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# The development of selective attention: A life-span overview [☆]

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## Abstract

This paper outlines research on selective attention within a life-span developmental framework. Findings obtained in both the infancy-child and adulthood-aging literatures are reviewed and discussed in relationship to four aspects of selective attention: orienting, filtering, search, and expecting. Developmental consistencies and inconsistencies are identified and integrative theories are evaluated. Although a single theory is unlikely to accommodate the diverse patterns of age effects, emergent themes are identifiable nonetheless and the essential ingredients of a life-span theory of attentional development are enumerated. Directions for future research and theory are suggested.

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## 1. Introduction

The primary purpose of this paper is to review extant research and theory on attention across the life span. To do so, we have drawn from the cognitive, child-developmental, and adult-aging literatures. Our most optimistic goal is that this review may lead one day to a life-span theory of attention. More realistically, we hope at least to be able to survey the literature that would be relevant in such an integration.

Although attention research has been conducted across a wide variety of age groups, very few studies to date have encompassed a life-span analysis within a single project. A first step in this direction was undertaken by one of us in an edited volume (Enns, 1990, *The Development of Attention*), which included contributions representing the entire human life span. That effort was stimulated in part by the dearth of life-span studies, and in part by a desire to compile in a single reference relevant research and theory to aid in undergraduate and graduate training. The present undertaking is intended as another step along this pathway, in that it combines within a single review, important themes and findings that may point to continuities and discontinuities in life-span attentional development. One service we hope to provide, therefore, is a compiling of data that any theory of life-span attentional development will have to account for. Furthermore, it is our view that even less ambitious theories (e.g., those restricted to attention in young adults, early perceptual development, or cognitive aging) that choose to ignore these trends will do so at their own risk.

In keeping with the now widely-accepted view of what constitutes a *life-span* orientation (Baltes and Reese, 1984), our view of the developmental process is one of open-ended change. Thus, contrary to mechanistic bio-decrement models that view the life span narrowly as growth, followed by maturity and eventual decline, we adopt a more context-sensitive perspective – one that allows for plurality (change may occur in several directions at a time) and for multi-dimensionality (change may take place on more than one level) in the developmental process. This orientation does not deny that maturational processes play important roles at numerous points in the life span, but rather recognizes that attention, like many other cognitive processes, involves a complex pattern of change, with some aspects exhibiting significant change and others exhibiting remarkable stability across the life span.

Our review suggests that the changes that characterize life-span attention are largely quantitative in nature: Attention allows for greater selectivity and speed of processing during childhood and adolescence, and generally less selectivity and greater slowing during later adulthood. Whether life-span development is also characterized by qualitative change is a question that remains unanswered. One aim of our review is to provide a point of departure for future studies of this question. Regardless of its resolution, however, it should be noted that a contextual perspective accommodates both quantitative and qualitative change (Baltes, 1987; Baltes et al., 1980). Another aim of our review is to identify profitable avenues of research/theory within this framework. Although it is unlikely that a single global model of attentional development can encompass the diverse patterns of age effects identified in our review, there may be local models that can account for developmental changes within the various aspects of attention that serve as the organizing themes of our review.

### *1.1. Historical overview*

The diversity of research and theory on attention, as well as on its development, is due in large part to a stubbornly persistent difficulty in defining the construct. In his seminal volume, *Psychology*, published over 100 years ago, William James (1890) identified no fewer than four senses of the term (i.e., awareness of internal states, awareness of external stimuli, habit, and consciousness). With the renaissance of this construct in modern psychology, commencing with Broadbent's (1958) *Perception and Communication*, there have been entire volumes (e.g., the *Attention and Performance* series) devoted to attention, including topics as diverse as sensory detection, prose comprehension, and complex problem-solving. Indeed, Parasuraman and Davies (1984) entitled their edited volume *Varieties of Attention* in order to reflect the diversity of the attention construct. Excellent historical reviews of attention theory and research in mainstream cognitive psychology have been published elsewhere (e.g., Johnston and Dark, 1986; Kinchla, 1980, 1992; Lachman et al., 1979) and the interested reader is directed to those sources. For the purpose of the present review, we restrict commentary to several points that are relevant to our focus on life-span issues.

### *1.2. Problems of definition*

Even though history has proven many times that a single definition of attention is elusive and perilous, it has also proven the usefulness of describing aspects of the construct in such a way that they are amenable to empirical research. One difficulty in opting for this approach, of course, is the potential for tautology: Attention is whatever attention tasks measure. This can be circumvented if one is careful to seek out converging evidence for the attention construct(s) at issue. One way to begin to partition the attention construct is to consider the three dimensions of *arousal*, *capacity*, and *selectivity*, that have proven to be empirically distinguishable (Posner and Boies, 1971; Plude and Doussard-Roosevelt, 1990). *Arousal* refers to the momentary level of excitation (alertness) in the information-processing system, *capacity* refers to the cognitive resources available to support information processing; while *selectivity* refers to the specificity with which resources are allocated to task demands. A theoretical assumption shared by all three of these dimensions is that human information processing is limited. Thus selective processing is mandated by a processing system that has insufficient resources to process simultaneously the plethora of stimuli (both internal and external) by which it is bombarded (Johnston and Dark, 1986).

Because it has been the focus of considerable research and theoretical efforts in the developmental literature at both ends of the life span, *selective attention* is the focus of the present review. It is our belief that sufficient evidence exists to differentiate (at least) four aspects of selective attention that are amenable to a life-span developmental analysis. Although we are by no means the first to suggest this particular compartmentalization of the attention construct (see Coren et al., 1994) we are probably the first to attempt a life-span review within it.

### *1.3. Problems of measurement*

Given the diversity of the attention construct, it probably comes as no surprise that there is considerable disagreement over how best to measure it. In the review that follows, we emphasize reaction time (RT) studies because they constitute by far the most common single procedure for inferring attentional function. This emphasis immediately gives rise to concern, especially evident within developmental studies, over the metric properties of RT and age-group comparisons based upon it. Although RT studies yield valuable information regarding attention and its development, it is important to recognize explicitly three issues that qualify RT procedures in developmental investigations.

One issue centers on the considerable variability associated with RT performance among very young children and elderly adults when compared with the standard comparison group of young adults (this is discussed in more detail elsewhere in this volume – papers by Cerella and Hale, and Salthouse and Kail). Not only does such variability complicate statistical comparisons between groups, but it also gives rise to concerns about comparing the magnitude of within-subject effects between the groups, i.e., age-by-condition interactions. Specifically at issue is the appropriateness of entering non-transformed RTs into analyses when age may be associated with changes in the duration of the so-called psychological moment (Birren, 1965; Welford, 1965). This issue has received considerable attention (no pun intended!) in the cognitive development literature (Kail, 1990) as well as within the cognitive aging literature (Salthouse, 1991).

A second issue, also related to the first, concerns the interpretation given to differences in RT. It is traditional in the cognitive literature to use an RT difference between conditions as a measure of 'attention', uncontaminated by sensory and motoric processes involved in the task at hand, since the experimental conditions are assumed to be equated with regard to these information-processing components. How then is a larger difference for one age group over the other to be interpreted? If one is willing to ignore the concomitant changes in variability, or even to believe that these are independent effects, interpretation is unhindered – the attention effect is larger for the group with the larger mean difference. Also, if one is willing to take an ecological view of processing time – organisms of all ages survive, mate, and find food in the same functional time units – then direct comparisons of RT differences seem warranted despite related differences in variability (Enns, 1990). However, if one is only willing to interpret RT as a relative and indirect measure of attentional effects, then much more caution must be exercised. In the present review, we have chosen to report non-transformed RT data at face value, largely because the majority of published studies are based on this measure. However, because of the continuing debate over the metric properties of RT, we must sound a cautionary note about its use, especially as it is related to development.

A third issue involving RT measures in developmental studies centers on the importance of coordinated RT and accuracy data. This is particularly noteworthy with respect to developmental comparisons because there is always the possibility that an age difference based solely on RT may be attributable to an underlying speed–accuracy tradeoff (see, for example, Pachella, 1974; Wickelgren, 1977). In brief, one must be careful to examine patterns of both RT and accuracy changes in order to infer underlying information-processing characteristics. The slower responding of very young children and elderly adults, when compared with young adults, may be symptomatic of a heightened emphasis on accuracy at the expense of speed. As such, interpretations based upon RT alone will be misinformed. It is of interest to note that in most cases where speed–accuracy tradeoffs have been examined in the developmental literature (see, for example, Plude and Doussard-Roosevelt, 1990; Enns, 1990; Cerella, 1990; Kail, 1990), they have not been found to account for the age effects obtained. Thus, error rate and RT tend to be positively correlated across task conditions within developmental studies, with separate analyses of error rate and RT typically yielding comparable patterns of age effects. Although this outcome supports an emphasis on RT data, it is nonetheless important to examine coordinated RT and accuracy data because even small changes in error rate may be associated with large differences in RT (see, for example, Pachella, 1974).

As implied in this brief historical and methodological review, developmental research on attention is relatively new on the scene. Among the earlier references to attentional constructs in the developmental literature are Sokolov's (1963) work on the orienting reflex in infants and Rabbitt's (1965) pioneering work on distractibility in aging. Perhaps it is poignant that both of these investigators were working outside of North America at the time of their seminal studies. The Zeitgeist in American psychology during the 1950's was not entirely receptive to mentalistic constructs like attention, but gradually through the 1960's, attention research began to emerge, with the trend in the adult-aging literature lagging somewhat behind the trend in the child development literature. For example, as early as 1970, Reese and Lipsitt's *Experimental Child Psychology* contained an entire chapter devoted to attention, whereas Birren and Schaie did not include a chapter on the construct in their *Handbook of the Psychology of Aging* until the most recent edition (3rd ed., 1990). Nevertheless, to this day, research and theory on attention remains somewhat of a lost orphan to a life-span developmental analysis.

## 2. Components of selective attention

Although our review of selective attention is organized around the attentional tasks of orienting, filtering, searching, and expecting, it should be noted that this is but one slice through a larger multidimensional space of attentional constructs (see Coren et al., 1994; Enns, 1990). Fig. 1 shows a three-dimensional model in which these tasks can be located along one plane. Perhaps the most fundamental dimension concerns the modality or source of the information being processed – it may be primarily visual, auditory, somatosensory, or even memorial. A second dimension concerns the distribution of attention over space and time – processing effort may be focused on a specific object or location or divided among a number of objects and events. The third dimension emphasizes the various tasks that

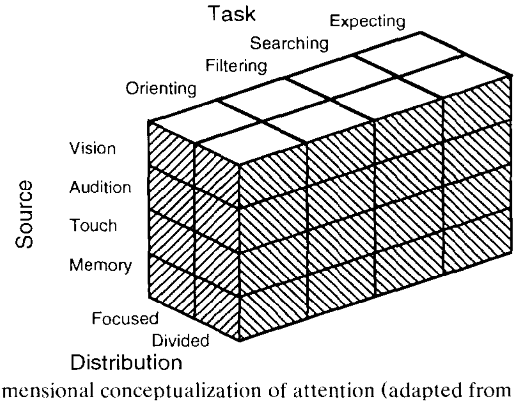

Fig. 1. Multidimensional conceptualization of attention (adapted from Coren et al., 1993).

require specialized selection mechanisms – orienting to particular stimuli, selecting objects based on specific attributes, and so on. We think of these dimensions as being largely independent of one another, meaning that in any given circumstance, we should be able to define an information modality, a degree of distribution, and a task.

