Selective Attention Over the Life Span: Behavioral Measures

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In this chapter we highlight some of the emerging patterns we have seen in our research on the development of visual attention over the life span. We began our studies of visual attention in children over 10 years ago (e.g., Enns & Brodeur, 1989; Enns & Gignus, 1985), but it is only within the past few years that we have begun to compare the trends observed at the beginning of life with those at the other end of life (Brodeur & Enns, 1997; Phuget, Enns, & Brodeur, 1994; Trick & Enns, in press; Trick, Enns, & Brodeur, 1996). We hope the following story will explain why we have been at times very optimistic, and at other times more cautious, about the possibility of linking behavioral changes over the life span to theories of development, theories of attention, and to the growing understanding of the underlying neural basis of both attention and development.

Our motivation in this work has been threefold. First, data from life-span studies are relevant to theories of perceptual and cognitive development. Some theories propose that development primarily reflects the changing effects of experience and knowledge on task performance (Chi, 1977; Roth, 1985). In childhood, performance improves with age because of the associated changes occurring in various skill domains. The young child as “novice” eventually becomes the older child and young adult as “expert.” Other theories account for life-span change with general biological mechanisms that are believed to wax and wane in a large inverted U-shape (Kail & Salthouse, 1994; Salthouse, 1985, 1991). They begin with the premise that the speed of any performance is limited by the maximum rate at which...
elementary cognitive operations can be executed. This limit is set by factors that would have very general consequences, such as the number of transient cortical connections and the degree of neural myelination; candidates in adulthood include increased neural noise through weakened inhibitory connections and decreased levels of key neurotransmitters. These two classes of theory thus propose very different views on the issue of task-specific life-span changes.

A second motivation, and one sometimes overlooked, is that developmental studies provide a unique opportunity to test the validity of general theories of attention (Kana, 1993). Developmental studies do this in the same way they do neuropsychological, cross-cultural, and species-comparative studies. First, important differences among participant groups are noted. Second, a mapping is established between theoretical constructs and these group differences. Finally, data are collected to determine whether performance on theory-relevant tasks is systematically related to the group differences. One of the unique strengths of developmental studies in this regard is the inborn continuity that can be studied, as the observer moves from childhood, to adulthood, and eventually to old age.

Finally, there is a need for normative and comparable data on measures of attention over the life span. It is fair to say that far more is known about life-span changes in many basic visual and auditory functions than is known about changes in attention (see Coren, Ward, & Enns, 1994, for typical textbook coverage). Yet, one observation that keeps driving us to collect more data is that the apparently striking factor on performance in many developmental studies (even those putatively studying low-level sensory function) is something that can go by no other name than attention.

In this chapter we first summarize our views on what constitutes attention by focusing on three separable aspects of attention that are known to vary in childhood as well as in old age. We then summarize several different views on "What develops?" in these aspects of attention. Finally, we present life-span data from our labs on these components of attention, considering these data in light of the several different theoretical viewpoints.

WHAT IS ATTENTION?

In order to investigate life-span changes in attention, it is first necessary to agree on the concept of attention. At this point, we believe there is considerable consensus on the central concepts. That is, attention is seen by everyone to involve issues of processing selectivity, whether that selectivity concerns locations of the visual field for closer inspection (see Schiller, chap. 1, this volume), shapes and objects that constitute "figure" amidst other shapes and objects that constitute "ground" (see Baylis, chap. 8, this volume), attributes of objects that are relevant to the performance of some task (see Hood, Atkinson, & Braddock, chap. 7, this volume), or even actions that must be inhibited while other actions are performed (see Raffal, chap. 6, this volume).

However, we acknowledge at the same time that there is considerably less consensus about the boundaries of the concept. Does attention always involve conscious awareness? How do biologically determined biases in selection (e.g., the orienting reflex to abrupt visual and auditory stimuli) interact with knowledge-based biases (e.g., the voluntary effort to maintain fixation in the face of moving stimuli elsewhere in the visual field)? Our strategy has been to steer clear of the contentious border issues, while trying to stay firmly rooted on the islands of agreement.

In the sections that follow we describe the tasks we have studied and the dominant theoretical perspectives associated with each.

Covert Orienting

One aspect of attention is the ability to detect change in the environment, whether that change results from the sudden appearance of a new object or an attribute change in an existing object. The ability to shift visual attention toward the location of such a change, without accompanying physical movements of the eye, head, and body, has been called covert orienting by Posner (1980). In a typical covert orienting task, participants make a speeded response to the onset of a target, or they are asked to discriminate rapidly to one of two possible targets. Response time (RT) and accuracy are measured. Cues are presented prior to the onset of the target, indicating possible target locations. Comparisons are made between trials in which the cue correctly indicates the subsequent target location (valid trials), trials in which the cue incorrectly indicates one of the possible locations (invalid trials), and trials in which no specific location is indicated by the cue stimulus (neutral trials).

