjects, it has been suggested that Nd reflects the allocation of processing resources (105). Because young children seem to pay attention to both stimulus streams, it was predicted that the Nd exhibited by younger children would be smaller than for older children. Consistent with this hypothesis, there was an age related increase in Nd amplitude. Further, this increase was primarily attributable to changes in the waveform elicited by the unattended stimulus, suggesting that younger children were processing the unattended stimuli differently from older children. Based on the model of Nd proposed by Näätänen (10), Berman and Friedman (105) suggest that the "children had more difficulty in the initial selection of stimuli that matched the attentional trace (for the attributes that characterized stimuli in the relevant channel)" (p. 23) making it more difficult to maintain an attentional focus on the appropriate channel. Thus this study lends support to the hypothesis of developmental differences in allocation of attention. However, it is still unclear what underlies younger children's inefficient allocation of attention: difficulties selecting the appropriate channel and maintaining an attentional focus, as suggested by Berman and Friedman (105), and Maccoby (61); or differences in degree of engagement in tasks and strategy use, as suggested by Gibson and Rader (19), and Guttentag and Ornstein (103).

3.3.2.3. Divided Attention in Children

Studies of selective attention have suggested that younger children process both the relevant and irrelevant stimulus streams. While this wider attentional focus negatively impacts performance on selective attention tasks, it might be thought that it could aid performance on divided attention tasks where the child is supposed to attend to both stimulus streams. This does not seem to be the case. Children of all ages perform better when attending to one channel than when attending to two channels, and performance on both selective and divided attention tasks improves with age (61, 101).

It has been argued that divided attention does not involve widening the focus of attention, but instead requires the rapid switching of attention between the channels (60-61). Consequently, divided attention would require all of the processes involved in selective attention, plus those necessary for efficiently and rapidly shifting attention from one channel to another so that stimuli in both channels can be searched in a given period of time. Framed in this way, younger children might be expected to perform substantially worse than older children, even when divided attention performance is adjusted for initial differences in performance on selective attention tasks.

Sexton and Geffen (101) evaluated divided and selective attention using a monitoring task, however, they did not directly compare their selective and divided attention conditions. Our examination of the data presented in their paper indicates that the rate of improvement with age was not different for the selective attention condition than for the divided attention condition, suggesting that the developmental improvement in performance on both tasks was attributable to selective attention processes, not to processes specific to divided attention.

This suggestion of no developmental improvement in the ability to divide attention when selective attention is controlled for is surprising, however, in light of the data on attention shifting. Pearson and Lane (107) examined attention shifting using two stimulus streams as in studies of selective and divided attention. In their study, on half the trials, subjects were signaled to shift their attention from one stimulus stream to the other midway through the trial. Younger children took significantly longer to reorient their attention than did older subjects as evidenced by the number of filler stimuli needed between the switch cue and the target to perform as well in the switch as in the no-switch condition. Further, the younger subjects made significantly more errors when required to shift their attention than when no shift was required. Their differential increase in number of errors was substantially larger than the increase seen in the older children. These two findings together suggest that shifting attention was more difficult and disruptive for younger than for older children. Attentional shifting requires an active, intentional response to the shift cue. In contrast, the attention shifting in divided attention tasks may be more automatic, potentially explaining the performance differences, if the differences remain after further research. Either way, the study by Pearson and Lane (107) provides strong evidence for developmental differences in the ability to form and implement the shift response.

In summary, these studies provide evidence for developmental improvements in attention switching. It remains to be seen whether there are also developmental changes in the ability to divide attention between channels, or if the performance improvements on divided attention tasks are attributable to selective attention processes.

3.3.3. Summary of Selective Allocation of Attention

Studies have shown that infants are able to selectively attend to stimulus features and stimulus streams in certain circumstances, despite the presence of irrelevant and distracting information. In children, studies suggest that there are developmental changes in automatic processing of stimuli and in voluntary shifting of attention. Further, clear developmental improvements in performance are seen in studies that require the active direction and division of attention; however, the source of this behavioral improvement remains unclear.

Children's automatic detection of infrequent or deviant stimuli, as evidenced by elicitation of the MMN, is not as sensitive as adults. One explanation for this poorer sensitivity is that automatic processing leads to a less precise representation of the frequent stimulus in children than in adults. In the study by Gomes *et al.* (87), attention appeared to improve the precision of the representation of the frequent stimulus making it easier to detect a stimulus change. Further, experience and learning associated with development might be expected to alter the encoding of the frequent stimulus and lead to better automatic processing (108-110).

