

Visual Search Across the Life Span

Bernhard Hommel

Max Planck Institute for Psychological Research
and Leiden University

Karen Z. H. Li

Max Planck Institute for Human Development
and Concordia University

Shu-Chen Li

Max Planck Institute for Human Development

Gains and losses in visual search were studied across the life span in a representative sample of 298 individuals from 6 to 89 years of age. Participants searched for single-feature and conjunction targets of high or low eccentricity. Search was substantially slowed early and late in life, age gradients were more pronounced in conjunction than in feature search, and all age groups were uniformly affected by eccentricity manipulations. However, developmental and aging trends were distinctly asymmetrical: Children's performance was particularly affected by the mere presence of distractors; whereas in late life, performance was particularly impaired on target-absent trials and with increasing numbers of distractors. The implications for life span theories of cognitive and attentional development and for cognitive-speed and inhibitory-control accounts are discussed.

Across the life span, perceptual and attentional processes are used to locate target objects among nontargets, or distractors. That is, people of all ages routinely carry out visual searches, whether

children are locating their favorite toys in the playground, adults are looking for their cars in a parking lot, or old people are searching for a particular brand of medication on the shelves of the pharmacy. The extant research on the development of visual search suggests that search proficiency increases from childhood to adolescence, peaks in young adulthood, and then decreases in late life (e.g., Plude, Enns, & Brodeur, 1994; Trick & Enns, 1998). This pattern is in accord with common views of life span cognitive development as a U-shaped, mirrored pattern of rise and fall in basic information-processing mechanisms (e.g., Belmont, 1996; Dempster, 1992). However, it is important to bear in mind that although there may be some similarities between child development and aging in some general aspects of cognitive processing, there could also be differences in mechanisms that are more task specific. Furthermore, similar levels of behavioral performance observed in child development and aging might be caused by different underlying mechanisms. In other words, maturation and senescence are not mere reversals of each other. Adopting a life span developmental perspective is helpful in identifying similarities and differences between the mechanisms contributing to child cognitive development and cognitive aging (S.-C. Li et al., 2004). Thus far, the published research on visual search and development covers discrete segments of the life span (e.g., Lobaugh, Cole, & Rovet, 1998; Plude & Hoyer, 1981) with few exceptions (Trick & Enns, 1998). Consequently, what is known about the life span development of visual search lacks coherence in terms of methodology and theory. Moreover, whereas much of the recent work has been directed toward understanding the effects of specific mechanisms (e.g., target-distractor similarity or target eccentricity), fewer studies have examined general factor theories of cognitive development, which may provide more parsimonious and integrative accounts of the published findings.

The present study reflects an attempt to examine the processes underlying age differences in visual search from a life span perspective. We focus on two candidate global aspects of information

Bernhard Hommel, Cognition and Action Research Group, Max Planck Institute for Psychological Research, Munich, Germany, and Department of Psychology, Cognitive Psychology Unit, Leiden University, Leiden, The Netherlands; Karen Z. H. Li, Center for Lifespan Psychology, Max Planck Institute for Human Development, Berlin, Germany, and Department of Psychology, Centre for Research in Human Development, Concordia University, Montreal, Quebec, Canada; Shu-Chen Li, Center for Lifespan Psychology, Max Planck Institute for Human Development, Berlin, Germany.

This study is part of the CoOP-MIND Study, a collaborative research project (investigating the CoOperation and intercorrelation between a broad class of elementary Perceptual and cognitive processes, such as Memory, visual search, and choice reactions, and psychometrically defined Intellectual abilities across life span Development) between the Max Planck Institute for Human Development and the Max Planck Institute for Psychological Research. In addition to the three authors who were directly involved in the present study, other members of the research project are G. Aschersleben, F. Miedreich, W. Prinz, and W. Schneider from the Max Planck Institute for Psychological Research and Paul B. Baltes and U. Lindenberger from the Max Planck Institute for Human Development.

We thank Annette Rentz-Lühning and many other student assistants for help in collecting the data. Karen Z. H. Li acknowledges the support of the Fonds pour la Formation de Chercheurs et l'Aide à la recherche (Quebec, Canada) and the Natural Sciences and Engineering Research Council of Canada during the preparation of the manuscript.