In studies of this kind, responses are typically fastest and most accurate when cues are valid, even if eye movements are prevented. According to Posner's (1980) theory of visual orienting, this is because attention resembles a spotlight that can be moved independently of eye movements. This spotlight is responsible for detailed analysis; objects falling within its focus receive enhanced perceptual processing. However, the spotlight cannot process every object in the image at once because the cognitive resources it demands are limited. Disengaging the focus from one location, moving the position of the focus in the visual field, and engaging the focus on a new location each require time and effort. Consequently, performance is expected to be best on valid cue trials, because the spotlight has been given a head start to move to the target location before the target actually appears.

When there is no information about where to put the attentional...
focus (neutral trials), or worse, incorrect information (invalid trials), performance suffers because the attentional focus has to be disengaged from its location of current activity, moved to the location of the source of change, and re-engaged on the new object.

Studies using single-cell recording techniques in monkeys (Wurtz, 1996), studies of human patients with various forms of brain injury (Rafal, chap. 6, this volume), and studies of brain imaging in humans engaged in cognitive tasks (Posner & Raichle, 1994) have converged in pointing to the superior colliculus (a midbrain structure) as being central in the normal functioning of covert orienting. In the most primitive form of orienting, this structure is the home of a subcortical reflex, which abruptly orients both attention and the direction of gaze to the location of a new stimulus in the visual field. This reflex is modulated by another complimentary reflex, controlled by other neurons in the same structure, to fix attention and gaze on the current object of interest. It is also modulated by cortical input from the parietal lobes, signaling the strategic goal of the organism to voluntarily orient toward a location in space. This complex array of relations, between the opposing reflexes to orient and fixate, and between the reflex to orient in one direction versus the higher-order goal to orient toward another, are thus a very promising place to begin examining developmental changes in attention.

Visual Search

Another aspect of attention is the ability to search for certain objects or attributes that are presented among other task-irrelevant objects or attributes. Visual search involves discriminating the presence versus absence of a particular target item among a varying number of distractor items. This task requires the ability to distinguish between targets and distractors, as well as the ability to deal with spatial uncertainty, multiple items, and displays that occupy large areas of visual space. Participants make a speeded response to indicate the presence or absence of the target on each trial. Again, response time and accuracy can be measured. The most important measure, however, is RT slope, which is a summary measure of the increase in task difficulty as a function of the total number of items in the display.

Previous research has revealed two broad patterns of performance on visual search tasks (e.g., Treisman & Gelade, 1980). When targets and distractors differ by an easily discriminable feature such as brightness, color, size, or orientation, RT slopes are small or even zero. When targets and distractors are not easily discriminable, or differ by a conjunction of features (e.g., a particular combination of brightness and orientation), RT slope is relatively large.

A popular interpretation of these results comes from Feature Integration Theory (Treisman & Gelade, 1980). This theory proposes that visual features such as brightness and orientation are initially registered in separate topographically organized regions of the brain. Consequently, information from remote brain regions must be brought together (integrated) to determine that a particular conjunction of features share the same location or belong to the same object. The theory also proposes the existence of a master map of spatial locations to which all feature maps have access. However, the binding together of different features at one location is a serial operation that can only be performed in relatively small regions at a time (perhaps as small as that occupied by one object).

Thus, according to feature integration theory, RT slopes in conjunction search are high because the effortful feature integration operation must be performed for each item in the display until the target is found. RT slopes in feature search, on the other hand, are low because targets can be identified on the basis of unique activity in a single feature map. No linkage between different feature maps is required and so display size is unimportant. Although the theory has undergone several modifications since its origin (Treisman, 1988; Treisman & Gormican, 1988; Treisman & Sato, 1990), it is widely accepted that targets defined by conjunctions demand more attentional processing than those defined by features (see Bundesen, 1990; Duncan & Humphreys, 1989; Wolfe, 1994).

Single-cell recording studies in awake monkeys (Moran & Desimone, 1985; Motter, 1995), studies of human patients with various forms of brain injury (Cohen & Rafal, 1991) and studies of brain imaging in humans engaged in cognitive tasks (Posner & Raichle, 1994) indicate that visual search involves coordinated activity between several cortical regions in addition to activity in the superior colliculus. In particular, the parietal lobes are engaged in processing aspects of object identity (e.g., form and color), the parietal lobes are involved in the voluntary guidance of spatial attention to visual field locations, and the superior colliculus is critical in the actual movements of the eye and attention to locations in space. As with covert orienting then, the task of visual search shows a great deal of promise in being able to provide behavioral indices of developmental changes in the brain interactions involved in visual attention.