### *2.1. Orienting*

The most primitive form of attentional selection involves aligning sensory receptors with certain locations in space and orienting away from others. Reflexive visual and auditory orienting of this kind is seen whenever a sudden movement or loud sound occurs in the environment. A cat will prick up its ears, a newborn infant will slowly turn its head, and adults will involuntarily move their eyes and head toward the location of a sudden sound. In addition to these location-specific responses there are changes in skin conductance, heart rate, blood flow and breathing associated with sudden events. These physiological events signal the onset of a more general arousal response (Donchin, 1981; Rohrbaugh, 1984). It is important to distinguish these overt forms of the orienting reflex from covert orienting, which has to do with an alignment of attention in the absence of a physical alignment of the sensory receptor surfaces (Posner, 1980). We first review developmental studies of the orienting reflex, and then studies involving covert orienting.

#### *2.1.1. Reflexive orienting*

The orienting reflex has often been studied in infants by using a sudden sound or light to generate head and eye movements (Muir and Clifton, 1985; Muir and Field, 1979). For instance, newborns will move their eyes and head in order to fixate a suddenly appearing light that is presented as far away as 20 degrees from the fovea (Aslin, 1987). At 1 month infants' eyes often become 'glued' to a particular contour for up to several minutes in length. This obligatory form of attention may lead to apparent frustration in the infant which ends only in crying. By 3 months infants will use their visual periphery to discriminate between preferred and non-preferred targets, moving their eyes to the preferred stimulus (Maurer and Lewis, 1991). However, the eye movements made by infants are still quite different from those of adults in the same situation. They are much slower in initiation time (several seconds vs. 200 ms) and instead of making a single, accurate saccade to the target, they make a series of smaller and more tentative movements (Aslin, 1987).

The newborn's orienting reflex has also been used to test for more general capacities. If an infant is shown a continuously moving pattern, such as a screen of moving stripes, a very stereotyped pattern of behavior is observed (Kremenitzer et al., 1979). The eye will track the movement of the contour quite smoothly for a short distance and then suddenly snap back in the opposite direction. The eyes then lock onto another moving edge and the process repeats itself. This eye-movement pattern is called optokinetic nystagmus and it is a reliable indicator of neurological problems (Brazelton et al., 1966). It can also be used to study infant sensitivity to stimulus attributes as color, brightness, form, and motion.

The mere presence of more than one target in the visual field seriously disrupts orienting eye movements in newborns. Initiation times are increased and accuracy of fixation is diminished (Atkinson et al., 1988). Until 3 months of age, when infants are given a choice between looking at a previously fixated target and a new one, they tend to look at the original one. By 6 months, this trend has reversed and infants will choose to refixate on the novel stimulus (Hood and Atkinson, 1991; Rothbart et al., 1990). This phenomenon is referred to as inhibition of return, and will be seen again in the adult work on covert orienting.

Neurophysiological research suggests that the reflexive orienting of the eye is governed by a midbrain structure known as the superior colliculus (Atkinson and Braddick, 1981; Hoffman, 1979; Johnson, 1990). This coincides with an important asymmetry observed in newborns' eye movements to nasal (toward the nose) and temporal (away from the nose) visual targets (Maurer and Lewis, 1991). Newborns show a much more consistent response to the temporal field. Interestingly, eye movements to this region may be initiated by the superior colliculus independent of cortical input. In contrast, eye movements to the nasal field require cortical input, simply because of the way in which retinal input is divided between the cerebral hemispheres. By 2–3 months of age the asymmetry in eye movements has diminished greatly, suggesting that the cortical connections to the superior colliculus have become established.

The orienting reflex has not been studied as extensively in the adult and aging literatures as in the infancy literature, but recent theorizing on age-related inhibitory processes (reviewed later in this paper) has sparked an interest in this basic reflex as a measure of attentional processing. For example, McDowd and Filion (1991) used a physiological measure of skin conductance to evaluate the arousal responses of young and elderly subjects performing a selective reading task. In one condition, subjects were instructed to ignore irrelevant tones that occurred during the reading task; and in the other condition, subjects were instructed to attend to the tones. Young adults' responses habituated to the tone in the 'ignore' condition but not in the 'attend' condition, whereas elderly adults exhibited persistent arousal in both conditions. These findings were taken as support for the view that older adults have difficulty suppressing unattended information. Electrophysiological evidence also suggests that the orienting reflex is less selective in later adulthood. Visual evoked potentials (VEPs) to patterned and unpatterned stimuli exhibit maximum separability in adolescents and young adults as compared with either younger or older subjects (Prinz et al., 1990). These findings suggest that young adulthood is characterized by maximally efficient excitatory and inhibitory processes in the central nervous system (CNS), whereas early childhood and later adulthood are characterized by less selective CNS responses. Thus, although the orienting reflex is exhibited across the life span, its selectivity and specificity may vary with age such that the response is maximally specific in adolescence and young adulthood and more generalized at the earlier and later ends of the life span.

### 2.1.2. *Covert orienting*

By the time children are 3 and 4 years of age, it is possible not only to study overt forms of orienting, such as those involved in head and eye movements, but it is also possible to measure covert forms of orienting. This has been done mainly using cost–benefit RT methodology to study the visual system (Posner, 1980). The subject is given a very simple task – to press a key whenever a predefined target stimulus is presented. The target may be the onset of a light or a simple shape such as a circle or square. The critical experimental manipulation is the presentation of a brief stimulus called a cue (e.g., a flash of light, brightening of a location marker) immediately preceding the target stimulus. If the cue is presented in the same location as the subsequent target, the trial is called a valid trial; if the cue is in a different location from the target the trial is called invalid. If no cue is presented, or if it is presented in all possible target locations, the trial is called neutral. A subtractive comparison of neutral and valid RTs is the measure of orienting benefit; the same comparison of invalid and neutral RTs is a measure of orienting cost. The relations between cue and target locations are determined randomly to ensure that the reflexive orienting response is not contaminated by higher-order expectations on the part of the subject (see later section on 'Expecting').

The temporal relation between the cue and the target also has several notable influences on RT. In young adults, costs and benefits reach their maximum when the cue–target stimulus onset asynchrony (SOA) is between 50–100 ms. By an SOA of 400 ms or so there is no longer any difference between valid and invalid RT, and by 800 ms invalid RTs are actually shorter than valid RTs (Maylor and Hockey, 1985; Posner and Cohen, 1984). This reversal in RT at longer SOA values has come to be called inhibition of return and it appears to require the programming of an eye movement as a necessary condition (Rafal et al., 1989). Its operation appears to bias the visual system to orient toward novel objects and locations and away from events already processed (Klein, 1988; Posner et al., 1985).

Within the child development literature, the cost-benefit method has shown that response times on valid trials are significantly shorter than those on invalid trials, even for children as young as 3 years of age (Enns, 1990). In one study of normal 6-, 8-, and 20-year-old subjects (Enns and Brodeur, 1989) there did not appear to be any age-related change in the size of the orienting benefit – all subjects appeared to be influenced in the same way by valid cues preceding targets. However, there was an age-related decrease in orienting cost – older subjects were able to switch attention to the invalidly-cued target location more efficiently than younger subjects. This suggests that although the orienting response may operate in a similar way at different ages, there are important developmental changes in the ability to shift attention from locations that have already captured attention. Further work is needed to determine whether inhibition of return undergoes developmental change during childhood.

At the adult-aging end of the life span, several studies have investigated covert orienting in response to abrupt-onset stimulus cues. Although these studies converge on finding roughly comparable costs and benefits across age, there is disagreement about the time course of these effects. For example, Hartley et al. (1990, Expt. 3) found comparable costs and benefits among young and elderly adults when a bar-marker indicated the likely position of a target letter on the circumference of an imaginary circle centered at fixation. Moreover, the magnitude of age-related cuing effects were comparable across various cue–target delays indicating an age-equivalent time course for cuing effects. Folk and Hoyer (1992, Expt. 1) also obtained comparable costs and benefits, and at equivalent rates, among young and elderly adults when a luminance change signaled the likely position of a target at one of four positions in a display. Madden (1990b) obtained a similar outcome when targets appeared in an otherwise empty display: both young and elderly adults exhibited modest benefits at equivalent rates when an asterisk indicated the likely position of the target in a six-position array. However, when targets were accompanied by distractors (the letter 'R' presented at 18 positions in the display), younger adults exhibited benefits sooner (beginning at 50 ms SOA) than did older adults (whose RT benefits materialized at 150 ms SOA). Thus, it appears that covert orienting is preserved in later life, and at least in simple detection/recognition situations in which targets appear in otherwise blank displays, the time course of visual orienting is comparable across adult age.

In sum, the combined developmental–aging literature indicates a fairly stable picture of covert orienting across the life span, with possibly some age-associated change in its time course. Several studies in the child and aging literatures have attempted to decompose the attentional mechanisms involved in covert orienting by comparing performance in cost–benefit tasks with performance in other attention tasks. For example, one study of children examined the relations between covert orienting and response priming (Enns and Brodeur, 1989), while another tested the relations between covert orienting and Stroop-type filtering (Akhtar and Enns, 1989). In both cases, tasks that involved both components of attention resulted in increases in RT and errors that were larger than could be predicted by a model in which the components relied on separate sets of cognitive resources. Studies such as these thus contribute to the belief that some age-associated changes seen in different tasks are actually reflective of the same underlying selection mechanisms.

### *2.1.3. Attentional gaze*

Before moving away from the topic of covert orienting, we address the metaphor of attentional gaze, which offers a useful way of organizing some of the findings in visual orienting (see Coren et al., 1994). We use this term in place of a variety of concepts (e.g., zoom lens, spotlight, mind's eye) because they all involve the metaphor of attention behaving in a way analogous to the eye. For example, visual acuity in the attentional window is highest at the center, with a decreasing gradient in the surround; in order to move from point A to point B the attentional gaze must move through intermediate positions; and the attentional gaze cannot be centered on more than one location at a time.

Very little of the work with infants has addressed itself to questions of attentional gaze. However, research on infants' eye movements over a picture suggests that neonates are often 'captured' by the first contour their eye encounters (Banks and Salapatek, 1983; Haith et al., 1977). If the stimulus has internal features (e.g., a face) they are ignored or missed by the eye-movement system. Sometime after 2 months the infant begins to explore all contours, including interior details, more systematically.

The nature of the attentional gaze is somewhat easier to study in children who are old enough to make reliable keyboard responses – 3 to 4 years old and up. One way this has been studied in young children involves presenting stimuli for rapid identification at the center of gaze and then measuring the extent to which task-irrelevant stimuli in the periphery of the visual field influence performance (Enns and Girgus, 1985). This procedure yields a measure of how narrowly attention can be focused. Another, somewhat complementary, way to study attentional gaze is to ask subjects to make same–different judgments of targets that are presented simultaneously at varying distances from one another (Enns and Girgus, 1985). This yields an estimate of how widely attention can be divided, or perhaps, switched rapidly from one target to the other.