Correspondence concerning this article should be addressed to Bernhard Hommel, Leiden University, Department of Psychology, Cognitive Psychology Unit, Postbus 9555, 2300 RB Leiden, The Netherlands. E-mail: hommel@fsw.leidenuniv.nl. Correspondence concerning the CoOP-MIND Study in general can be addressed to Shu-Chen Li, Center for Lifespan Psychology, Max Planck Institute for Human Development, Lentzeallee 94, D-14195, Berlin, Germany. E-mail: shuchen@mpib-berlin.mpg.de

processing that are hypothesized to improve in early life and decline in late life: cognitive speed and inhibitory control. Besides examining these two global factors, we also consider other factors more specific to visual search that might account differentially for the search performance observed in early versus late life. In the following section, we first briefly outline major theoretical models of visual search processes.

Major Theories of Visual Search

Visual search is widely thought to involve both parallel and serial processes (e.g., Treisman & Gelade, 1980; Wolfe, 1994). Search is especially easy if the target differs from its context by a single visual feature (*feature search*: e.g., a red target among green items) but is more difficult if the target and nontargets differ in how multiple features are combined (*conjunction search*). For instance, if subjects search for a red X among green Xs and red Os, performance is not only worse but is also slowed as a linear function of the number of nontargets. Early accounts of this contrast between feature- and conjunction-search conditions assumed that the former could be conducted in parallel, resulting in relatively flat search slopes (< 10 ms/item), whereas the latter required an item-by-item search strategy, resulting in significant effects of display size (*feature integration theory*: Treisman & Gelade, 1980). Similarly, the ratio of target-absent versus target-present search latencies often approximated 2:1, suggesting that search was exhaustive for target-absent cases and required, on average, roughly twice as much time as for target-present cases.

Subsequent findings have revealed important exceptions: Target-distractor similarity and distractor heterogeneity have been found to influence search slopes during feature search (e.g., Duncan & Humphreys, 1989; Scialfa, Esau, & Joffe, 1998), whereas relatively flat search slopes have been observed during conjunction search when targets and distractors are very dissimilar (e.g., Scialfa & Joffe, 1998). Likewise, some combinations of features do not produce the expected slopes under conjunction-search conditions (e.g., Theeuwes & Kooi, 1994).

Revisions of the feature integration theory propose that observers may search groups of items at a time, the size of which varies with search difficulty and practice (the *group scanning hypothesis*: Treisman & Gormican, 1988; see also Scialfa & Joffe, 1998). Others have incorporated an inhibitory mechanism that suppresses nontarget features (Treisman & Sato, 1990). More recently, Wolfe and colleagues have proposed that conjunction search is guided by the interplay between bottom-up activation, which increases as a function of the feature contrast between a given item and items at neighboring loci, and top-down activation, which reflects the match between a given item and the current target representation (the *guided search model*: e.g., Cave & Wolfe, 1990; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). Findings of absent-present ratios of less than 2:1 are consistent with such revised models. Although this article is aimed specifically at examining the life span development of visual search performance, instead of arbitrating between the various models of visual search, constructs such as attentional control (e.g., Wolfe, 1998) and inhibition (Treisman & Sato, 1990) are relevant to our subsequent discussion of life span age differences in general aspects of cognitive processing.

Gains and Losses in Visual Search Across the Life Span

Knowing the basic findings reviewed above, what can one expect when examining age differences in visual search across the life span? Given that the majority of developmental studies examine either childhood or adult aging, in the following sections we highlight findings from each area in turn.

Improvements During Childhood

Relatively few studies have investigated attentional control in visual search during child development. Ruskin and Kaye (1990) compared the performance of three young age groups (mean ages = 6, 8, and 12 years) in feature- and conjunction-search tasks. In general, reaction time (RT) decreased with development. More interestingly, with stimuli composed of separable dimensions, feature search produced better performance and shallower display-size functions than did conjunction search. However, display size did affect performance in both feature and conjunction search, although this effect diminished with increasing age. Similarly, Lobaugh et al. (1998) investigated three groups of children (mean ages = 8, 10, and 12 years) and adults (mean age = 26 years) and reported decreasing slopes in both feature and conjunction search as a function of age, the former slopes always being much shallower (< 10 ms/item) than the latter. Age-related improvements in conjunction search were also reported by Thompson and Massaro (1989), who compared 4- to 5-year-old children with young adults, and by Trick and Enns (1998) in their recent life span study. Notably, age effects on feature search were not found in these latter studies, which suggests that age effects in the feature-search condition were weaker and less reliable. Taken together, it appears that child cognitive development from about 6 years onward improves attentional top-down control (i.e., serial search) and has negligible positive effects on stimulus-driven performance (i.e., parallel search).