Visual Enumeration

A third component of attention is the ability to register the presence of two or more distinct items in a display. Visual enumeration is the term given to the ability to specify the number of target items in a spatial array. Like visual search, enumeration involves the ability to deal with multiple-item displays that cover extended areas. However, unlike visual search, participants must register the presence of every single target, not just the first they see. In order to avoid missing targets or enumerating them more
than once, targets must be kept distinct from one another. This process is referred to as individuation.

Typically, there are two patterns of response in tasks of this kind. When there are only a small number of targets (up to 5 for most adults), the error rate is minimal, and the increase in RT with each additional item (the slope) is relatively shallow (40–100 ms per item). When there are larger numbers (5 or more) the error rate grows rapidly and the RT slope is much larger (250–300 ms per item). Subitizing is the term given to the cognitive processes involved when the slope is shallow, and thus the subitizing range is the range over which this shallow slope remains linear. Counting is the term applied when the cognitive processes involved when the slope steepens, and the counting range refers to the numbers of items that are beyond the elbow in the RT function.

Interestingly, subitizing only occurs in some situations. Participants can subitize complex objects (i.e., with multiple contours) of varying sizes; they can subitize O targets in X distractors, and items of one color or orientation amidst a variety of distractor items of other colors or orientations. However, when spatial attention is required to differentiate the target item as a whole from its background (e.g., the enumeration of nested concentric items), or to distinguish the target from distractors (e.g., the enumeration of O's in Q's, items connected by a line, or items with a particular conjunction of orientation and color), then subitizing does not occur (Trick & Pylyshyn, 1993). In these cases, the discontinuity in the RT function is absent; RT slopes are uniformly high throughout the number range, as if the more effortful counting process were used for both large and small numbers of items.

From data such as these, Trick and Pylyshyn (1994a) have surmised that subitizing is performed by a limited-capacity mechanism that individuates and selects a small number of distinctive items for further processing (Pylyshyn, 1989). This mechanism can be used for enumeration when the items to be enumerated are preattentively discriminable from distractors (Trick & Pylyshyn, 1994b), provided that the number of items does not exceed a limited number of internal reference tokens. When attention is required to discern individual items, either because they are spatially overlapping, or not sufficiently distinct from distractors, or when the number of items exceeds the number of available reference tokens, enumeration requires attention. The counting process therefore involves moving an attentional focus from location to location, using and reusing the same limited number of reference tokens at successive locations.

This behavioral analysis of visual enumeration indicates that it has much in common with both covert orienting and visual search. Like voluntary orienting and search, enumeration requires the planning and execution of movements of the attentional spotlight to specific locations in space.

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As such, the superior colliculus and parietal lobes must be involved. Also like search, enumeration requires the repeated inspection of visual items to determine whether they match the criteria of the target item. This would suggest that both orienting and search is that it demands that some record be kept of target items that have already been determined to belong to the target set. The behavioral data indicating that this record keeping can be accomplished with little effort for small numbers of items, but is cognitively demanding for larger numbers, strongly suggests that different brain regions are probably involved for subitizing and counting. For instance, whereas the individuation of a small number of items may be accomplished by sub cortical mechanisms that are shared between nonhuman mammals, human infants, and adults, the individuation of larger numbers may require complex cognitive strategies and the involvement of distributed cortical regions. Unfortunately, there is as yet no relevant neurophysiological evidence on this issue. Perhaps the developmental dissociations reported below for subitizing and counting may help to initiate such studies.

WHAT DEVELOPS?

Armed with this range of attentional measures, constructs, and theories, it makes sense to ask the question "What is developing?" when performance changes over the life span.

Developmental Theories

According to almost all developmental theories, RT in each of these tasks should vary in a U-shaped fashion over the life span. However, the reason for the U-shape is very different for an expertise view than it is for the speed of processing view. The expertise view holds that increasing amounts of practice in childhood, together with the "use it or lose it" principle in old age, account for the U-shaped trend. Speed of processing makes the same prediction because each task taps into a common set of cognitive operations that are subject to the neural factors contributing to cognitive slowing. For the present tasks, these might include sensory registration, perceptual identification of shapes, response selection, and response execution.

These two views differ considerably, however, in their predictions for the life-span patterns of measures that are specifically attentional. Consider, for example, the RT difference between valid and invalid cues in covert orienting, the RT slope in visual search, the subitizing and counting slopes in visual enumeration. The speed of processing view would contend
that each of these measures should show a U-shape function over the life span, since each involves neural processing of the sort that is speeded and slowed by developmental processes. The expertise view, on the other hand, permits more diversity. Some of the measures may not change at all over the life span (e.g., if they are tapping into operations that are not changed with practice and use), others may show improvement even into old age (e.g., if they reflect operations that are in consistent use throughout life) and others may show the familiar U-shape (e.g., if the operations are exercised most vigorously in young adulthood). The difficulty lies, of course, in the mapping of practice and exercise onto the cognitive components of laboratory tasks.