Less precise representations of unattended stimuli in younger than in older children could account for some of the developmental differences seen in paradigms requiring the active allocation of attention. Less precise representations may interfere with the differentiation of attended and unattended channels in turn making it harder to maintain focused attention on the relevant stream, leading to increased errors in performance. Further, the degree of similarity between the stimuli in the attended and unattended channels should exaggerate this effect, suggesting that younger children should be more affected by similarity than older children or adults. This possibility could be tested by varying the degree of difference between the frequent stimuli in the attended and in the unattended channels (see 111).

Finally, there also appear to be developmental improvements in the ability to actively and intentionally direct and control auditory attention. For instance, infants do not seem to use listening strategies whereas older children are able to use contingent task expectancies to detect expected stimuli at lower intensities than unexpected stimuli. Further, younger children have more difficulty than older children focusing all of their attention on the relevant channel in selective attention paradigms. Younger children also require more time than older children to shift their attention in response to a cue and still exhibit increased errors. Consequently, some of the improvement in performance on selective attention tasks is probably due to higher cognitive processes, such as regulation of attention, planning, and motivation.

3.4. Sustained attention

Sustained attention or vigilance is the ability to maintain attentional focus over time. It is usually assessed by examining the change in the number of correct detections as a function of time on task. Most studies of children and adults have found that subjects' ability to sustain their attention deteriorate over time (112-114). Studies employing signal detection theory have suggested that these performance decrements are due to variations in response criterion, as opposed to changes in sensitivity (115). In addition to time on task, level of arousal (116), reinforcement, and feedback (117) have been shown to affect sustained attention in adults.

Researchers have debated whether sustained attention should be considered ongoing selective attention (18) or a distinct attentional process (24). Results from Halperin's lab (24) exploring visual attention have shown different developmental patterns for sustained and selective attention and consequently they have argued that different mechanisms may be involved.

In one of the few studies of sustained auditory attention in children, Gale and Lynn (112) found that older children made significantly fewer omission errors overall on a sustained attention task; however, all groups decreased in accuracy with time on task. Although rate of performance decline was not reported in this study, an examination of the change in error rates (calculated as the change in mean errors from the first 8 minute block to the second 8 minute block divided by the errors in the first block) across age finds that the performance of younger children did not deteriorate at a faster rate than that of older children. Consequently, it appears that the developmental differences in this study are not due to sustained attention, but to differences in baseline performance.

Swanson's (115) study, in contrast, suggests developmental differences in sustained attention. She found that younger children's ability to identify targets correctly began to deteriorate earlier than in older children. The finding is complicated, however, since this two-way interaction emerged from a 4-way ANOVA collapsed over group (normal and learning-disabled children) and modality. Additional research is clearly needed to determine if there are developmental differences in performance on sustained auditory attention tasks.

If it is established that there are developmental differences in performance on auditory sustained attention tasks, the contribution of motivational factors (such as feedback and reinforcement) would need to be assessed. Given that these factors affect adult performance, it is reasonable to expect that they would also affect the performance of children. Further, developmental differences have been found in the ability to wait for delayed rewards (118-119) so it would not be surprising to find developmental differences in the effects of motivation on children's ability to sustain their attention.

4. SUMMARY AND FUTURE DIRECTIONS

This paper has considered developmental studies of four components of auditory attention: arousal, orienting, selective attention and sustained attention. State of arousal in newborn infants is fluid and changeable, but within the first months of life sleep/wake cycles become more predictable, states become more differentiable, and duration of alert wakefulness increases substantially. Later developmental changes in the control of arousal seem to be attributable to higher cortical, self-regulatory systems. Arousal is important at the most basic level of information processing, and consequently, for learning and development (4, 18, 120).

With respect to the orienting system, it is largely the physical characteristics of the stimuli that initially determine whether or not a response will be elicited. Within the first months, novelty becomes more important than physical characteristics in determining which stimuli will elicit an orienting response. It is likely that infants need to establish some sort of cognitive templates to be able to differentiate old and new stimuli and need to be able to maintain an arousal state for short periods of time before novelty can become a salient feature of a stimulus. Preferential orienting to novelty alerts infants to new information and allows them to expand their fund of knowledge. Further research is required to identify potential developmental changes in optimal stimulus characteristics for eliciting orienting and degree of change in a stimulus needed to elicit recovery of the orienting response. Later development in the orienting system seems to be primarily associated with the changes in planning and regulatory functions.

Young infants exhibit selective attending in certain circumstances. They are also able to attend to features that are critical for discrimination of complex stimuli in many situations, and there is growing evidence that they can automatically discriminate some stimuli. Further development probably involves improved automatic discrimination, possibly due to more precise representations of stimuli in memory. Increases in automatic processing would free attentional resources for employment in other ways. Development in this system is also associated with advancements in higher cognitive functions involved in the ability to plan, regulate, and direct one's own attention according to the demands of specific situations (5).