Declines During Senescence

In adult developmental samples, at first glance a “mirrored” pattern appears to prevail: Early studies found significant age-related impairments in conjunction search, in contrast to largely robust feature-search performance across adult age groups. Rabbitt (1965) provided early evidence of negative adult age differences in a search-based card-sorting task. He attributed this effect to the greater difficulty older participants had in ignoring irrelevant information, an anticipation of more recent inhibition approaches to cognitive aging (Dempster, 1992; Hasher & Zacks, 1988; West, 1996). Using more standard search procedures, Plude and Doussard-Roosevelt (1989) compared young (mean age = 20 years) and old (mean age = 71 years) adults on feature- and conjunction-search tasks. In feature-search conditions, older adults reacted more slowly than younger adults, especially if the target was absent, but performance in both groups was independent of display size. In contrast, substantial display-size effects were obtained in conjunction-search conditions. Moreover, consistent with earlier (see Plude & Hoyer, 1985, for an early review) and more recent (e.g., Folk & Lincourt, 1996; Foster, Behrmann, & Stuss, 1995; Madden, Pierce, & Allen, 1996; Oken, Kishiyama, & Kaye, 1994; Scialfa & Joffe, 1997; Zacks & Zacks, 1993) studies, these

effects were more pronounced in the old group than the young group, especially for target-absent trials.

More recent findings in the aging literature reveal important refinements to the prior dichotomy between feature and conjunction search: For example, Scialfa and Joffe (1998) demonstrated that age effects varied as a function of target–distractor similarity. Scialfa et al. (1998) found that the search slopes of young and old adults were equally affected by manipulations of target–distractor similarity. Kramer, Martin-Emerson, Larish, and Andersen (1996) found that young and old adults performed equivalently when conjunction search involved movement as a defining feature. Humphrey and Kramer (1997) found that young and old adults were able to search in parallel under conjunction conditions with sufficiently differentiated features. Thus, it does not appear in all cases that feature search is age invariant, nor does it appear that conjunction search differentially penalizes old adults in all cases.

Life Span Cross-Sectional Findings

Of particular interest is a cross-sectional life span study of visual search conducted by Trick and Enns (1998). Unlike most other studies that examined either child cognitive development or cognitive aging separately, the Trick and Enns study examined life span age differences in visual search in five discrete age groups that covered the age range from 6 to 72 years (mean ages = 6, 8, 10, 22, and 72 years). In line with Treisman and Gelade's (1980) feature integration theory, feature binding was found to improve early in life and remain intact into late life: Strong age trends were observed at either end of the life span during conjunction-search conditions, which the authors attributed to a developmental rise and fall in the ability to disengage attention voluntarily.

If one considers the child and adult developmental findings together, explanations for the U-shaped pattern appear to go beyond the earlier view that effortful, attention-demanding serial search is equally penalizing to children and aged adults. The adult aging work, more so than the child developmental research, points to attentional selectivity as an important factor that mediates age differences in visual search performance in old age (e.g., Plude & Doussard-Roosevelt, 1989; Scialfa & Joffe, 1997; but see Humphrey & Kramer, 1997; Scialfa, Jenkins, Hamaluk, & Skaloud, 2000). Hence, although there are similarities between both ends of the life span in terms of general aspects of visual search, there may also be specific processes that are differentially sensitive to child development and aging.

Theories of Life Span Developmental Differences

Although notable for its careful evaluation of factors underlying visual search performance, the study reported by Trick and Enns (1998) was but a beginning to further needed investigations of visual search across the life span. As with much of life span developmental research, a major challenge is to consider the possible effects of other processes or phenomena that may also be changing over time in parallel with the specific processes that are more pertinent to the specific task under investigation. Therefore, besides examining specific factors identified by more basic visual search research (e.g., feature binding, à la Trick & Enns, 1998), we also draw from the cognitive development and aging literatures to identify candidates of general aspects of information processing (i.e., cognitive speed and inhibitory efficiency).