Attention Theories

The three theories of attention we have summarized provide for a large number of theoretical constructs. These theories, however, are for the most part silent on the issue of development. This has given us opportunities to consider the possible life-span course for each of them. In some cases, it is not too difficult to make a plausible conjecture, based on other (nondevelopmental) characteristics that are claimed for the construct by the theory. For example, if a theory proposes that some operation is "low-level" and therefore impervious to strategy and intention on the part of the observer, then it is tempting to hypothesize that this operation will show little developmental change. For the majority of the proposed attentional constructs, however, the question of developmental change is still open. Consequently, life-span data can be used to evaluate the plausibility of the theories.

Neurodevelopmental Data

A number of constructs in the neurodevelopmental literature may eventually prove to hold the key to understanding the relation between development and visual attention. We give examples of several, but hasten to add that none of these is at present developed fully enough to make specific predictions, especially with regard to early development versus aging. They can and should, however, guide research at the level of informing the choices made concerning the ages of observers that are tested and the types of tasks that are chosen.

One very natural place to begin looking for developmental change is in the relative rates at which various regions of the brain become fully myelinated in childhood. Neuroanatomical studies indicate that youthful development is fastest for the brainstem and midbrain, slower for the primary cortical areas and parietal lobes, and slowest for the prefrontal cortex. One of the more striking findings of these studies is that the brainstem is fully myelinated in early infancy whereas the cortex continues to mature through the teen years (Lecours, 1975). Thus one might expect attentional functions supported by lower brain centers to develop faster (or appear earlier) in childhood than those supported by higher cortical centers.

Another promising avenue can be seen in anatomical research on neuron number, density, and interconnectedness (Huttenlocher, 1990). One lesson of this research is that neural development is not about number of neurons, but rather about the density of synaptic connections. In childhood, one measure of synaptic density (the number of synapses per neuron) has an inverted U-shaped function over age. There is rapid growth in this measure following birth, which peaks at 2 years of age. The measure then declines, reaching a stable adult level at approximately 11 years of age. In senior adults there is yet another decline toward the end of life. It is, of course, tempting to relate such a trend in neuroanatomy to various behaviors that can be correlated with these age markers. To do this properly, however, behaviors must be carefully linked to the brain centers that are undergoing the change. Sadly, at this point we know little more on this score than that brain development follows a pattern of inside-out development, meaning that the cortical centers are the last to develop.

Finally, there is very promising research elsewhere in this volume (see chapters by Shiller, Maurer & Lewis, Johnson & Gilmore, Richards & Hunter, Ralof, and Hood et al.) on developmental changes in the way various brain centers coordinate their activity. Clearly, behavior guided by attention is the final output of a complex interaction among competing forces in various brain regions. A successful cognitive neuroscience of attentional development will therefore rely equally on (a) behavioral tasks that isolate separable functions of attention, (b) behavioral tasks that are appropriately linked to brain activity in specialized centers, (c) an understanding of the computations performed by given brain regions, and (d) studies of the developmental course of brain region activity. The studies that follow contribute most to the first objective.

RESULTS OF LIFE-SPAN STUDIES

In three studies we compared healthy volunteer participants with normal, or corrected-to-normal vision, from five groups with mean ages of 6, 8, 10, 22 and 72 years. The senior adults were screened for both glaucoma and cataracts. For each task, participants responded by pressing one of two keys. Their instructions were always to respond as quickly as they could, without sacrificing accuracy. These instructions were understood uniformly across
the age groups, as shown by the high levels of response accuracy. As a result, we focus our discussion on the RT data, although it should be born in mind that the patterns discussed were also always evident in the accuracy data.

Covert Orienting

Both theory and research point to an important distinction between orienting that is elicited by a stimulus cue (usually abrupt luminance transients at the location to be attended) and an information cue (typically arrows or digits at the center of gaze that refer to pre-designated locations). Stimulus-induced shifts are often said to be reflexive because they are not easily influenced by higher-level goals such as voluntary shifts in attention (Jonides, 1981; Jonides & Yantis, 1988; Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Yantis & Jonides, 1984, 1990). Moreover, stimulus-driven shifts generally result in rapid effects of a short duration, whereas information cues produce effects that are slower to emerge and longer lasting (Jonides, 1981; Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Posner & Cohen, 1984). These theoretical and empirical distinctions suggest that there might be different life-span courses for these two forms of cueing.