The study of the development of auditory attention is in its early stages and there is much to be learned. Four suggestions for lines of potentially fruitful research are suggested. First, additional work is needed to determine the nature and size of developmental changes in selective, divided and sustained attention. To date, the age related changes in performance on tasks of divided and sustained attention seem to be attributable to selective attention effects. This is intuitively surprising because of the increased task demands inherent in divided and sustained paradigms. It is possible that the developmental changes specific to these processes are smaller than those associated with selective attention and consequently harder to differentiate. Additional work in selective auditory attention is also needed to dissociate developmental changes due to self-regulatory processes and those due to attention mechanisms.

A second line of research that appears promising is related to the role of auditory attention in lexical development and language acquisition. Jusczyk (14; also see 121-122) has proposed a model of lexical development that is dependent upon differential processing and encoding of certain aspects of the auditory stream determined by infant's preferences. He suggests that the infant is innately "primed" to attend to some types of auditory signals. The attended aspects of the stimuli are more likely to be encoded and stored in secondary memory forming the early auditory templates. Further, the infant's preferences, in conjunction with distributional characteristics of the input, determine the structure of the infant's "interpretive schemes" which then begin to direct information processing. More detailed knowledge of what infants attend to is necessary in order to understand the way in which auditory and lexical templates develop.

A third line of potentially fruitful research concerns the impact of development of self-regulatory functions on attention and the relationship between these functions and the frontal lobe (123). Relatively early in development, higher cognitive processes begin to influence and gradually dominate the allocation and regulation of all four components of attention. For example, it has been postulated that there is a cognitive arousal system that can modulate the reticular arousal system in order to establish and maintain an appropriate level of arousal for performing a valued task. The size of the orienting response can be affected by expectations, personal interests, and engagement in concurrent activity. Selective and sustained attention are influenced by listening strategies, motivation, task experience, and the ability to disregard or inhibit processing of certain information. These higher-order processes are aspects of the functional system involved with self-regulation and planning of goal-directed behavior, which have been shown to develop through childhood (118-119, 124-126) and to be mediated by the prefrontal cortex (127). Studies using a variety of dependent measures such as, myelination rates, EEG coherence, neuronal density, and performance in animals following cortical lesions, have found that development of the prefrontal cortex is protracted and can, in at least some instances, extend into adulthood (for a reviews see 126, 128). Further, studies have found significant correlations between activation of the orbital frontal cortex and performance on a visual attention task (129-130). However, to the best of our knowledge, no studies have examined the relationship between auditory attention, self-regulator functions and frontal lobe development.

Finally, research in visual attention has highlighted individual differences in attentional processes, especially the allocation and maintenance of attentional focus (5, 131), and has suggested that these differences have implications for learning and development (113). It would be reasonable to expect that there would also be individual differences in auditory attention, both in the stimulus preferences exhibited and in performance on selective, divided and sustained attention tasks. Further, given Jusczyk's model (14) of lexical development, differences in auditory attention might be expected to be related to differences in lexical development and language acquisition, as well as other aspects of auditory information processing. In addition, although speculative, it is possible that deficits in auditory processing as seen in some children with specific language impairments and autism might be related to deficiencies in auditory attention.

5. ACKNOWLEDGEMENTS

This work was supported by National Institutes of Health Grants HD01799, NS30029, DC00223, and HD21338. We would like to thank Holly Ruff and Vivien Tartter for comments on a previous draft.

6. REFERENCES

1. Gerken, L.: Sentential processes in early child language: Evidence from the perception and production of function morphemes. In: The development of speech perception. Eds: Goodman J. C., Nusbaum H. C., MIT Press, Cambridge, MA, 271-298 (1994)

2. Cowan, N.: Attention and memory: An integrated framework. Oxford University Press, NY (1995)

3. Mirsky, A. F.: Disorders of attention: A neuropsychological perspective. In: Attention, memory, and executive function. Eds: Lyon, G. R., Krasnegor, N. A., Paul H. Brookes Publishing, Baltimore, MD, 71-95 (1996)

4. Posner, M. I., & S. E. Peterson: The attention system of the human brain. *Annu Rev Neurosci* 13, 25-42 (1990)

5. Ruff, H. A., & M. K. Rothbart: Attention in early development: Themes and variations. Oxford University Press, NY (1996)

6. Baddeley, A., & L. Weiskrantz: Attention: Selection, awareness and control. A tribute to Donald Broadbent. Clarendon Press, NY (1993)

7. Burack, J. A., & J. T. Enns: Attention, development and psychopathology. Guilford Press, NY (1997)

8. Enns, J. T.: Development of attention: Research and theory. Elsevier, Amsterdam (1990)

9. Lyon, G. R. & N. A. Krasnegor: Attention, memory, and executive function. Paul H. Brookes Publishing, Baltimore, MD (1996)