A study that examined these measures in 5-, 8-, 10-, and 20-year-olds showed strong age-related improvements in both attentional narrowing and attention dividing/switching (Enns and Girgus, 1985). The responses of younger children were not only slowed more by stimuli in the visual periphery (i.e., the involuntary intrusion was more disruptive) but the disruption was evident over a larger visual region (i.e., attentional gaze could not be narrowed as effectively to a small region). In addition, responses of younger children were slowed more by increasing distance between stimuli in the same–different task, suggesting that they were less able to increase or switch the attentional gaze when the task demanded it.

Note that these results cannot be explained either by a general improvement in peripheral acuity with age or by a general improvement in narrowing the attentional gaze. The first hypothesis is inconsistent with the results from the selective attention task – poor peripheral vision should lead to less interference from peripheral stimuli; the second is inconsistent with the results from the divided attention task – a narrower attentional window should lead to poorer performance in the same–different task. Instead, the results point to increasing voluntary control with age over the size of the attentional gaze.

Once gained, it appears that voluntary control over the attentional gaze is maintained well into later adulthood. A variety of studies have shown that, similar to younger adults, older adults adjust the extent of the attentional field in accord with the demands of the task. For example Ball et al. (1990) found that the spatial extent of the attentional gaze varied as a direct function of the information-processing demands of performance for both young and elderly adults. Thus, when performance required a simple detection response, the spatial extent of the gaze was much broader than when complex discriminations involving identification were involved, and this was true for both younger and older adults.

Although dynamic control of attentional gaze appears to be spared in adult aging, there is disagreement over its spatial extent. Studies by Cerella (1985) and Scialfa et al. (1987) suggest that the useful field of view is more constricted for elderly than younger adults. In these studies, subjects were required to identify characters that fell increasingly further away from central fixation, with the result that the acuity decrement in elderly adults was more precipitous and occurred at smaller eccentricities than in younger adults. However, these studies do not take into account the attentional demands of the primary task (i.e., character recognition) as a mediator of this result. If one takes into account all three components of the attentional gaze construct – locus, extent, and detail level (Coren et al., 1994) – the picture becomes more complex. Following this line of reasoning, Plude and Doussard-Roosevelt (1990) argued that rather than viewing the useful field of view as a fixed commodity, it may more appropriately be viewed as a flexible one that can be adjusted to meet task demands. Thus, the extent of the gaze may depend directly on the difficulty of the primary task, with age effects in turn tied to this difficulty dimension. Tasks which are more difficult for senior adults will therefore inevitably result in a smaller field of view, as has already been shown for factors such as visual display density (Mackworth, 1976), and feature detection versus character classification (Downing, 1988). Thus, rather than being a consequence of the aging process per se, decrements in the extent of the attentional gaze may reflect a deficit in cognitive resources that are needed to control its other aspects (i.e., locus and detail level).

#### 2.1.4. *Developmental themes*

The findings reviewed in this section indicate that the orienting reflex is both present at birth and largely spared by aging. Thus, infants, young adults, and older adults orient toward stimuli involving an abrupt change. There is electrophysiological evidence that the selectivity of the orienting reflex improves during child development, peaks in adolescence and young adulthood, and then wanes in later life. Although this evidence has important implications regarding inhibitory processing across the life span, it is nonetheless true that the orienting reflex is operative across the life span. Also clear is that young children and older adults can both orient attention covertly, and can adjust their attentional gaze in accordance with task demands (i.e., smaller focus for complex/dense displays, wider for simpler/sparse displays). There are clear improvements in the efficiency of gaze adjustment in the early childhood years and equally clear decreases in this ability in older age. Nonetheless, age differences in attentional gaze measurements should be made with caution, since there appear to be a number of related, but as yet largely unexplored, aspects involved in its control.

### 2.2. *Filtering*

Many attention tasks require the subject to process certain attributes of an object to the exclusion of other attributes and objects. This has often been referred to as filtering, to capture the implication that only certain perceptual attributes are permitted through a processing 'gate'. With this definition in mind, the careful reader may note that the previous attention task of orienting merely involves filtering in the spatial domain. Nonetheless, we think these tasks deserve separate status, because of both psychophysical (Bundesen, 1990; Tsal, 1983; Nissen, 1985) and neurological evidence (Mishkin et al., 1983; Ungerleider and Mishkin, 1982) pointing to the unique status of an object's location versus other of its attributes such as size, color, pitch, and volume.

Infant research on filtering is largely confined to studies examining the selective preferences of neonates and older infants. The limited behavioral repertoire of the newborn prevents researchers from asking questions that go far beyond the procedures that comprise forced-choice looking preference and habituation–dishabituation (Banks and Salapatek, 1987). Studies in the auditory domain have shown newborn preferences for speech over nonspeech, infant-directed speech over adult-directed speech, and certain temporal and melodic regularities in music over other regularities and nonregularities (Trehub and Trainor, 1990). In the visual domain, there is a general principle of infant preferences for moderate novelty and complexity that summarizes much of the work (Fantz et al., 1975). Although newborns look longer at patterned than unpatterned stimuli (Fantz, 1965) they nonetheless prefer patterns with moderate rather than dense inter-item spacing (Fantz et al., 1975). When stimuli are comparable with regard to pattern density, it appears that newborns look equally as long at scrambled versus unscrambled faces (Fantz and Nevis, 1967). Between 1 and 3 months of age, neonates prefer more dense checkerboard patterns over sparser ones (Greenberg, 1971) and they prefer randomly checked patterns over regular checkerboards (Fantz et al., 1975).

### *2.2.1. Auditory selection*

With young adult subjects, filtering in the auditory domain has often been studied with a method based on observations at a typical cocktail party – the dichotic listening task (Cherry, 1953). This name refers to several aspects of attention easily observed at a party where multiple conversations are underway. For instance, it is relatively easy to listen to the speaker who is directly in front of you, at the same time ignoring other speakers who are equally loud but are not the present focus of attention. Furthermore, it is possible to switch one's attention from one speaker to the other, although at any moment only one conversation is at the center of attention. Finally, there are some sounds that intrude into our consciousness, even when they are spoken by an unattended speaker, such as one's own name, or very large changes in volume or pitch.

Developmental studies of the dichotic listening task have most often been conducted with school-age children, with the most common finding being that younger children are less able to defend against involuntary intrusions and process the 'attended' information less accurately (Doyle, 1973; Sexton and Geffen, 1979). One study made a careful comparison of the same stimuli (i.e., word lists in two ears) under conditions of either focused attention (i.e., one ear was cued prior to the list) or divided attention (i.e., one ear was probed only after the list was presented). Ten-year-olds were much better able than 7-year-olds to focus only on the cued list, and were also somewhat better at dividing their attention between lists.

Pearson and Lane (1991a) studied the time course of the attention-shifting process between lists and also found large age-related improvements between 8 and 11 years. Whereas 8-year-olds required more than 3.5 s to completely switch from monitoring one list to another, 11-year-olds and adults appeared to complete the switch in less than 2.5 seconds.

In his elegant review of dichotic listening and shadowing tasks involving older adult samples, Craik (1977) concluded that there is a divided attention decrement associated with aging. Thus, when required to report the contents of two lists presented simultaneously to both ears, older adults exhibit a greater decrement than younger adults on reporting the second list. This dichotic deficit may owe in part to diminished working memory capacity on the part of the elderly (Hasher and Zacks, 1988; Salthouse, 1990). However, it may also reflect diminished selective attention because older adults exhibit higher error rates than younger adults in shadowing tasks that include a competing message on the to-be-ignored channel. Recently, Barr and Giambra (1990) found that the shadowing deficit exhibited by older adults remains even when performance is adjusted for monaural shadowing performance, fluid intelligence, and pure tone hearing loss. Thus, similar to young children, older adults exhibit greater susceptibility than young adults to the cocktail party phenomenon.

### 2.2.2. *Visual selection*

Although it is possible to design visual filtering experiments that mirror the important aspects of the dichotic listening task (Neisser and Becklin, 1975), most of the work in the visual domain has its roots in the classic Stroop (1935) effect. The original work was conducted with words that spelled color names and various ink colors in which the words were printed. Subjects were asked to name the ink color as rapidly as possible (central stimulus dimension) and to ignore the meaning of the words spelled out on the page (secondary or incidental stimulus dimension). The main finding was, of course, that subjects were unable to ignore the word meanings when they referred to color names. This was shown by comparing RT and accuracy in color word lists with noncolor word lists, lists of nonwords, and lists of solid color patches (see MacLeod, 1991, for a thorough review). In one of the few life-span studies conducted, Comalli et al. (1962) found that the magnitude of the Stroop effect diminished throughout childhood and into early adulthood, but increased thereafter into later adulthood. Indeed, Comalli et al. interpreted this pattern of results as being consistent with the so-called 'orthogenetic principle' of life-span perceptual development. According to this view, development comprises a linear progression of increasing control over perceptual analyses until maturity after which perceptual processes regress back to infantile levels in later life. The suitability of this principle for accommodating the findings reviewed in this paper is addressed in the 'General discussion' section of the paper. For now, suffice it to say that the empirical results of Comalli et al.'s research have been replicated repeatedly in both the child and aging literatures.

The key features of the Stroop task have now been replicated with many other visual stimuli, including picture naming as the central task with printed words as the incidental stimuli (Guttentag and Ornstein, 1990), picture naming as the central tasks with other pictures as incidental stimuli (Well et al., 1980; Day and Stone, 1980), and even line length estimation as the central task with various contextual shapes as the incidental stimuli (Enns and Girgus, 1985; Coren and Girgus, 1978). Almost without exception, these studies have shown strong age-related improvements in the ability of school-age children to focus on the central task and to ignore the incidental stimulus dimensions. Although follow-up on the Stroop task has been somewhat less comprehensive in the aging literature, there are several studies that converge on Comalli et al.'s findings of increased perceptual intrusions coupled with diminished perceptual sensitivity in the aged (Layton, 1975; Rogers and Fisk, 1991). However, these findings are not without controversy as described below.

One of the largest controversies in the attention literature over the past 25 years has been the question of whether the attentional filter or 'bottleneck' is relatively early in the processing stream (i.e., at a sensory-perceptual stage) or whether it is late (i.e., at the response selection and execution stage). Early-stage theorists (Broadbent, 1958; Posner, 1980; Treisman, 1969) and late-stage theorists (Norman, 1968; Keele, 1973) have each presented arguments and data in support of their own sides in this debate (see also Yantis and Johnston, 1990, for a more recent discussion). Out of this controversy emerged an elegant procedure for studying attentional interference at both of these potential locations (Eriksen and Eriksen, 1974). Subjects were asked to make speeded responses to a small set of targets that appeared at the center of gaze (i.e., the central task). On some trials, these target items would be flanked on either side by distractor items of various kinds (i.e., incidental stimuli). Distractors that were of similar visual complexity to the target items, but were not assigned to any response, were used to measure the amount of perceptual interference. Distractors that were assigned to responses were used to measure the degree of response selection interference.

This filtering task was studied in 4-, 5-, 7-, and 20-year-old subjects and significant interference effects were found for both perceptual and response stages at all ages (Enns and Akhtar, 1988). Interestingly, only the perceptual interference measure showed large decreases in magnitude with age, suggesting that, at least for this task, only the perceptual filter improves in efficiency over the early school-age years.