Brodeur and Enns (1997) compared orienting to the two cues over a range of cue-target intervals from 150 to 800 ms. Participants were instructed to press one key if the target was an O and another if the target was an X, and targets were centered in one of four locations: 2.0° left, 2.0° right, 6.0° left, or 6.0° right of fixation. Targets were preceded by 50 ms cues: stimulus cues in one condition and information cues in another. The stimulus cue was a small black disk that appeared at fixation (neutral cue), or at one of four target locations. The information cue was either an equal sign (neutral cue), or arrows pointing left or right. The cues were valid in 20% of the trials for stimulus cues (i.e., entirely non-predictive), as compared to 80% of the trials for information cues (i.e., highly predictive).

Participants in both conditions were instructed to keep their eyes at fixation throughout the trial sequence and to blink, when necessary, between trials. Eye movements were monitored with a video camera. Participants in the stimulus cue task were warned that there would be a flash in one of the target locations before the target (the cue), but they were told to ignore it. In contrast, participants in the information cue condition were told to use the arrow cues as a very helpful indicator of the target’s likely location.

The results indicated that stimulus-driven covert orienting undergoes relatively minor developmental change over the life span, as shown in Fig. 13.1. The three groups of children are combined in this graph because there were no significant differences among them. All age groups showed an orienting effect, which diminished at longer intervals. This is consistent with previous reports made separately for children (Akhtar & Enns, 1989; Enns & Brodeur, 1989) and senior adults (Hartley, Kiedel, & Slabach, 1990; Hoyer & Pamhant, 1987; Maddon, 1990). The young adults showed slightly less orienting than the other groups, perhaps because they were less able to follow the explicit instructions to ignore the stimulus cues. They were also the only group to show any signs of the inhibition of return effect at the longer intervals.

There were larger age-related changes for information cues. The young adult group demonstrated the most consistent orienting effects across the temporal intervals, as shown in Fig. 13.2. By comparison, all three groups of children showed strong effects at short intervals with marked decreases in the effects after 200 ms. Senior adults were different again, showing an information cue orienting effect only at the longest interval.

These results concur with those from previous studies on information cues. Children have often been reported to have difficulty sustaining stra-
the offset of the fixation marker. After a variable interval (140, 400, or 800 ms), a stimulus cue was presented. The stimulus cue-to-target interval was a constant 133 ms. Participants were instructed to use the information cue, as in first experiment, and told that there would also be a flash (the stimulus cue) on each trial, which they should try to ignore.

Although the design and associated data were complex, there was one finding of particular importance to the question of the separability of the two forms of cuing. Only the young adults were capable of partially discounting the information cue when the stimulus cue was valid. This is shown in Fig. 15.3, where the interval between the informative arrow cue and the target was 800 ms, and the interval between the noninformative stimulus cue and the target was 133 ms. Whereas the children and the senior adults showed additive contributions of the two forms of cuing (the validity effects of one cue type were constant over the validity effects of the other cue type), the young adults showed a clear cue interaction. The invalid stimulus cue was clearly less effective in the face of a valid informational cue. This indicates that only the young adults were able to override the orienting reflex in this case with the intention to orient to the location indicated by the arrow. This kind of cognitive flexibility is in general con-

etric aspects of attention over time (e.g., Kupietz & Richardson, 1978), and senior adults have previously been shown to be slower in the use of information cues for spatial orienting (e.g., Hartley et al., 1990; Hoyer & Familiant, 1987). However, contrary to theories appealing to similar mechanisms for the reduced levels of performance at the beginning and end of life (e.g., cognitive slowing, see Kail, 1990, and Saltzoue, 1985), these results suggest different underlying mechanisms. Children were able to make use of the information cue very rapidly (i.e., at least by 150 ms), but they clearly had difficulty sustaining their attention voluntarily in the cued location. In contrast, older adults were simply unable to respond very quickly to the cue. A theory premised on a common mechanism for U-shaped age changes in information-based orienting would have difficulty accounting for the differences observed here.

A second experiment in the same study (Brodeur & Enns, 1997) looked more closely at the interaction between the two types of orienting. Stimulus and information cues were presented together in the same trial in the following sequence. An information cue was presented for 50 ms upon
sistent with other research showing young adults to be most adaptive in their approach to a task (e.g., Enns & Girgus, 1985; Guttag, 1989; Mc Dowd & Craik, 1988). However, in the present case it points to a very specific form of adaptability in regard to visual orienting. In everyday terms, it can probably be related to the ability to "stay on task" with overt and covert gaze mechanisms in the face of abrupt and unexpected visual events.

**Visual Search**

Two findings are well established in regard to this aspect of attention. One is that there is a U-shaped pattern of performance over the life span: Visual search speed improves in childhood and declines again in old age. The second finding is that in conjunction search tasks this pattern is true of both baseline RT (intercepts of the search function over display size) and the increase in RT with display size (RT slope). When feature search has been tested it seems only to be true of baseline RT (Phadé et al., 1994). RT slopes in feature search tasks are almost flat for children as young as 5–6 years of age and in seniors as old as 80 years. This suggests at a minimum that not all aspects of the search task are subject to the same developmental limitations.