10. Näätänen, R.: Attention and brain function. Lawrence Erlbaum, Hillsdale, NJ (1992)

11. Parasuraman, R.: The attentive brain. MIT Press, Cambridge, MA (1998)

12. Richards, J. E.: Cognitive Neuroscience of Attention. Lawrence Erlbaum, Hillsdale, NJ (1998)

13. Fischler, I.: Attention and language. In: The attentive brain. Ed: Parasuraman, R., MIT Press, Cambridge, MA, 381-399 (1998)

14. Jusczyk, P. W.: Infant speech perception and the development of the mental lexicon. In: The development of speech perception. Eds: Goodman J. C., Nusbaum H. C., MIT Press, Cambridge, MA, 227-270 (1994)

15. Kagan, J.: The determinants of attention in infants. *Am Sci* 58, 298-305 (1970)

16. Berg, W. K., & K. M. Berg: Psychophysiological development in infancy: State, sensory function, and attention. In: Handbook of infant development. Ed: Osofsky J. D., John Wiley & Sons, NY, 283–343 (1979)

17. Posner, M. I.: Cognitive neuropsychology and the problem of selective attention. In: The London Symposia (EEG Suppl. 39). Eds: Ellington R. J., Murray N. M. F., Halliday A. M., Elsevier, Amsterdam, 313-316 (1987)

18. Cooly, E. L., & R. D. Morris: Attention in children: A neuropsychologically based model for assessment. *Dev Neuropsychol* 6, 239-274 (1990)

19. Gibson, E., & N. Rader: Attention: The perceiver as performer. In: Attention and cognitive development. Eds: Hale G. A., Lewis M., Plenum Press, NY, 1-21 (1979)

20. Halperin, J. M., K. E. McKay, K. Matier, & V. Sharma: Attention, response inhibition, and activity level in children: Developmental neuropsychological perspectives. In: Advances in child neuropsychology (Vol.2). Eds: Tramontana M. G., Hooper S. R., Springer-Verlag, NY, 1-54 (1994)

21. Molholm, S., H. Gomes & W. Ritter: The detection of constancy amidst change: A dissociation of preattentive and intentional processes in children (submitted)

22. Halperin, J. M.: Conceptualizing, describing, and measuring components of attention: A summary. In: Attention, memory, and executive function. Eds: Lyon, G. R., Krasnegor, N. A. , Paul H. Brookes Publishing, Baltimore, MD, 119-136 (1996)

23. Shapiro, M. B., R. D. Morris, M. K. Morris, C. Flowers & R. W. Jones: A neuropsychologically based assessment model of the structure of attention in children. *Dev Neuropsychol* 14, 657-677 (1998)

24. McKay, K. E., J. M. Halperin, S. T. Schwartz & V. Sharma: Developmental analysis of three aspects of information processing: Sustained attention, selective attention, and response organization. *Dev Neuropsychol* 10, 121-132 (1994)

25. Friedman, D.: The endogenous scalp-recorded brain potentials and their relationship to cognitive development. In: Handbook of Cognitive Psychophysiology: Central and Autonomic Nervous System Approaches. Eds: Jennings J. R., Coles M., John Wiley & Sons, NY, 621-656 (1991)

26. Hillyard, S. A. & J. C. Hansen: Attention: Electrophysiological approaches. In: Psychophysiology: Systems, processes, and applications. Eds: Coles M. G. H., Donchin E., Porges S. W., Guilford Press, NY, 227–243 (1986)

27. Yerkes, R. M. & J. D. Dodson: The relation of strength of stimulus to rapidity of habit formation. *J Comparative Neurological Psychol* 18, 459-482 (1908)

28. Campos, J. J. & Y. Brackbill: Infant state: Relationship to heart rate, behavioral response and response decrement. *Dev Psychobiol* 6, 9-19 (1971)

29. Graham, F. K. & J. C. Jackson: Arousal systems and infant heart rate responses. *Adv Child Dev* 5, 59-117 (1970)

30. Tokioka, A. B., J. W. Pearce & D. H. Crowell: Endogenous event-related potentials in term and preterm infants. *J Clin Neurophysiol* 12, 468-475 (1995)

31. Bench, J. & L. Mentz: Neonatal auditory habituation and state change. *Q J Exp Psychol* 30, 355-362 (1978)

32. Shibagaki, M., M. Sakamoto & T. Furuya: Age differences in characteristics of the attention process of

electrodermal activity during auditory stimulation. *Percept Mot Skills* 79, 403-410 (1994)