Interestingly, we know of only two instances to date in which young children have been shown to be able to filter as efficiently as adults. In the first (Akthar and Enns, 1989) children showed adult-like filtering performance when the Eriksen task was combined with a reflexive covert orienting manipulation. On each trial subjects were asked to respond to a target at the center of a small cluster of items. The target was surrounded either by response-interfering distractors or by response-compatible distractors and its location was either precued by a brief flash of light in the appropriate location (valid cue) or by a flash in the opposite location (invalid). On validly-cued trials, 5-year-olds were able to filter out the distractor items just as efficiently as adults. On invalidly cued trials these children showed the typical pattern of inefficient filtering. It was as though the reflexive orienting response had been used to help the children focus their attention on a smaller region of space than was possible when they attempted to do so voluntarily.

A second instance of adult-like filtering in children was obtained in a task modified to allow children to make more 'ecologically- valid' responses to stimuli (Tipper and McLaren, 1990). Instead of asking subjects to respond to the identity of a target (target naming), based on its spatial location (at the center of gaze), these authors had subjects make a location-based response (target localization) based on the target's identity (its name). This situation mirrors the one children most often find themselves in, as for example, when they reach (i.e., make a location-based response) for an object based on its identity (e.g., a favored toy). Much less often do they name an object (e.g., the same toy) simply because of where it is located (e.g., in a particular spot in the room). Tipper and McLaren found that 6- and 12-year-old children showed no more interference than adults when tested with the location-response task.

Within the aging literature, filtering tasks have yielded evidence of preserved functioning well into later adulthood. Wright and Elias (1979) used the Eriksen filtering task to show that, if anything, younger adults were more susceptible to distractors than were the elderly. Some investigators have suggested that an age-constricted 'perceptual window' (attentional gaze) may underlie this effect (Cerella, 1985; Scialfa et al., 1987) by insulating older observers from interference by peripheral distractors. However, Plude and Hoyer (1986) found that nontarget interference effects were comparable for young and elderly adults in a nonsearch task but were much greater for older than younger adults in a search task. In comparing foveal targets in search against the foveal targets in nonsearch, the differential age effects remained. Thus, peripheral distractors were problematic for older adults under a search instructional set but not under a filtering instructional set. Because the critical comparison involved foveal targets in both conditions, it cannot be concluded that the elderly are insulated from distractors purely on the basis of a constricted useful field of view. More recent work by D'Aloisio and Klein (1990) leads to a similar conclusion. In a filtering task involving nonfoveal targets and distractors, younger and older adults exhibited comparable distractor interference effects. Thus, on balance, it appears that visual filtering is preserved in later life, at least in situations where the target information is spatially distinct from distractors and when the location of the target is prespecified. This is reminiscent of the finding that children are able to filter efficiently when the target location is precued (see Akthar and Enns, 1989 above). Note that both of these findings appear to punctuate a point raised at the outset of this section regarding the distinctive status of spatial location as a processing cue (a point that is revisited in the 'General discussion' section).

Another issue of long-standing interest in filtering tasks is the fate of the stimuli that are not attended while a focal stimulus is being processed. Early selection theorists believed, largely on the basis of post-test memory measures, that unattended stimuli were simply not processed very deeply, if at all. Late selection theorists, on the other hand, believed that all stimuli were processed to the extent that they were able to access mental routines for response selection. An elegant method for studying this question systematically was developed by Tipper and colleagues (Tipper, 1985; Tipper et al., 1989) and has come to be known as the negative priming procedure.

Negative priming is most easily understood as an extension of the standard Stroop task. As with the standard task, on each trial subjects are asked to report on one attribute of the display (the central task) while a secondary attribute is ignored (incidental stimulus attribute). Two different trial types are then compared – those in which the attribute to be attended in the present trial was the ignored attribute on the immediately preceding trial (ignored repetition trials), and those in which the attended attribute bears no relationship to attributes on the previous trial (control trials). In Tipper's (1985) original work with young adult subjects, he found a significant slowing of response on the ignored repetition trials compared to control trials. Moreover, this negative priming effect could be obtained for stimuli that were not even identical to one another, but merely shared perceptual and conceptual attributes (Tipper et al., 1988). Interestingly, subjects did not have explicit memory of the unattended stimuli when tested with standard recognition and recall tests. These results suggest that the unattended stimuli were being processed well beyond a superficial sensory level before being inhibited, although not with the subject's conscious awareness.

Studies of the negative priming effect in school-age children typically report reduced priming effects and larger interference effects in younger subjects (McLaren and Bryson, 1988; Tipper et al., 1989). This suggests that children are unable to inhibit the automatic response tendencies to incidental stimuli. Inconsistent with this view is the one instance in which children have shown adult-like negative priming effect – in the ecologically-valid selection task cited earlier (Tipper and McLaren, 1990), 6-year-old children showed adult-like interference (i.e., reduced distractor effects) and adult-like negative priming (i.e., increased inhibition effects).

The few studies of negative priming involving elderly subjects converge on a similar pattern of results as that obtained with young children: increased interference effects accompanied by diminished (i.e., nonexistent) negative priming effects. For example, Hasher et al. (1991) replicated Tipper's letter-naming task and found that compared with young adults older adults exhibited increased interference on control trials and no negative priming effects on ignored-repetition trials. Similar findings have been obtained by Tipper (1991) using a picture-naming task. In an attempt to strengthen the inhibitory requirement of the negative priming task, McDowd and Oseas-Kreger (1991) used a letter-naming task involving superimposed stimuli. Targets appeared in one color (e.g., red) and distractors another (e.g., green) with the two letters superimposed but slightly offset to allow for target naming. Despite the inhibitory requirement of the task being strengthened, younger adults exhibited negative priming whereas the elderly did not.

Thus, the negative priming studies replicate the traditional pattern of Stroop effects by revealing larger interference effects earlier and late in development as compared with young adulthood. Moreover, these studies suggest that the interference is due at least in part to diminished inhibitory processes that subserve selective attention. Before accepting these findings at face value, however, it is important to note that the magnitude of negative priming effects typically is on the order of 10–20 ms, and as noted in the Introduction, one might question the statistical power of developmental investigations to detect small effects in light of the large RT variability that characterizes the performance of young children and older adults.

### 2.2.3. *Developmental themes*

At the beginning of life, filtering effects (i.e., involuntary perceptual intrusions and response activation) are among the largest attentional effects to be observed in children. They are ubiquitous and almost impossible to diminish with special instructions or training. In a similar vein, the studies of negative priming in older adults converge on the notion of decreased inhibitory processing in later life. Although this life-span picture replicates the essential features of the Stroop data reported by Comalli et al. (1962), it is complicated by stimulus-cued filtering results on the part of children (Akhtar and Enns, 1989) and nonsearch filtering performance on the part of elderly adults (Plude and Hoyer, 1986). These findings suggest that the apparent filtering 'deficit' is not attributable to the absence of a functional filtering mechanism. Instead, the mechanism seems not to be fully controlled by the strategic processes of either young children or aged adults.

Perhaps one clue to understanding why young and old can filter efficiently under some conditions centers on the role of spatial localization in nonsearch versus negative priming studies. In nonsearch tasks, the target's location is pre-determined, whereas in the typical negative priming task, the target's position is randomized across trials, thus necessitating both localization and identification for correct performance. The joint demands of locating and identifying targets (and distractors) may precipitate larger distractor interference effects among the elderly at the same time that the joint processing overloads inhibitory processing. Although this proposition is speculative, it is noteworthy that requiring only a location response on the part of children (Tipper and McLaren, 1990) and older adults (Connelly and Hasher, 1993; Schwartz et al., 1993) yields negative priming effects comparable to those obtained with young adults.

More generally, the life-span pattern of interference effects suggests a developmental pattern of increasing control over selective attention, including both the active facilitation of task-relevant stimuli and the active inhibition of task-irrelevant stimuli. The notion of increasing control over attention (Flavell, 1977) and perception (Gibson, 1969) has long characterized the child development literature. The notion of decreasing control over selective attention has been vigorously debated over the past two decades in the cognitive aging literature (Layton, 1975; Madden, 1990b; Plude, 1990). The proposition of impaired selective attention and the ensuing debate have been fueled not only by the findings reviewed above, but also by the findings reviewed in the next section.

## 2.3. *Searching*

One popular laboratory attention task comes very close to a kind of behavior we engage in almost everyday. We leave a grocery store and try to locate our car in the parking lot; we arrive at an airport and scan the crowd for a glimpse of someone we love returning from a trip; we go to a bookstore in search of a book on our favorite topic. All of these examples involve searching for a particular constellation of visual attributes. In one sense, then this task is very much like filtering, where only certain attributes are of relevance and therefore at the center of our attention. What gives searching its unique status is that it also contains the important aspect of orienting. This orienting, unlike that of the previous section, however, is no longer entirely reflexive. In many situations we must engage in a voluntary and deliberate set of actions in order to find the object of our search. We must move our attention deliberately from item to item. Sometimes, we will conclude that the object of our search does not exist, at least not in the place we were looking, and so discontinue our search.

### *2.3.1. Eye movements*

The eyes have long been said to be the window to the mind – this is nowhere more true than in the searching literature, where eye movements and fixations are seen as a window on the mind's eye. Ever since the technology to record eye movements became available, researchers have used to it to study the influence of meaning, intention, and expectation on visual perception (Antes and Pentland, 1981; Findlay, 1981; Stark and Ellis, 1981; Yarbus, 1967).

Although most adults inspect visual displays very systematically in order to detect a target that may be present, children do not show much systematicity until the early school years – 6 and 7 years (Cohen, 1981; Green et al., 1983). As mentioned earlier, newborns scan only a limited portion of any object placed into their visual field – usually a border contour or corner. By 1 month, infants' eyes are often drawn toward one distinctive feature, which they then dwell on it as though their eye-movement system had been held hostage. Between 2 months and 3 years children scan much more of a stimulus, but still with relatively little systematicity.

The classic eye-movement work in children was conducted by Vurpillot (1968) who monitored the eye movements of children between 2 and 9 years. They were presented with pictures of houses containing different windows and asked to indicate whether the houses were the same or different. Younger children were inefficient in several ways, including not terminating a search even after two different windows had been inspected, and responding 'different' even when houses with identical windows had been compared. It is unlikely that these age changes reflect fundamental differences in eye-movement control and accuracy, since by 3 years of age children can initiate eye movements and control saccades with adult-like efficiency (Kowler and Martins, 1982). Whether the same conclusion holds true for so-called 'express' saccades (which are of very brief duration; e.g., Fischer and Breitmeyer, 1987) remains to be determined.

Within the aging literature, few investigations have examined eye movements directly, perhaps because of the many difficulties encountered in calibrating eye-movement equipment for individuals sporting bi- or tri-focals and eye structures that have undergone considerable age-related changes (Fozard, 1990; Klein and Schieber, 1985). Nonetheless, in the few studies that have been conducted, the major age effect centers on the increased latency of eliciting saccadic movements (e.g., Carter et al., 1983; Rabbitt, 1982). In all other respects, older adults appear to have control over eye movements on par with their younger counterparts. Although it may be tempting to attribute visual search decrements to differences in saccadic latency, the findings reviewed below have been replicated in constrained viewing situations in which stimuli are presented too briefly for eye movements to play a role. Nonetheless, it is important to recognize that other visual changes (at both ends of the life span) may impose 'data limits' that contribute to the obtained patterns of age effects (see Ahktar, 1990, on child research and Scialfa, 1990, on aging research).