We considered the possibility that the age-related changes in RT slope in conjunction search might originate from a number of sources, including changes in peripheral acuity, eye movement speed, feature integration ability, attentional filtering of distractors, movement of the attentional focus, and uncertainty. In order to determine which, if any, of these factors were important, observers were tested on three variations of a search task (Trick & Enns, in press). In the first condition, which we called Fixed Location—No Distractors, all uncertainty about the location of the target was eliminated. A single item always appeared at the center of the display and observers indicated as rapidly as possible whether or not it was the target. If feature conjunction was relatively more difficult than feature discrimination for some age groups, it would suggest a fundamental difficulty in feature integration for that age group.

We then added location uncertainty in a condition we called Random Location—No Distractors. The single item now appeared in random locations anywhere in the display area and observers judged whether it was the target or not. Two questions were of interest. First, did the addition of spatial uncertainty and increased foveal eccentricity influence any age groups disproportionately? A result would point to a fundamental difficulty in either peripheral acuity and/or moving attention to a new location in the visual field. Second, was the relationship between conjunction and feature discrimination any different across ages in this task than the previous one? If so, it would suggest that the difficulty of feature integration for that age group was only observed when spatial attention was not already focused on the target location.

If the mere presence of distractors hindered search selectively for some age groups, it would indicate difficulty in ignoring items that were competing for attention. Furthermore, as the number of distractors increased, it is possible that search became disproportionately more difficult than feature search for some age groups, it would suggest a problem specific to voluntary movements of attention from one search item to another.

For all search tasks, participants were given the task of indicating the presence or absence of the same target—a dark outline circle. In feature detection the distractors were randomly divided between light gray outline circles and squares, making the target distinctive on the basis of brightness alone. In conjunction detection the distractors were randomly divided between light gray outline circles and dark gray outline squares, making the target distinctive on the basis of a particular combination of brightness and shape.

The results from the three tasks are presented in Figs. 13.4 and 13.5. We found no evidence that the efficiency of feature integration changed with age. There were, of course, baseline differences in the mean correct RT across age. As expected, RT decreased with age from childhood to young adulthood and then increased again in old age. The important question, however, concerned the RT differences between conditions. When a single item was presented at a fixed location in the display (Fig. 13.4), conjunction detection was indeed more difficult than feature detection. Remarkably, however, the age of the observer had no effect on this degree of difficulty. Similarly, when a single item was presented at a random location, conjunction detection was slower than feature detection by approximately the same amount, and there was no age-related change in this difference.

Moreover, there was no evidence that age affected the efficiency of moving the attentional focus to a single display item. Responding to a single item in a random location was slower than responding to an item at a fixed location for all observers, but age played no role in this difference. These stable RT differences across age are an important finding, because they rule out age differences in peripheral visual acuity (Akhatar, 1980), saccadic movement speed (Miller, 1973), and the speed of reflexive orienting to new stimuli (Enns & Brooks, 1989) as sources for the age effects in search. At least we can say that such age differences were not evident when the search task involved responding to a single item in an otherwise empty display field.
FIG. 13.4. Mean correct RT and percentage errors in the two No Distraction search tasks. Items were presented either at a fixed or random screen location, and targets differed from distractors by either a single feature or a conjunction of features. Bars represent standard errors of the mean. Adapted and redrawn from Trick and Enns (in press).

FIG. 13.5. Mean correct RT and percentage errors in the Distraction-Random Location search tasks. The number of display items (Display Size) was varied randomly between 2, 10, and 18 in both feature and conjunction search tasks. Bars represent standard errors of the mean. Adapted and redrawn from Trick and Enns (in press).
In fact, the age differences in performance only emerged when there was more than one item in the display. Although there were no age differences in the RT slopes in the feature search task as a function of the number of distractors, there was a large U-shaped life-span trend in the conjunction search task. These data are shown in Fig. 13.5. We attribute this slope effect to a difficulty in voluntary movements of attention from item to item. This conclusion is warranted because we were able to rule out differences in the processes of feature integration, as well as in the processes involved in moving attention to a single item in a visual display. Both of these are ordinarily valid candidate mechanisms for explaining slope differences in conjunction search.