33. Dittrichova, J. & V. Lapackova: Development of the waking state in young infants. *Child Dev* 35, 365-370 (1964)

34. Broadbent, D. E.: Decision and Stress. Academic Press, NY (1971)

35. Eysenck, M. W.: Attention and Arousal: Cognition and Performance. Springer, Berlin, Germany (1982)

36. Sokolov, E. N.: Higher nervous functions: The orienting reflex. *Annu Rev Physiol* 25, 545-580 (1963)

37. Kinsbourne, M., & Swanson, J. M.: Developmental aspects of selective orientation. In: Attention and cognitive development. Eds: Hale G. A., Lewis M., Plenum Press, NY, 119-134 (1979)

38. Cowan, N.: Evolving conceptions of memory storage, selective attention, and their mutual constraint within the human information-processing system. *Psychol Bull* 104, 163-191 (1988)

39. Doolittle, E. J. & H. A. Ruff: Distractibility during infants' examining and repetitive activity. *Dev Psychobiol* 32, 275-283 (1998)

40. Tellinghuisen, D. J. & L. M. Oakes: Distractibility in infancy: The effects of distractor characteristics and types of attention. *J Exp Child Psychol* 64, 232-254 (1997)

41. Morrongiello, B. A. & R. K. Clifton: Effects of sound frequency on behavioral and cardiac orienting in newborn and five-month-old infants. *J Exp Child Psychol* 38, 429-446 (1984)

42. Lecanuet, J., C. Granier-Deferre & A. Jacquet: Decelerative cardiac responsiveness to acoustic stimulation in the near term fetus. *Q J Exp Psychol* 44B, 279-303 (1992)

43. Moffitt, A. R.: Intensity discrimination and cardiac reaction in young infants. *Dev Psychol* 8, 357-359 (1973)

44. Field, J., D. Muir, R. Pilon, M. Sinclair & P. Dodwell, P.: Infants' orientation to lateral sounds from birth to three months. *Child Dev* 51, 295-298 (1980)

45. Graham, F. K., B. J. Anthony & B. L. Zeigler: The orienting response and developmental processes. In: Orienting and habituation: Perspectives in human research. Ed: Siddle D., John Wiley & Sons, NY, 371-430 (1983)

46. Kearsley, R. B.: The newborn's response to auditory stimulation: A demonstration of orienting and defensive behavior. *Child Dev* 44, 582-590 (1973)

47. Clarkson, M. G., R. K. Clifton, I. U. Swain & E. E. Perris: Stimulus duration and repetition rate influence newborns' head orientation toward sound. *Dev Psychobiol* 22, 683-705 (1988).

48. Clarkson, M. G. & W. K. Berg: Cardiac orienting and vowel discrimination in newborns: Crucial stimulus parameters. *Child Dev* 54, 162-171 (1983)

49. Trehub, S. E., & L. J. Trainor: Rules for listening in infancy. In: Development of attention: Research and theory. Ed: Enns J. T., Elsevier, Amsterdam, 87-119 (1990)

50. Zelazo, P. R., L. R. Brody & H. Chaika: Neonatal habituation and dishabituation of head turning to rattle sounds. *Infant Beh Dev* 7, 311-321 (1984)

51. Moffitt, A. R.: Consonant cue perception by twenty- to twenty-four-week-old infants. *Child Dev* 42, 717-731 (1971)

52. Weiss, M. J., P. R. Zelazo & I. U. Swain: Newborn response to auditory stimulus discrepancy. *Child Dev* 59, 1530-1541 (1988)

53. Horowitz, A. B.: Habituation and memory: Infant cardiac responses to familiar and discrepant auditory stimuli. *Child Dev* 43, 43-53 (1972)

54. Taylor, E.: Development of attention. In: Scientific foundations of developmental psychiatry. Ed: Rutter M., William Heinenmann Medical Books Limited, London, England, 185-197 (1980)

55. Cycowicz, Y. M. & D. Friedman: A developmental study of the effect of temporal order on the ERPs elicited by novel environmental sounds. *Electroencephalogr Clin Neurophysiol* 103, 304-318 (1997)

56. Posner, M. I., & C. R. R. Snyder: Attention and cognitive control. In: Information processing and cognition: The Loyola Symposium. Ed: Solso R. L., Erlbaum, Hillsdale, NJ, 55-85 (1975)

57. Schneider, W., S. T. Dumais & R. M. Shiffrin: Automatic and control processing and attention. In: Varieties of attention. Eds: Parasuraman R., Davies D. R., Academic Press, Orlando, FL, 1-27 (1984)

58. Schneider, W. & R. M. Shiffrin: Controlled and automatic human information processing: I. Detection search and attention. *Psychol Rev* 84, 1-66 (1977)