### *2.3.2. Visual search*

One of the most popular tasks in the attention literature is that of visual search (e.g., Treisman, 1986; Treisman and Gormican, 1988). Subjects are asked to look for a target item that is present on a random 1/2 of the trials and to respond with a simple 'present' or 'absent' response. The primary independent variable is the number of total items in the display. Broadly speaking, two different patterns of results are often reported in such tasks. The first, typically taken as evidence of serial search, is a linear (or at least monotonic) increase in RT and/or errors as a function of display size, accompanied by a much steeper (often 2 times steeper) increase for 'absent' than for 'present' responses. The second pattern of results, typically taken as evidence of perceptual pop-out or parallel search, is a relatively flat or shallow increase in RT ($<10$ ms per item) and errors as a function of display size, with very little difference, if any, between 'present' and 'absent' responses. Subjects' eye movements and fixations are rarely monitored in these experiments, and when they are (Klein and Farrell, 1989), the RT and error pattern do not seem to be affected.

The conventional way to interpret these two patterns of results is given by feature integration theory (Treisman, 1986; Treisman and Gelade, 1980; but see Duncan and Humphreys, 1989, and Bundesen, 1990, for alternative interpretations). This theory proposes that simple visual attributes such as color, orientation, and length are registered automatically in independent spatiotopic maps. Thus, if a search task can be performed by monitoring one of these maps for unique activity (e.g., a red target against a background of green distractors) there will be no influence of increasing the number of distractors, and pop-out search will result. In contrast, if a search task requires feature information from two separate maps to be coordinated (e.g., a red vertical target against a background of red horizontal and green vertical distractors) then a serial mechanism is required to inspect each spatial location in the display in turn. Attention, in this theory, is therefore a consequence of the divide-and-conquer strategy of the preattentive visual system, which in order to register so much information rapidly, must store it in separate feature maps.

Very few researchers to date have investigated the differences between simple feature search and feature conjunction search in children. Of these few studies, all report that school-age children are no different from adults on simple feature search tasks involving brightness, color, or orientation – there is little or no influence of increasing display size, although there are the expected age-related decreases in RT intercept (Enns et al., in preparation; Kaye and Ruskin, 1990). In sharp contrast to this is children's performance on conjunction search tasks (Doussard-Roosevelt, 1989) – here there are large increases with age in search rate (i.e., measured by a decrease with age in RT slopes over display size). In attempting to determine whether younger children engage a similar conjunction search strategy as older children and adults, Doussard-Roosevelt (1989) included an 'unconfounded conjunction' condition in which the number of nontargets sharing the target's color were held constant while the number of nontargets sharing the target's shape varied with display size (see Egeth et al., 1984). Similar to the older children and adults, preschoolers exhibited mixed parallel and serial search in the unconfounded condition: Serial search was confined to those items sharing the target's color. Thus, it appears that younger children engage in strategic processing that is similar to that of young adults, however, more research on this issue is needed.

In another recent attempt to determine which of several aspects of the conjunction search task was critical for obtaining these age-related differences, Enns et al. (in preparation) compared a standard conjunction search task (multiple items in a spatial array) with the same task in which only one item was presented at a time. In one condition these single items were presented at the center of the screen (known location), in another they were presented at any one of the many locations that were possible in the standard task. Interestingly age differences were observed only in the standard task, that is, when multiple items were spatially arrayed across the visual field. This suggests that there is nothing about feature conjunction processing per se, that is difficult for younger subjects. Instead, it is the operations involved in moving attention from one item to another that seem to be changing with age. Clearly, further work is needed to determine which of these movement operations are responsible (e.g., having a systematic plan for inspecting all items, tagging items that have already been inspected, disengaging attention from a nontarget item, moving to the next candidate item, and so on).

Visual search tasks have been a mainstay of research on aging for over a quarter century (Plude, 1990), and although older adults usually exhibit age decrements (in the form of increased search slopes) the magnitude of decrement can be minimized and sometimes eliminated completely by manipulating characteristics of the search task. Rabbitt's (1965) classic demonstration of an age decrement in visual search set the standard against which other visual search studies can be compared. In that study, young and elderly adults sorted specially prepared cards into various piles depending upon which of two or eight targets appeared on the card. The targets were accompanied by either 0, 1, 4, or 8 distractor letters, and older adults were slowed more dramatically than younger adults as a function of the number of distractors (i.e., display size). Although Rabbitt (1965) attributed this outcome to an age decrement in the ability to ignore irrelevant information, the studies reviewed above in the section on 'Filtering' challenge this interpretation. Hence, much research has been devoted to determining the boundary conditions of the age decrement in visual search, and identifying underlying mechanisms (Madden, 1986; Plude and Hoyer, 1985; Plude, 1990). To date, age decrements in visual search have been attenuated by a host of manipulations including target–nontarget categorization (Madden, 1982), spatial cuing (Madden, 1984), and consistent practice (Madden and Nebes, 1980; Plude and Hoyer, 1981; Plude et al., 1983). Although there is some debate over the specific benefits associated with extensive periods of consistent practice in visual search tasks (see Fisk et al., 1988; Fisk and Rogers, 1991) typically such practice attenuates important aspects of age-related search deficits (Madden and Plude, 1993).

Recently, Plude and Doussard-Roosevelt (1989) reported an investigation in which the standard age decrement in visual search was completely eliminated. Both young and elderly adults were required to conduct simple feature search and conjunction search as described above. Whereas the conjunction search condition yielded the standard age decrement in visual search, with search slopes for older adults being nearly twice as steep as those of younger adults, the feature search condition yielded zero slopes (denoting pop-out) on the part of both young and elderly adults (see also, D'Aloisio and Klein, 1990). In an attempt to determine strategic factors underlying age-related search effects, a third, unconfounded condition was included (see Doussard-Roosevelt, 1989). In this condition, older adults produced search slopes that were comparable to those of young adults (i.e., involving mixed serial and parallel components), suggesting that similar strategies were employed by both age groups. Within the context of feature integration theory, these findings suggest age-preservation of feature-extraction processes coupled with age-impaired feature integration processes. Regardless of the particular theoretical framework, it is clear that older adults are not always deficient with regard to visual search. Moreover, there is accumulating evidence to suggest that within expert domains, such as skilled radiography, older experts outperform younger novices despite exhibiting normative search decrements on standard visual search tasks (Hoyer, 1990).

There are several alternative interpretations of age effects obtained in visual search experiments. One possibility that has been investigated and essentially dismissed centers on the notion that older adults are deficient in ignoring irrelevant information. The findings reviewed above regarding filtering in nonsearch tasks do not support this interpretation, and neither do the findings in feature tasks and spatial cuing tasks as outlined above. Another possibility that has been subjected to empirical study centers on the requirement of distributed or divided attention in search tasks. Nonsearch tasks can be construed as 'focused attention' situations because attention can be centered on the pre-determined location of the relevant display position. Search tasks, on the other hand, require several display positions to be monitored (and compared) in order to determine whether or not they contain the target. Perhaps older adults are deficient with respect to divided attention skills.

Although some studies have reported age-related divided attention decrements (Salthouse et al., 1984), other studies have not (Somberg and Salthouse, 1982). In a systematic comparison of focused and divided attention situations, McDowd and Craik (1988) found that task complexity influenced the magnitude of age effects even more so than did the attention manipulation. This finding led them to conclude that divided attention situations are more complex than focused attention situations, and that it is the differential complexity of such tasks, rather than the requirement to divide attention per se, that mediates age decrements in divided attention situations. Thus, it appears that age decrements in search, when they are obtained, are not due to the requirement to distribute attention across display positions in a visual search task (see also the section above on the 'Attentional gaze' and Plude, 1990).

In an attempt to decompose adult age effects in search, filtering, and the attentional gaze, D'Aloisio and Klein (1990) directly compared age effects in a nonsearch filtering task modeled after Eriksen and Eriksen (1974), a visual search task modeled after Treisman (1986), and an attention gaze task modeled after LaBerge (1983). They found that whereas the overall pattern of age effects pointed toward the preservation of the spatial dynamics of attention, intercorrelations between the three tasks revealed an age decrement in disengaging from an attended location. One consequence of this age decrement, as yet untested, is that the costs and benefits obtained in covert orienting should be correlated with the speed of visual search among older adults but not among younger adults. As stated earlier in discussing covert orienting among young children, further research is needed to determine whether or not this age effect might also reflect a breakdown in the mechanism underlying inhibition of return.

The main contribution of these kinds of integrative developmental studies is their identification of underlying mechanisms that may account for patterns of age differences and similarities. We encourage continued efforts along these empirical lines, especially those including a life-span orientation, since it is only with the aid of such data that more all-encompassing models will be developed.

### *2.3.3. Developmental themes*

The life-span data concerning visual search reveal stable and consistent age differences early in life, with the selectivity and efficiency of visual search improving throughout childhood, and more variable decrements later in life, with the magnitude of decrement influenced by a host of factors. Although the aging literature shows that the efficiency of search is preserved in skilled domains, and that elderly adults derive benefits at least on par with younger adults from 'environmental support' (Craik, 1986) in the form of distinctive features, category differences between targets and distractors, and practice, the basic deficit in 'standard' visual search persists nevertheless. How best to conceptualize these findings is a point of some controversy and relates directly to alternative theories of the development of attention which are addressed more fully in the 'General discussion' section.

## *2.4. Expecting*

So far we have reviewed mechanisms for orienting, which draw our attention to conspicuous objects, operations involved in filtering, which allow us to attend to only those stimuli of relevance to us, and strategies of searching, which allow us to investigate likely locations of stimuli important to us. However, sometimes we have specific advance information about where and when an event will occur – we will refer to such an attention task as expecting. Expectancy information can come either from relatively new information we have just learned (we will call this form of expectancy *priming*), or from information we have already stored in long-term memory (we will call this *prompting*).

### *2.4.1. Priming*

Probably the simplest demonstration of the effects of information priming involves the cost–benefit procedure that was introduced in the 'Orienting' section. There it was used to study the nature of the reflexive orienting response generated by sudden events in the visual field. However, Posner (1980) also used it to study the voluntary (also called endogenous) orienting of attention to locations in the visual field. Instead of the orienting cue being a bright flash of light in a potential target location, the cue was now an arrow appearing at fixation, but pointing either to the right or left. On 80% of the trials involving an arrow, the target actually appeared in the location signaled by the arrow (valid trial). On the remaining 20% of these trials, it appeared in the noncued location (invalid trials). Neutral trials were also included in which the arrow was replaced by a plus sign and targets were equally likely on the left and right. Observers were not allowed to move their eyes from the fixation point for the duration of the trial; they could only orient their 'mind's eye'.