Visual Enumeration

How might subitizing and counting RT slopes be expected to change with age? Subitizing involves registering target items as discrete items, individualizing them, and selecting the appropriate number name response (Trick & Pylyshyn, 1994b). With the exception of response selection, most of the current literature suggests that these processes change little with age. For example, visual search for simple features is comparable in children, senior adults, and young adults (see the previous study and Flude et al., 1994) and even very young infants can distinguish between 2 and 3 items (e.g., Starkey & Cooper, 1980; van Loonbroek & Smithman, 1990). Therefore, the reported decline in the subitizing slope during childhood (Chi & Klahr, 1975; Senso & Sjoberg, 1978) probably reflects improvements in efficiency in retrieving number names from memory and matching them to individuated items in order to select a response. Once the process of retrieving number names from memory is overlaid, however, there is no reason to expect it to deteriorate with normal aging, and consequently, no reason to expect the subitizing slope to increase again for senior adults. Thus, the subitizing slope should decline with age to adulthood, and then stabilize.

In contrast, the counting process involves a number of operations in addition to those required for subitizing, including moving the attentional focus from item to item. The findings of the previous two studies would thus predict that counting slopes should be higher for both elderly subjects and children than they would be for young adults.

We investigated enumeration with a number discrimination task (Trick et al., 1996). In each condition, random arrangements of one of two alternative numbers had to be discriminated by the observer: 1 vs. 2, 3 vs. 4, 6 vs. 7, and 8 vs. 9. RTs are shown in Fig. 13.6. The data revealed a different pattern over the life span for numbers in the subitizing range (1–4 items) versus those in the counting range (5–9 items). The RT slope in the small number range decreased monotonically with age between 6 and 22 years (from 159 ms per item to 62 ms per item) and then did not decline significantly thereafter. In fact, the 72-year group had the smallest slope estimates of all (51 ms per item). This might be expected if the process that was changing with age involved matching individuated display items with number names retrieved from memory. Once this process becomes automatic, there would be no reason to expect it to deteriorate with age.

In contrast, RT slopes in the large range declined into young adulthood (547 ms, 458 ms, 399 ms 250 ms for 6, 8, 10, and 22-year-olds, respectively), but then increased again in old age (354 ms per item). Given that the position of the attentional focus has been shown to be important in the counting range (Trick & Pylyshyn, 1994a), and that other studies have shown children and elderly subjects to be less efficient at shifting attention (see previous two studies and Flude et al., 1994), it seems likely that attentional factors are responsible for this change. Though the counting process involves many other operations, such as storing and retrieving information from short-term memory, and performing addition, attentional factors logically precede these operations. Therefore, it is parsimonious to conclude that voluntary control over spatial attention is a primary candidate for the U-shaped life-span trend in counting slopes.
SUMMARY AND CONCLUSIONS

These results indicate that some measures of attention are relatively stable between 6 and 72 years of age, whereas others follow a U-shaped trend. Among the stable components are reflexive covert orienting to the location of a sudden visual event, search for a target that stands out from distractors because it differs in a simple visual feature, the ability to discriminate a visual item based on a conjunction of two features, and the ability to rapidly enumerate small numbers of items. The attentional components following a U-shaped trend include voluntary covert orienting to nontarget locations, visual search for a target amidst distractors when the target is defined by a conjunction of two features, and the ability to enumerate items for numbers larger than 5. An obvious common element to these measures of attention is voluntary control over, and guidance of, the location of attention.

Implications for Theories of Development

It appears that the highly touted U-shaped pattern of performance over the life span accurately describes mean response time and accuracy in our tasks, but it does not account for all measures of performance that are specifically attentional. Some of these measures show no hint of a U-shaped pattern.

Why is there a discrepancy between measures of overall task performance and finer-grained measures of attention? We think the answer lies in the observation that a measure of overall task performance, in even the simplest of tasks, involves influential cognitive components that do indeed follow the U-shaped pattern predicted by both expertise-based and speed of processing theories. However, these components serve to obscure most of the theoretically interesting attentional effects.

For example, most of the response time measures reflect cognitive operations that are of little interest to the visual attention theorist. This would include the target identification stage, the response decision stage, and the response execution stage. In the case of visual search, these components are reflected in the baseline RT (intercept). The slope of the RT function over display level reflects the unique contribution of the increasing number of display items. If there is a measurable difference in RT between conditions, and this difference does not change with age despite large changes in baseline RT, then one is compelled to conclude that it reflects a cognitive operation that does not wax or wane over the life span. Exclusive reliance on overall response time would make it impossible to investigate the changes unique to attention. Instead, finer-grained analysis is required.

ATTENTION OVER THE LIFE SPAN

The studies reported in this chapter employ measures useful for investigating age-related changes in the components of attention. We found that our two measures of covert orienting, one of them changes very little with age (stimulus-cued orienting), while the other changes a great deal (information-based orienting). Furthermore, even the age changes in this latter case were not unidimensional over the life span. Children had more difficulty than young adults sustaining their attention voluntarily to a cued location, whereas senior adults needed more time than young adults to take advantage of the cue.