59. Shiffrin, R. M. & W. Schneider: Controlled and automatic human information processing: II. Perceptual learning, automatic attending, a general theory. *Psychol Rev* 84, 127-190 (1977)

60. Broadbent, D. E.: Task combination and selective intake of information. *Acta Psychol* 50, 253-290 (1982)

61. Maccoby, E.: The development of stimulus selection. *Minn Symposia Child Psychol* 3, 68-96 (1969)

62. Goodman, J. C. & H. C. Nusbaum: The development of speech perception. MIT Press, Cambridge, MA (1994)

63. Jusczyk, P. W.: The Discovery of Spoken Language. MIT Press, Cambridge, MA (1997)

64. DeCasper, A. J. & W. Fifer: Of human bonding: Newborns prefer their mothers' voice. *Science* 208, 1174-1176 (1980)

65. Mehler, J., P. Jusczyk, G. Lambertz, N. Halsted, J. Bertoncini, & C. Amiel-Tison: A precursor of language acquisition in young infants. *Cognition* 29, 143-178 (1988)

66. Fernald, A.: Four-month-old infants prefer to listen to motherese. *Infant Beh Dev* 8, 181-195 (1985)

67. Colombo, J. & F. D. Horowitz: Infants' attentional responses to frequency modulated sweeps. *Child Dev* 57, 287-291 (1986)

68. Newman, R. S. & P. W. Jusczyk: The cocktail party effect in infants. *Percept Psychophys* 58, 1145-1156 (1996)

69. Trehub, S. E. & L. A. Thorpe: Infants' perception of rhythm: Categorization of auditory sequences by temporal structure. *Can J Psychol* 43, 217-229 (1989)

70. Jusczyk, P. W., D. B. Pisoni & J. Mullennix: Some consequences of stimulus variability on speech processing by 2-month-old infants. *Cognition* 43, 253-291 (1992)

71. Goodsitt, J. V., P. A. Morse, J. N. Van Hoeve & N. Cowan: Infant speech recognition in multisyllabic contexts. *Child Dev* 55, 903-910 (1984)

72. Marcus, G. F., S. Vijayan, S. B. Rao & P. M. Vishton: Rule learning by seven-month-old infants. *Science* 283, 77-80 (1999)

73. Steinschneider, M., D. Kurtzberg & H. G. Vaughan, Jr.: Event-related potentials in developmental neuropsychology. In: Handbook of neuropsychology, Volume 6. Eds: Rapin I., Segalowitz S., Elsevier, Amsterdam, 239-299 (1992)

74. Alho, K.: Cerebral generators of mismatch negativity (MMN) and its magnetic counterpart (MMNm) elicited by sound changes. *Ear Hear* 16, 38-51 (1995)

75. Alho, K., K. Sainio, N. Sajaniemi, K. Reinikainen & R. Näätänen: Event-related brain potential of human newborns to pitch change of an acoustic stimulus. *Electroencephalogr Clin Neurophysiol* 77, 151-155 (1990)

76. Kurtzberg, D., H. G. Vaughan Jr., J. A. Kreuzer & K. Z. Fliegler: Developmental studies and clinical applications of mismatch negativity: Problems and prospects. *Ear Hear* 16, 105-117 (1995)

77. Cheour, M., R. Ceponiene, A. Lehtokoski, A. Luuk, J. Allik, K. Alho & R. Näätänen, R.: Development of language-specific phoneme representations in the infant brain. *Nat Neurosci* 1, 351-353 (1998)

78. Werker, J. F.: Cross-language speech perception: Developmental change does not involve loss. In: The development of speech perception. Eds: Goodman J. C., Nusbaum H. C., MIT Press, Cambridge, MA, 93-120 (1994)

79. Greenberg, G. Z., N. W. Bray & D. S. Beasley: Children's frequency-selective detection of signals in noise. *Percept Psychophys* 8, 173-175 (1970)

80. Bargones, J. Y. & L. A. Werner: Adults listen selectively; Infants do not. *Psychol Sciences* 5, 170-174 (1994)

81. Shafer, V. L., M. L. Morr, J. A. Kreuzer & D. Kurtzberg: Maturation of mismatch negativity in school-age children. (submitted)

82. Ceponiene, R., M. Cheour & R. Näätänen: Interstimulus interval and auditory event-related potentials in children: Evidence for multiple generators. *Electroencephalogr Clin Neurophysiol* 108, 345 – 354 (1998)

83. Gomes, H., E. Sussman, W. Ritter, D. Kurtzberg, N. Cowan & H. G. Vaughan Jr.: Electrophysiological evidence of developmental changes in the duration of auditory sensory memory. *Dev Psychol* 35, 294-302 (1999)

84. Korpilahti, P., & H. A. Lang: Auditory ERP components and mismatch negativity in dysphasic children. *Electroencephalogr Clin Neurophysiol* 91, 256-264 (1994)