Results from tests of adult subjects in this procedure are very similar in some ways to the reflexive orienting studies: RTs reveal both a benefit on valid trials (valid RT is shorter than neutral RT) and a cost on invalid trials (invalid RT is longer than neutral RT). However, there are also some important differences. First, the time required for attention to shift in this task is much longer – the cue-onset to target-onset duration (the SOA) that produces maximum costs and benefits is around 300–500 ms rather than 50–100 ms (Shepard and Muller, 1989). Second, information cues can be easily ignored, unlike abrupt stimulus cues, especially if the subject discovers that they are often wrong (Jonides, 1981). The orienting made in response to information cues can also be easily interrupted by other attention-grabbing events (Muller and Rabbitt, 1989). Third, the benefits and costs of these cues can be sustained for quite a long time (i.e., more than a second), with no evidence of an inhibition of return effect, as seen for stimulus cues (Rafal et al., 1989).

There have only been a few studies to date on voluntary visual orienting (based on information cues) in school-age children. In one study (Pearson and Lane, 1991b, Expt. 2) the orienting effects of stimulus and information cues were compared in 8- and 11-year-old children. Even 8-year-olds showed strong orienting effects in response to an arrow cue that was valid 80% of the time. This effect was already present with a cue–target SOA of 83 ms, although it was even larger with longer SOA intervals.

In another study, children aged 6, 8, 11 years, young adults aged 20 years, and senior adults aged 65 years or more, were all examined with the same methodology (Brodeur and Enns, in preparation). The subject's task was to discriminate an 'O' from an 'X', that is to make a simple visual discrimination. The target shape was presented in one of four possible locations in a horizontal array and was preceded by arrow cues that were 80% valid (single arrow for near location, double arrow for far location, and plus sign for neutral cue). Cue–target SOA was varied between 130–800 ms and subject's eyes were monitored for movement. The results showed a strong orienting effect in the RT data for all ages, although there were some important age differences – the cue–target SOA that resulted in the largest orienting effect varied with age. For all three groups of children, as well as for adults, the orienting effect was already maximal at the shortest SOA values. However, for the senior adults, only the longest SOA values revealed a sensitivity to the cues. One way in which the children differed from the young adults was in their ability to sustain the attentional set in response to the cue – orienting effects diminished relatively quickly for the children (by an SOA of 400 ms), but were maintained at a high level by young adults through 800 ms.

Considerably more research has addressed voluntary orienting among younger and older adults. This research has been driven in part by the notion that voluntary orienting represents an elementary cognitive process that is under direct conscious control. Some of the first research was conducted by Nissen and Corkin (1985) who presented symbolic spatial cues at SOAs of either 2 or 3 seconds prior to a target's appearance at either the left or right side of central fixation. Older adults exhibited larger costs and benefits compared with younger adults in this situation, however, the long SOAs employed leave open the possibility that eye movements mediated the effects rather than attentional shifts per se. Subsequent research involving symbolic cuing has indicated comparable costs and benefits among young and elderly adults. For example, Madden (1983) obtained comparable benefits for young and elderly adults when a central cue designated which two of four display positions would contain the target letter. Similarly, Hartley et al. (1990, Expt. 2) obtained comparable cuing effects for young and elderly adults when a central cue indicated the likely position of a target in a circular array centered at fixation. Moreover, the time course of cuing was comparable across age groups. Although Hoyer and Familant (1987) also obtained roughly comparable costs and benefits across age groups with centrally-located information cues, the time needed to obtain this effect was longer among elderly than younger adults. Hartley (1992) has suggested that this longer time may owe to the nature of the simple detection response required in their procedure. Unlike other studies that involved a recognition response (e.g., which target letter is present?), Hoyer and Familant's study required subjects to indicate which of four horizontally arrayed boxes contained a luminance increment. Hartley suggests that cuing in this situation may lead to response priming that takes longer to accumulate and disperse in later adulthood. Another possibility is suggested by Folk and Hoyer (1992) who found no benefits of information cues among older adults (Expt. 2) unless those cues were easily encoded (Expt. 3), in which case approximately equal benefits (and costs) were obtained among young and elderly adults. Because these effects varied across cue–target SOA, Folk and Hoyer concluded that the age-related time course of cuing depends upon the symbolic processing demands (i. e., complexity) of the cue. Thus, although the spatial dynamics of voluntary orienting are comparable for young and elderly adults, the time required to encode symbolic cues appears to be a function of advancing adulthood age.

In summary, several investigations in the aging literature have established that the magnitude of costs and benefits associated with central cues is roughly comparable for young and older adults, but there is some disagreement regarding the time course of these effects. These discrepancies in time course may be due to varying task demands in different studies (Hartley, 1992; Plude and Doussard-Roosevelt, 1990), or to a more variable allocation of attention over trials by older adults than younger adults (Madden and Plude, 1993). This debate over time course notwithstanding, there is consensus on the preservation of voluntary covert orienting in later adulthood. Moreover, recent evidence suggests that comparable patterns of costs and benefits are obtained regardless of whether the cues are presented symbolically (endogenous orienting) or concretely (exogenous orienting) for young and elderly alike (Folk and Hoyer, 1992).

### *2.4.2. Prompting*

In order to perceive and compare stimuli efficiently, an individual must not only be able to orient to the appropriate spatial locations and be able to register the information there, but the individual must also be able to remember information from previous glances and schemata associated with entire classes of stimuli. When this information is shown to influence visual processing, it is called *prompting*.

Studies that have directly compared the ability of school-age children to encode (merely register) versus remember (recall or recognize) visual stimuli indicate that the largest developmental changes lie in the memory component. For instance, when children are presented with a 100 ms flash of eight items arranged in an imaginary circle, they are able to report the identity of the items with adult-like accuracy, provided that the stimulus prompt (a small visual marker) appears within 50–200 ms after the onset of the display (Morrison, et al., 1974; Sheingold, 1973). As the display-prompt SOA increases in length, the accuracy of the children falls away from that of adults very rapidly. Other studies have come to similar conclusions by varying both the spatial and the temporal intervals between pieces of information that must be integrated (Enns and Girgus, 1986; Enns and King, 1990).

A useful procedure for directly comparing effects of perception (bottom-up processing) with those of memory (top-down processing) was designed by Sebrechts and Garner (1981). Subjects were given a sequential same–different task in which the stimulus factors to be compared could be manipulated by the experimenter independently in the two temporal positions. This task was used to study the perception and memory of simple visual forms in subjects aged 6–22 years (Enns, 1987). On each trial subjects simply had to report whether the two patterns were the same or different – the critical manipulation involved the degree of symmetry in the forms being compared. This study showed clearly that age-groups differed only on their ability to compare forms in memory – here the effect of symmetry changed considerably with age. There was no difference in the efficiency with which various-aged subjects were able to encode the forms – here subjects of all ages showed a similar advantage for symmetrical forms.

One way prompting has been studied in the aging literature is very similar to the standard priming procedures (see previous section), except that the prompt now depends on information stored in long-term memory (Madden and Plude, 1993). For example, Hartley et al. (1990, Expts. 4 and 5) prompted young and elderly adults about the type of decision required for stimuli presented in a visual display, (i.e., letter or color response) and found not only equivalent costs and benefits for both age groups, but also age-equivalent time courses for these effects. Madden (1984) also found comparable age-related costs and benefits with prompts that informed about the likely set of targets in a visual search task. Madden (1985) replicated the age-equivalent prompting effect in another experiment in which prompts indicated which of two targets would be *less* likely in the display. However, in this study younger adults exhibited prompting effects at shorter SOAs than did the elderly, indicating age-related slowing in memory-driven selective processing.

Other approaches to prompting have also yielded evidence of age decrements in memory-driven selection. In a study involving prompts that conveyed the alphanumeric category membership of stimuli to be classified, Rabbitt (1964) found that younger adults derived benefits from the prompts relative to a no-prompt control condition. In contrast, older adults did not show this advantage. This age difference was not due to the older adults ignoring prompts, because on invalid trials both age groups exhibited RT costs relative to the no-prompt control condition. In another approach to prompting, Rabbitt and Vyas (1980) examined stimulus–response repetition effects among young and elderly adults. Although both age groups benefited from the repetition of a physically-identical target, only younger adults exhibited benefits when physically-different but response-compatible targets were repeated. This may indicate differential sensitivity on the part of the elderly to the processing demands of relatively late response-selection stages of processing (Greenwood and Parasuraman, 1991).

### *2.4.3. Developmental themes*

With regard to priming effects, the literature is somewhat mixed, but suggests that priming effects can be observed at least as early as the beginning school years. However, there are clearly additional improvements in efficiency that occur in later childhood. Several studies have shown that the time course and pattern of cuing costs and benefits in Posner's spatial cuing task are comparable for young and elderly adults, at least once the complexity of the task is taken into account. In contrast, when the advance information is conveyed more subtly in the form of prompts, which require memory-driven selective processing, then age decrements ensue.

Prompting procedures appear to consistently show developmental differences that persist longer at the beginning of life and more severe deficits in later life.

Even the simplest of memory cuing tasks leads to age-differences in school-age children, suggesting that schema formation and strategy maintenance are effortful and attention-demanding for children. Similarly, many prompting tasks reveal age-related declines in performance at the other end of life, suggesting that memory-driven processes are suffering disproportionately with advancing age.

## 3. General discussion

### *3.1. Summary of life-span review*

Clearly the life-span developmental picture that emerges from our review of the four components of selective attention represents diversity. Consistent with the multidimensionality of both the attention construct and life-span developmental theory, the developmental patterns observed do not converge on a single, linear progression. Rather, the findings suggest a complex pattern of growth and development, with different components of selective attention exhibiting different developmental patterns. We briefly summarize the developmental patterns within each component before identifying emergent themes.

Of all the components, orienting exhibits the largest degree of developmental stability across the life span. The orienting reflex is present at birth and is essentially spared by aging. Some data suggest, however, that the selectivity of the orienting reflex peaks at maturity and tapers off thereafter. Although such evidence has important implications regarding inhibitory processing, it does not negate the fact that the orienting reflex can be seen very consistently across the life span.

Covert orienting in response to sudden-onset stimulus cues is also exhibited across the entire life span, at least in all ages that it has been possible to test. Thus, young children and older adults can both orient attention in space in the absence of head and eye movements, and furthermore, can adjust the size of their attentional gaze in accordance with task demands. Reports of developmental differences in the extent of attentional gaze can be attributed, in large part, to differences in its strategic control rather than in its fixed size. Also, whereas the dynamics of spatial covert orienting in response to a sudden stimulus onset are similar across the life span, the ability to disengage attention from such a stimulus appears to be compromised both in early and later life.

Life-span data on filtering suggest a more complicated developmental picture. Interference effects in the form of involuntary perceptual intrusions and response activation are among the largest attentional effects observed in children; they are ubiquitous and nearly impossible to diminish. Although exaggerated interference effects occur among the young and the elderly in Stroop-type tasks, these effects can sometimes be greatly attenuated when location information (e.g., spatial precuing in children, targets at known locations in older adults) is available to aid in filtering. Overall, the life-span data suggest a developmental pattern of increasing control over selective attention, including both the facilitation of task-relevant stimuli and the inhibition of task-irrelevant stimuli, throughout young adulthood, followed by selective preservation in later adulthood. The notion of selective preservation accommodates the finding that when appropriate environmental supports are available, older adults are equally as effective as younger adults in filtering out irrelevant stimuli.