In visual search we found that targets defined by simple features showed no age-related change, whereas search for conjunction-defined targets showed a U-shaped pattern. Closer examination of several possible reasons underlying this pattern pointed to a factor that appears to have much in common with information-based orienting. In visual search this manifested itself as a U-shaped trend in the ability to voluntarily shift attention among multiple items.

For visual enumeration we again found a dissociation for separate cognitive components. The enumeration of small numbers of items showed a monotonically improving trend even into old age, whereas the enumeration of larger numbers showed a U-shaped pattern. Once again, it appears that this pattern can be traced to difficulties directing the spatial focus of attention among multiple objects.

This diversity of life-span patterns among components of visual attention can be understood from either an expertise or a speed of processing perspective, but it certainly complicates research in both areas. For example, for the expertise theory, it now becomes important to understand how factors of practice and knowledge preserve some aspects of attention while other aspects deteriorate. For the speed of processing view, it becomes important to understand why some cognitive operations are impervious to factors influencing neural conduction rates and conduction fidelity. Are different brain regions responsible for different attentional components? Do development and aging influence the neural speed and fidelity of these brain regions differentially? Although no direct data is available, it is tantalizing to hypothesize these kinds of connections, especially given the rapid growth in the understanding of the neural bases of attention (e.g., Posner & Raichle, 1994; Zeki, 1993).

Implications for Theories of Attention

How do these life-span data constrain theories of attention? Consider first feature integration theory (Treisman & Gelade, 1980), which proposes that RT slopes in conjunction search tasks reflect the incremental time associated with integrating visual features one item at a time. Furthermore,
the initial location of the focus of attention should be critical for predicting performance, because features can only be integrated once attention is focused on the location of visual features in question. If this were true, then the difference between feature and conjunction search should have been larger in our Random Location task than in our Fixed Location task. The data did not support this prediction. This result, taken together with the failure to find age differences in feature integration itself, suggests that the mechanisms emphasized by feature integration theory do not play a large role in age-related trends in visual search. This should also lead researchers to question the degree to which feature integration is a "high-level" cognitive operation.

The implications for Posner’s visual orienting theory (Posner, 1980) are less specific. According to this theory, conjunction search is less efficient than feature search because the target item does not trigger reflexive orienting mechanisms. As a consequence, observers must intentionally guide the spotlight of attention from item to item. This involves repeated uses of the disengage, move, and engage operations (Posner & Petersen, 1990; Posner & Raichle, 1994). The present studies suggest that the youngest and oldest participants had difficulty moving their attentional focus systematically through other items, though they are capable of moving the focus in response to stimulus and information cues.

This difficulty could stem from any or all of Posner’s three operations, which in itself suggests promising avenues for future research. For example, the disengage operation could be studied directly by using search tasks in which there are variable temporal gaps between the offset of a currently attended stimulus and the onset of a stimulus to be attended (Fisher & Breitmeyer, 1987; Kingstone & Klein, 1993). Similarly, the move operation could be studied by manipulating the spacing and configuration of items in the display. Finally, the engage operation could be tested by comparing psychometric functions of visual acuity in regions of the display that were either attended or not attended. Some researchers have already begun to speculate on which subset of the three attention orienting components are at issue when age differences are found, but at this point the directly relevant research has yet to be done.

Implications for Understanding the Normative Development of Attention

These behavioral data represent only the beginning of what must be studied if a foundation is to be laid for the normative development of attention. Progress will only be made if behavioral researchers of attention and development work hand-in-hand with neurophysiological researchers of these topics. Because so few attempts to build bridges among these four disci-

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Summary and Commentary.
Selective Attention:
Its Measurement in a
Developmental Framework

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The preceding three chapters are rich in the amount of data presented and in the discussion of methods for studying attention. They also offer the reader some intriguing ideas about the cognitive and neural processes that underlie attention. The challenge for me has been to integrate three very different approaches to the issue of visual selective attention. The approaches differ in both the techniques used and the age range being investigated, and yet they all contribute to our understanding of a number of key issues. These issues are: the conceptualization of selective attention; the role of attention in performance, learning, and memory; and the course of development of attention, or to borrow a phrase from Enns, Brodeur, and Trick, “What develops?”

THE CONSTRUCT OF ATTENTION

As Enns and his colleagues point out, selectivity is central to the construct of attention. Selection is an ongoing, dynamic process; not only is it essential that we orient to only some events and objects out of the multitude of possibilities that are available, we must be able to sustain selection whenever it is appropriate and adaptive to do so. This “maintenance of a stimulus selective state” (Näätänen, 1992, p. 396) requires an active resistance to distracting events. Dynamic, active selectivity involves both facilitation and inhibition; selection effectively enhances the perception of the