85. Kraus, N., T. McGee, T. D. Carrell, S. G. Zecker, T. G. Nicol & D. B. Koch: Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science* 273, 971-973 (1996)

86. Ritter, W., D. Deacon, H. Gomes, D. Javitt & H. G. Vaughan, Jr.: The mismatch negativity of event-related potentials as a probe of transient auditory memory: A review. *Ear Hear* 16, 52-67 (1995)

87. Gomes, H., S. Molholm, W. Ritter, D. Kurtzberg, N. Cowan & H. G. Vaughan, Jr.: Developmental differences in the effects of attention on the mismatch negativity. (submitted)

88. Tipper, S. P., T. A. Bourque, S. H. Anderson & J. C. Brehaut: Mechanisms of attention: A developmental study. *J Exp Child Psychol* 48, 353-378 (1989)

89. Kinsbourne, M.: Development of attention and metacognition. In: Handbook of neuropsychology, Vol. 7: Child neuropsychology. Eds: Segalowitz S., Rapin I., Elsevier, Amsterdam, 261-277 (1992)

90. Lane, D. M., & D. A. Pearson: The development of selective attention. *Merrill-Palmer Quarterly* 28, 317-337 (1982)

91. Pick, A. D., D. G. Frankel & V. L. Hess: Children's attention: The development of selectivity. In: Review of Child Developmental Research, Volume 5. Ed: Hetherington E. M., University of Chicago Press, IL, 325-383 (1975)

92. Plude, D. J., J. T. Enns & D. Brodeur: The development of selective attention A life-span overview. *Acta Psychol* 86, 227-272 (1994)

93. Doyle, A: Listening to distraction: A developmental study of selective attention. *J Exp Child Psychol* 15, 100-115 (1973)

94. Boothroyd, A.: Auditory development of the hearing child. *Scand Audiol* 26, 9-16 (1997)

95. Elliot, L. L., M. A. Hammer, M. E. Scholl & J. M. Wasowicz: Age differences in discrimination of simulated single-formant frequency transitions. *Percept Psychophys* 46, 181-186 (1989)

96. Jensen, J. K., & D. L. Neff: Development of basic auditory discrimination in preschool children. *Psychol Science* 4, 104-107 (1993).

97. Werner, L. A., & E. W. Rubel: Developmental Psychoacoustics. American Psychological Association, Washington, DC (1992)

98. Wightman, F., & P. Allen: Individual differences in auditory capabilities among preschool children. In: Developmental Psychoacoustics. Eds: Werner L. A., Rubel E. W., American Psychological Association, Washington, DC, 113-133 (1992)

99. Sussman, J. E.: Auditory processing in children's speech perception: Results of selective adaptation and discrimination tasks. *J Speech Hear Res* 36, 380-395 (1993)

100. Dempster, F. N.: Memory span: Sources of individual and developmental differences. *Psychol Bull* 89, 63-100 (1981)

101. Sexton, M. A., & G. Geffen: Development of three strategies of attention in dichotic monitoring. *Dev Psychol* 3, 299-310 (1979)

102. Geffen, G., & M. A. Sexton: The development of auditory strategies of attention. *Dev Psychol* 14, 11-17 (1978)

103. Guttentag, R. E., & P. A. Ornstein: Attentional capacity and children's memory strategy use. In: Development of attention: Research and theory. Ed: Enns J. T., Elsevier, Amsterdam, 305-320 (1990)

104. Kail, R.: The development of memory in children. W. Freeman & Co, NY (1990)

105. Berman, S., & D. Friedman: The development of selective attention as reflected by event-related potentials. *J Exp Child Psychol* 59, 1-31 (1995)

106. Machinskii, N. O., R. I. Machinskaya & V. D. Trush: Electrophysiological study of the functional organization of the human brain during selective attention: II. Normal children aged 11-22 years. *Human Physiol* 16, 159-165 (1990)

107. Pearson, D. A., & D. M. Lane: Auditory attention switching: A developmental study. *J Exp Child Psychol* 51, 320-334 (1991)

108. Kraus, N., T. McGee, T. D. Carrell, C. King, K. Tremblay & T. Nicol: Central auditory system plasticity associated with speech discrimination training. *J Cogn Neurosci* 7, 25-32 (1995)

109. Näätänen, R., E. Schröger, S. Karakas, M. Tervaniemi & P. Paavilainen: Development of a memory trace for a complex sound in the human brain. *Neuroreport* 4, 503-506 (1993)

110. Tremblay, K., N. Kraus, T. D. Carrell & T. McGee: Central auditory system plasticity: Generalization to novel stimuli following listening training. *J Acoust Soc Am* 102, 3762-3773 (1997)