The data concerning visual search reveal stable and consistent age differences early in life, with the selectivity and efficiency of visual search improving throughout childhood, and more variable decrements later in life, with the magnitude of decrement influenced by a host of factors. Although the aging literature shows that the efficiency of search is preserved in skilled domains, and that elderly adults derive benefits at least on par with younger adults from environmental support in the form of distinctive features, category differences between targets and distractors, and practice, the basic deficit in 'standard' visual search persists. The notable exception to this trend in the search data concerns pop-out search for targets defined by simple distinctive features. To the small extent that it has been investigated, features that pop out in search tasks for young adults do the same in tests involving young children and older adults. This form of search thus bears a strong resemblance to automatic covert orienting in both task demand (i.e., detect the presence of an abrupt change in visual attribute) and life-span pattern (i.e., stability over age).

With regard to priming, the literature is somewhat mixed, but suggests that information cues can be used strategically at least as early as the beginning school years. However, there are also improvements in the efficiency of voluntary spatial orienting that can be seen in later childhood. Whether older adults consistently require more time to use information cues than younger adults is still open to further study. Prompting studies appear to consistently show developmental differences that persist longer at the beginning of life and result in larger deficits in later life. Even the simplest of memory cuing tasks leads to age differences in school-age children, suggesting that schema formation and strategy maintenance are effortful and attention-demanding. Similarly, many prompting tasks reveal age-related declines in performance at the other end of life, suggesting that memory-driven processes are suffering disproportionately with advancing age.

### *3.2. Emergent themes*

Although the four components of selective attention yield divergent age trends, there are several emergent themes. For example, despite different patterns among the various components, there is evidence of a degree of developmental consistency at a higher-order level – the components that show little change at the beginning of life are also usually those that are relatively stable at the end of life (e.g., automatic covert orienting, pop-out visual search); components that change dramatically with development are also likely to do so at the other end of the life span (e.g., visual filtering of distractors, visual search for attribute conjunctions).

A second theme that emerges is that age effects tend to be associated with those components of selective attention that are also more effortful for young adults.

That is, to the extent that a task places heavier demands on a limited-capacity or task-sharing system in college students, it also is slower to develop and more difficult to maintain in later life. For instance, visual search tasks that demand serial inspection of items or display regions in young adult subjects also yield substantial age effects at both ends of the life span; whereas covert orienting in response to stimulus cues (involuntary) exhibits relatively meager age effects if any. We recognize that this theme borders on tautology: age-related selective attention effects are most easily observed under conditions requiring the largest amount of selective attention. However, evidence from both mainstream experimental psychology and cognitive neuroscience converge on a distinction between so-called automatic (effortless) and controlled (effortful) processes, and identifying a developmental theme related to this distinction has established precedents (e.g., Hasher and Zacks, 1979).

Before moving to a consideration of theoretical conceptualizations that may accommodate these themes it is important to sound a cautionary note. We must be careful not to confuse similarities in developmental trajectories with similarities in underlying mechanisms. Although it is tempting to draw parallels between developmental progressions early in life and age-related decrements later in life, doing so runs the risk of underestimating the complexities of attentional development. Thus, for example, life-span developmental functions may be influenced to a greater or lesser degree by biological and environmental factors (and their interaction) at different points in the life span (Baltes et al., 1980). For example, one possibility is that changes in selective attention are driven largely by maturational processes early in life and by environmental influences later in life. Thus, the increasing control over selective attention that characterizes early child development may reflect, for example, the myelinization of neural pathways that support selective attention mechanisms; the selective preservation of various aspects of selective attention in later adulthood may reflect the accumulation of age-normative (common to age group) and non-normative (unique to individual) experiences associated with, for example, the development of expertise in particular domains (see, for example, Rybash et al., 1986).

### *3.3. Models and theories*

At the outset we stated that there exists no life-span developmental theory of selective attention, and little if any life-span research on this topic. However, it must be noted that there has been some life-span research on visual perception (Comalli, 1970; Pollack and Atkeson, 1978). Although the database for these studies is largely comprised of tasks testing for susceptibility to classic perceptual illusions, some of the pioneering work by Werner and his colleagues (Comalli et al., 1962) did involve the Stroop task. In light of the necessarily fuzzy distinction between attention and perception, and because some of the perception research relates to Werner's (1948, 1957) *orthogenetic principle*, it is perhaps appropriate to consider first the viability of this theory for the data we have summarized.

The orthogenetic principle holds that development follows a specific and predictable trend from disorganized and global perception early in life, to differentiated and hierarchically integrated perception in maturity, with regression back to a disorganized state late in life. The idea of a progressive advancement toward increasingly differentiated levels, followed by regression to chaotic states is not perfectly compatible with the diverse findings reported here. Although it appears to hold for some components of attention (e.g., inhibitory processes underlying the selectivity of the orienting reflex), it clearly does not apply to others, (e.g., covert orienting and filtering). Just as in evolutionary theory, where the orthogenetic principle has been found unsatisfactory in accounting for phylogenetic development (see Gould, 1977), so too here it appears overly restrictive. Any model calling for progressive differentiation, increasing control, and increasing flexibility throughout the early part of the life span, followed eventually by regression back to child-like modes of attentional function simply does not withstand the summarized empirical data.

Gould (1977) argues that the traditional metaphor of a branching tree, which abides by the orthogenetic principle, is not consistent with Charles Darwin's ideas regarding selective survival as put forth in the *The Origin of Species* (1859) and the *Descent of Man* (1871). The branch metaphor suggests a linear evolutionary sequence in which ever-more complex species evolve from their less complex forbearers, giving rise to elusive 'missing links' in the evolutionary record of species. As an alternative, Gould suggests the metaphor of a dense bush whose branches are periodically pruned by nature. This allows for parallel evolutionary sequences, some of which are adaptive and others not – at any moment in time only the tips of adaptive branches are in evidence, the pruned ones cannot be seen. Thus rather than being direct descendants of primitive hominids, for example, humankind would have evolved along a separate but parallel line from other primates.

Might the ontogeny of selective attention recapitulate this theme? That is, rather than selective attention comprising a single construct with a fixed ontogenetic plan, might it be better conceptualized as a multidimensional construct with separate, parallel developmental trajectories for different components. To carry the analogy still further, might the specific developmental progression for a particular component of selective attention be determined by the adaptive fit of that component with the individual's 'environmental press'? Although such a conjecture rekindles the tenet of *ontogeny recapitulates phylogeny* long since abandoned in physiological development (e.g., Dixon and Lerner, 1985), we suggest that it may nonetheless provide an overarching framework within which to cast life-span research and theory on the development of selective attention. Moreover, invoking Darwin's ideas on selective survival brings to the forefront the interplay between biological and environmental forces that is the crux of the contextual perspective underlying life-span developmental psychology.

At the very least, a comprehensive life-span theory must incorporate a contextual perspective allowing for selective development and selective preservation of certain components of attention. Because attention can be construed as a set of mechanisms by which perceptual analyses are brought to bear on the goals of the observer (e.g., Gibson and Spelke, 1983), it seems necessary to include a contextual element, perhaps akin to task dependency, because selective attention should operate with respect to the momentary demands of information processing. The pattern of developmental effects may therefore depend upon the particular context within which the performance is assessed.

Although we are unable to identify a life-span developmental theory that adequately accommodates the findings reviewed above, it is possible nevertheless to consider theories/hypotheses that have been derived separately within the child development and adult-aging literatures in order to evaluate their suitability as candidates for a life-span theory. These theories tend to cluster in two broad classes: theories that postulate general mechanisms of development, and those that postulate more specific or local mechanisms.

### *3.3.1. General mechanisms*

Three popular theories of generalized mechanisms are: resource allocation, speed of processing, and neural noise. In brief, the resource allocation model suggests that development comprises increasing control over attention by providing increased attentional resources (Guttentag and Ornstein, 1990; Siegler, 1983) that are initially established in childhood and eventually wane in the elderly (Hoyer and Plude, 1982; Madden, 1990a, b; McDowd and Birren, 1990). One way to conceptualize such resources is in the form of 'working memory' (Baddeley, 1986) which appears to gain efficiency throughout childhood (Case, 1985) and lose efficiency during later adulthood (Salthouse, 1990). Note that unlike the dogma of the orthogenetic principle discussed earlier, however, the idea here is that age differences will not always be obtained but rather will depend upon the demand placed on limited capacity resources. Thus, when resources are low, either because of immaturity early in life or senescent processes later in life, selective attention will be impaired. Despite its widespread appeal in the developmental literature, however, the focal deficiency with the resource allocation model is defining exactly what is meant by processing resources (see Chapman, 1990, Navon, 1984, or Salthouse, 1991, for excellent reviews).

An alternative model centers on the speed of information processing as opposed to the capacity of processing resources. According to the speed-of-processing view, age-related information-processing effects rest entirely upon the speed of elementary cognitive processes. Thus as tasks become increasingly complex (i.e., require more processing steps) age effects will likewise increase. The central strength of this model is its parsimonious account of a wide range of age-related behavioral data (see paper by Cerella and Hale, this issue). Despite this strength, however, the speed-of-processing model is not without its limitations. First, as argued by Salthouse (1985, 1991), it is almost impossible to distinguish this account from the resource allocation model described above and is therefore prey to the same pitfalls. Second, its parsimonious account may be an artifact of the very RT data it intends to explicate (e.g., Fisk et al., 1991). Third, it fails to incorporate coordinated consideration of error rate data (Cerella, 1990). In addition to these limitations, the speed of processing account, which stipulates age-associated slowing in the adulthood years, cannot easily accommodate findings of age equivalent effects. Consider, for example, the data pertaining to visual search. A parsimonious account of these data might postulate a single mechanism, such as speed of processing, that comprises increasing efficiency (speed) throughout childhood, maximum efficiency at maturity, and progressive inefficiency in later adulthood. However, children and older adults do not exhibit age decrements in simple feature search, for example, and the single mechanism theory cannot easily accommodate this diversity. Although one might argue that *environmental support* (Craik, 1986), say, for example, in the form of distinctive features, could simplify information processing so that fewer stages are involved, this argument is still unsatisfactory. It is lacking because it relies upon information-processing components that themselves, rather than their speed of execution, may mediate age effects. Thus, for example, changing from conjunction search to feature search may minimize age decrements not by reducing the number of comparisons required by serial search (which it would, of course) but by eliminating an age-sensitive component of processing such as spatial localization (Plude, 1990).

The third general model postulates biomaturational processes as the mechanism of life-span developmental change. According to the neural noise hypothesis, performance will be impaired in any situation involving the selective processing of neural signals against a background of random noise, particularly when the signal-to-noise ratio is low (e.g, Welford, 1965, 1984). Such a situation would apply to the immature nervous system prior to and during the process of myelinization and to the senescent nervous system that is experiencing neuronal depletion and increased spontaneous random activity. Thus neural myelinization early in life (promoting efficiency) followed by progressive cell loss during the remainder of life (promoting inefficiency) would seem to offer an attractive and parsimonious fit to the data. One limitation of the biomaturational model, though, is its characterization of the aging processes as essentially destructive. Such a biodecrement view is incompatible with the developmental variability across components of attention identified in the current review as well as other psychological research (Baltes, 1987; Birren and Renner, 1977; Rybash et al., 1986). Although recent neural noise models have incorporated a brain–environment interaction component to accommodate different patterns of age effects across tasks (e.g., Allen, 1991; Allen et al., 1993), it seems that incorporating such compensatory mechanisms, whether they are psychological, social, or cultural, moves such models from a mechanistic orientation to a contextualistic one (Baltes and Goulet, 1970; Birren and Bengston, 1988; Labouvie-Vief and Chandler, 1978).