111. Cherry, R. S.: Development of selective attention skills in children. *Percept Mot Skills* 52, 379-385 (1981)

112. Gale, A., & R. Lynn: A developmental study of attention. *Br J Ed Psychol* 42, 260-266 (1972)

113. Kirchner, G. L., & I. J. Knopf: Differences in the vigilance performance of second-grade children as related to sex and achievement. *Child Dev* 45, 490-495 (1974)

114. Kupietz, S. S., & E. Richardson: Children's vigilance performance and inattentiveness in the classroom. *J Child Psychol Psychiatry* 19, 145-154 (1978)

115. Swanson, H. L.: A developmental study of vigilance in learning-disabled and nondisabled children. *J Abnorm Child Psychol* 11, 415-429 (1983)

116. Parasuraman, R., J. S. Warm & J. E. See: Brain systems of vigilance. In: The attentive brain. Ed: Parasuraman R., MIT Press, Cambridge, MA, 221-256 (1998)

117. Halcomb, C. G., & P. Blackwell: Motivation and the human monitor, I: The effect of contingent credit. *Percept Mot Skills* 28, 623-629 (1969)

118. Green, L., A. F. Fry & J. Myerson: Discounting of delayed rewards: A life-span comparison. *Psychol Science* 5, 33-36 (1994)

119. Mischel, W., Y. Shoda & M. L. Rodriguez: Delay of gratification in children. *Science* 244, 933-938 (1989)

120. Mesulam, M. M.: Principles of behavioral neurology. F. A. Davis, Philadelphia, PA (1985)

121. Nittrouer, S., & C. S. Crowther: Examining the role of auditory sensitivity in the developmental weighting shift. *J Speech Hear Res* 41, 809 – 818 (1998)

122. Nittrouer, S., & M. E. Miller: Predicting developmental shifts in perceptual weighting schemes. *J Acoust Soc Am* 101, 2253 – 2266 (1997)

123. Barkley, R. A.: Linkages between attention and executive functions. In: Attention, memory, and executive function. Eds: Lyon, G. R., Krasnegor, N. A. , Paul H. Brookes Publishing, Baltimore, MD, 307-325 (1996)

124. Bell, M. A.: Frontal lobe function during infancy: Implications for the development of cognition and attention. In: Cognitive Neuroscience of Attention. Ed: Richards J. E., Lawrence Erlbaum, Hillsdale, NJ, 287-315 (1998)

125. Posner, M. I., & M. K. Rothbart: Attention, self-regulation and consciousness. *Phil Trans R Soc Lond B* 353, 1915-1927 (1998)

126. Smith, M. L., M. H. Kates & E. R. Vriezen: The development of frontal-lobe functions. In: Handbook of Neuropsychology, Vol. 7: Child Neuropsychology. Eds: Segalowitz S. J., Rapin I., Elsevier, Amsterdam, 309-330 (1992)

127. Luria, A. R.: The working brain: An introduction to neuropsychology. Basic Books, NY (1973)

128. Krasnegor, N. A., G. R. Lyon & P. S. Goldman-Rakic: Development of the Prefrontal Cortex. Baltimore: Paul H. Brookes, Baltimore, MD (1997)

129. Casey, B. J., R. Trainor, J. Giedd, Y. Vauss, C. K. Vaituzis, S. Hamburger, P. Kozuch & J. L. Rapoport: The role of the anterior cingulate in automatic and controlled processes: A developmental neuroanatomical study. *Dev Psychobiol* 3, 61-69 (1997)

130. Casey, B. J., R. J. Trainor, J. L. Orendi, A. B. Schubert, L. E. Nystrom, J. N. Giedd, F. X. Castellanos, J. V. Haxby, D. C. Noll, J. D. Cohen, S. D. Forman, R. E. Dahl & J. L. Rapoport: A developmental functional MRI study of prefrontal activation during performance of a go-no-go task. *J Cogn Neurosci* 9, 835-847 (1997)

131. Harman, C., & N. A. Fox: Frontal and attentional mechanisms regulating distress experience and expression during infancy. In: Development of the prefrontal cortex. Eds: Krasnegor N. A., Lyon G. R., Goldman-Rakic P.S., Paul H. Brookes, Baltimore, MD, 191-208 (1997)

Key words: Attention, Auditory, Children, Infants, Review

Send correspondence to: Dr Hilary Gomes, Psychology Department, NAC 7/120, City College of New York, 137th and Convent Avenue, New York, NY 10031, Tel:212-650-5720, Fax:1-212-650-5659; E-mail: hilary@balrog.aecom.yu.edu

This manuscript is available on line at:

http://www.bioscience.org/2000/v5/d/gomes/fulltext.htm