### 3.3.2. *Specific mechanisms*

Developmental models that focus on specific mechanisms purport that age differences in selective attention are mediated by a single process (or set of processes). For example, strategy-based models propose that age effects are due to the utilization of different strategies by different age groups. At the early end of life, for example, several theorists (e.g., Kemler, 1983; Shepp et al., 1987) have proposed that young children engage in a holistic mode of perception whereas older children and adults engage in more analytic processing. Contrary to this notion, however, the bulk of evidence indicates the existence of comparable perceptual strategies at different ages, some of which are more likely to be engaged in than others at different ages, or at least with varying degrees of competence and consistency (Smith, 1989; Ward, 1980; Ward et al., 1986). At the aging end of the life span, there is considerable evidence that elderly adults engage in comparable strategies to those employed by younger adults (Plude and Doussard-Roosevelt, 1990), including speed-accuracy emphases that are sometimes alleged to underlie age-associated RT effects (Cerella, 1990).

Another strategy-based difference at the aging end of the spectrum is not so readily dismissed. Fisk and colleagues (Fisk et al., 1988; Fisk and Rogers, 1991) have found evidence that whereas a visual search task involving a consistent mapping of targets to responses yields automatic detection among younger adults (Schneider and Shiffrin, 1977), the same does not obtain for the elderly. Whether this age difference owes to a deficit in differential strengthening of targets/nontargets as suggested by Fisk, or whether it reflects some other aspect of the task, such as the use of categorically distinct stimuli (Madden and Plude, 1993) is yet to be determined. Nonetheless, it is generally the case that where strategy differences have been examined, there is little evidence to support the notion that age differences in strategy use fully account for age differences in selective attention.

Another specific mechanism that has been alleged to account for age differences in selective attention involves various developmental differences that can be classified as so-called data limitations (Norman and Bobrow, 1975). Data limitations comprise peripheral processing factors, such as optical structures, that are sub-optimal for transmitting adequate data to central processing (attentional) structures. Data limitations can mimic resource limitations, and therefore constitute potential confounds for an unambiguous account of attentional effects. Thus, for example, impairments in the extra-foveal visual field may compromise visual search while facilitating visual filtering by reducing the clarity of stimuli occupying more peripheral parts of a visual display (Ahktar, 1990; Scialfa, 1990). However, where they have been investigated, data limitations have been unable to account exclusively for age decrements in selective attention (e.g., Enns and Brodeur, 1989; Brodeur and Enns, in preparation, for child research; and Plude and Doussard-Roosevelt, 1990, for aging research). Although the bulk of evidence indicates that data limitations alone cannot accommodate the diverse findings reviewed in this paper, we state our unqualified support for taking such effects into account within any developmental investigation of selective attention.

Another class of specific mechanisms focuses on components of information processing as the loci for age differences in selective attention. For example, Plude and Hoyer (1985) hypothesized that spatial localization underlies age decrements in visual search and age equivalence in nonsearch tasks. Specific tests of this hypothesis in the aging literature have been equivocal at best (Scialfa and Kline, 1988; Plude, 1990), and suggest that although spatial location may be an important dimension in certain selective attention tasks, it is not so across all tasks (Kinchla, 1992).

In view of the multidimensional nature of the attention construct identified in Fig. 1, we reserve judgment on the adequacy of specific mechanisms in explicating age differences in selective attention. It is our belief that developmental changes will vary as a function of the specific combinations of tasks, modalities, and processes emphasized within particular studies. We are unwilling (if not unable!) to provide closure on this issue. Our reticence notwithstanding, we consider the essential elements of a life-span theory of the development of selective attention in the next section.

### *3.4. Essential ingredients of a life-span theory*

The developmental themes identified in our review indicate that some components of selectivity undergo little change in early development and are maintained well into the later adult years whereas other components exhibit remarkable developmental change involving both increments and decrements. One theme that pervades much of the developmental work reviewed is that when environmental support is available, such as in the form of distinctive target–distractor differentiation (e.g., color, size, or form) or pre-existing information regarding the spatial location of targets and distractors, age differences in selectivity are greatly attenuated and sometimes eliminated altogether.

Environmental support may be viewed as a means of enhancing the active selection of relevant information (by making target features more salient or by isolating the target's location apart from distractors), and/or of inhibiting the processing of nontargets (by de-emphasizing their features or excluding their locations from further processing). These developmental patterns may be brought to bear directly upon recent theorizing in both developmental work as well as in the mainstream of cognitive literature that distinguishes between the active selection (or facilitative) components and the strategic suppression (or inhibitory) components of selective attention. Recent theorizing in cognitive psychology holds that selective attention comprises two complementary processes: facilitation of a selected signal (or channel) and suppression/inhibition of non-selected signals (or channels) (Cowan, 1988; Kinchla, 1992). In this conceptualization, age decrements in selective attention may be ascribed to either or both components of attention, and a central goal of current developmental research at both the early (Tipper et al., 1989) and later (McDowd and Oseas-Kreger, 1991) ends of life is to determine the relative contributions of each component to age differences in selective attention tasks. Although there is accumulating evidence that inhibitory processes may be deficient at both ends of the human life span (see Tipper et al., 1989, for childhood and Hasher et al., 1991, for aging) there is also evidence that inhibitory processes function adequately under certain circumstances as well (e.g., Connelly and Hasher, 1993; Tipper and McLaren, 1990; Schwartz et al., 1993). Thus, it may be premature to conclude that inhibitory deficits underlie the variety of age effects reported in the current review. Clearly an important goal for future research is to reconcile the discrepant findings and explore the boundary conditions of the alleged inhibitory deficit.

Another feature of the two-process model of attention is that it makes different predictions about the fate of information that is facilitated versus inhibited: Facilitated information is likely to be remembered whereas inhibited information is unlikely to be remembered (Cowan, 1988). The assessment of age-related selective attention effects has for the most part been conducted quite separately from developmental work on memory, with notable exceptions involving research within the levels-of-processing framework. Although some research (and theory) within the child and aging literatures acknowledges the probable role of attentional processes in mediating age effects in memory, few studies have explicitly tested or controlled for such effects (see, for example, Ackerman, 1990; Guttentag and Ornstein, 1990; Light, 1991; Madden et al., 1992). Thus another important goal for future developmental research (and theory) is to examine patterns of age differences and similarities at the interface of attention and memory, in hopes of providing a more comprehensive and integrated picture of life-span cognitive development.

Another feature of current theorizing in mainstream cognitive and developmental research centers on multidisciplinary efforts to integrate behavioral, psychophysiological, and neuroanatomical approaches in the study of attention (Kinchla, 1992; Posner, 1992; Posner and Peterson, 1990). This work began in the 1980s with efforts to study the electrophysiology of attention in various animal preparations, using single-cell electrode recording (Wurtz et al., 1980). More recently, this work has capitalized on technological breakthroughs which allow high resolution neuro-imaging in intact and alert human subjects (Posner and Peterson, 1990). The techniques include, but are not limited to, positron emission tomography (PET), event related potentials (ERPs), and magnetic resonance imaging (MRI) (see Posner and Carr, 1992, for review).

The picture that is emerging from this revolutionary work is one of multiple attentional centers serving different functions and distributed widely throughout the brain. For instance, there appears to be a fundamental difference between the attention functions subserved by the posterior versus anterior portions of the cerebral cortex – the posterior centers being involved in sensory and perceptual analysis of object attributes such as shape and color (temporal cortex) and the anterior centers being involved in the voluntary and strategic aspects involved in the execution of hand and eye responses. Interestingly, especially for the argument made earlier concerning the special status of location as a visual attribute, attention involving spatial location is centered in a region that is distinct from other object attributes (posterior parietal cortex). Future research and theory should therefore be able to capitalize on this work in many ways, including (a) its help in the formation of reasonable hypotheses about the rate of development of various attentional components (given other knowledge on relative rates of brain development and senescence), (b) its promise to yield direct insight into the changes that occur in the brain during the automatization of an initially attention-demanding task, and (c) its help in the formation of hypotheses concerning which attention tasks would be likely to share resources and therefore develop in tandem.

## 4. New directions in life-span research and theory

In closing, we recommend four specific avenues for future research and theory. First, we encourage continued efforts to bring multiple levels of analysis to bear on the study of selective attention and its development. As noted above, recent research and theory within cognitive neuroscience promises exciting new integrations between computational and neurophysiological levels of analysis. Coupled with more precise behavioral methods and affordable neuro-imaging techniques, these advancements should usher in better integrated and more comprehensive models of life-span attentional development. In conjunction with multidisciplinary efforts in other areas of psychology, this work should yield substantial new insights into the workings of the mind and its development in this, the decade of the mind-brain (*Scientific American*, 1992 [September]). It must be cautioned, however, that integrating the different levels of analysis, each of which differs with regard to its emphasis on molecular-versus-molar analyses, poses no small obstacle to life-span theories of attentional development.

A second recommendation stems from an inadequacy that is starkly apparent in the studies we have reviewed: longitudinal/sequential designs must be undertaken to promote a clearer picture of life-span developmental trends. Our entire review comprises cross-sectional studies of age-related selective attention effects. Cross-sectional designs are appropriate for descriptive forays into developmental phenomena but are inadequate for explicating developmental (i.e., intraindividual) functions (Baltes et al., 1977; Wohlwill, 1973). In order to tease apart cohort, time-of-test, and age effects, sequential research designs are both desirable and necessary (e.g., Schaie, 1965).

A third recommendation also stems directly from the studies reviewed: methodologies and research designs must be sought that promote age comparisons across the entire span of life. Almost without exception, the studies we reviewed compared ages at one end of life or the other. Data that clearly elucidate the different reasons for less than optimal performance at either end of life will only be available when: (a) researchers are able to make comparable measurements on subjects across a wide range of ages, and (b) the measurements themselves distinguish the various cognitive components contributing to a given behavioral response.

Finally, we recommend that empirical studies and theory construction be undertaken within a context that includes optimization and intervention as long-term goals. Evaluating patterns of age effects in the facilitative and inhibitory aspects of selective attention, and establishing their connection to age-related memory function would not only provide a more comprehensive and integrative developmental theory, but would also promote the development of attention-based training regimes for compensating memory (and other cognitive) deficits commonly associated with early childhood and aging. Taking the lead from closed-head injury rehabilitation programs, attention-based training strategies will likely prove to be valuable adjuncts to currently available memory/cognitive interventions for ameliorating age decrements (Ben-Yishay et al., 1987; Posner and Rafal, 1987). The goals of optimization and intervention are inextricably woven into the fabric of a life-span developmental psychology (e.g., Baltes et al., 1977) and should therefore be carried over as central themes in the study of selective attention over the life span.

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