Cognitive Speed

There are at least two general-resource accounts for the observed U-shaped function of visual search performance that are worth consideration (see Plude et al., 1994, for a similar discussion). Approaches of the first type attribute age-related differences in cognitive capabilities to the development of information-processing speed across the life span (e.g., Cerella & Hale, 1994; Kail & Salthouse, 1994). Whereas child development is associated with gains in information-processing speed (e.g., Kail, 1991), cognitive aging is related to the general slowing of information processing (e.g., Cerella, 1985; Salthouse, 1996). Under the assumption that central processing is more affected by age-related speeding up during child development or slowing during aging, one would expect age effects at both ends of the life span to be more pronounced as cognitive complexity increases or when more items must be searched serially, for example. Aside from visual search paradigms, measures of perceptual speed have been shown to contribute to age-related variance in other aspects of cognitive performances observed in childhood and in late life. For instance, a recent cross-sectional study of individuals 7–82 years of age found that measures of perceptual speed partially accounted for individual differences in task-switching performance observed in childhood and in old age (Cepeda, Kramer, & Gonzalez de Sather, 2001). Given the pervasive evidence showing age-related differences in cognitive or perceptual speed, and the reliance on RT as a measure of search performance, we acknowledge the importance of considering cognitive speed as a theoretical construct in our investigation, if only as a point of departure for examining more task-specific mechanisms.

Attentional Control and Inhibition

The second type of general-resource approach emphasizes mechanisms of attentional control. Most prominent are inhibition accounts, which assume that many cognitive tasks require the efficient inhibition of irrelevant information and/or unwanted, stimulus-induced response tendencies. Accordingly, improvements in performance early in life are attributed to the development and strengthening of inhibitory mechanisms (e.g., Dempster, 1992; Diamond, 1990; Harnishfeger, 1995), whereas cognitive aging is assumed to go hand in hand with the decline of efficient inhibitory mechanisms (e.g., Dempster, 1992; Hasher & Zacks, 1988; Tipper, 1991). Early cross-sectional work on developmental differences in Stroop interference (Comalli, Wapner, & Werner, 1962) indicates the expected pattern of increase and decline in resistance to competing responses. More recently, Williams, Ponesse, Schachar, Logan, and Tannock (1999) investigated the performance of subjects from 6 to 81 years of age in a stop-signal task to measure the inhibition of prepotent responses. The speed with which responses could be executed (go trials) followed a U-shaped age function. However, the age function for no-go trials, indicating response inhibition, showed more substantial age effects in childhood than in late life. Importantly, the age effect stayed significant even after general speed (as measured by RTs in go trials) was partialled out, suggesting that other mechanisms in addition to processing speed are involved. As Kramer and colleagues (e.g., Kramer, Humphrey, Larish, Logan, & Strayer, 1994) demonstrated with an adult aging sample, inhibition appears to be multifaceted and multidirectional rather than unitary; thus some inhibitory

mechanisms may indeed follow a U-shaped age function, whereas others do not.

In the context of visual search, if one assumes that inhibiting distractors is more important (and/or more difficult) in conjunction search than in feature search, and that inhibitory difficulty increases with the number of distractors, then the development of inhibitory efficiency seems a reasonable candidate explanation for life span differences in visual search performance. This perspective also dovetails nicely with the basic findings that implicate controlled attention or inhibition in visual search (Treisman & Sato, 1990). Notably, Scialfa and colleagues (Ho & Scialfa, 2002; Scialfa et al., 2000) have recently reported that older and younger adults are equally proficient at ignoring irrelevant features and selectively examining items with target-relevant features given sufficient training—even though less is known about the inhibitory efficiency of children in this regard.

In summary, we have reviewed the cognitive speed and inhibitory control theories of cognitive development and aging in relation to visual search. In line with others (e.g., Light, 1991; Zacks, Hasher, & Li, 2000), we do not assume that processing speed and inhibitory efficiency are mutually exclusive influences on cognitive performance. Rather, we see them as plausible explanatory concepts that have been shown to improve and decline across the life span and that fit conceptually with the particular task under investigation.

Overview and Hypotheses

As in much of the work on life span age differences in cognitive or attentional performance, the lack of coherence on both empirical and theoretical levels stems largely from the dearth of studies that encompass enough age groups ranging from childhood to late life (Plude et al., 1994; cf. Trick & Enns, 1998) or that involve continuous age sampling (cf. Cepeda et al., 2001; Williams et al., 1999). To address these needs, we recruited participants from a large population-based sample (cf. Trick & Enns, 1998; Williams et al., 1999), using city registry information to minimize the effects of positive selection (i.e., only using highly educated, very healthy, or affluent individuals). Furthermore, to assess points of inflection with reference to age-related improvement versus decline, we also oversampled at the low and high ends of the age range to create a continuous and rectangular age distribution. This enabled us to partition the age groups in terms of increasing versus decreasing functions (see Williams et al., 1999, for a similar method).

Regarding hypotheses central to the current investigation, in accordance with the literature reviewed, we expected a U-shaped age function for search times across all conditions, though we expected conjunction-search and target-absent conditions to produce steeper age functions at both ends of the age range. More specifically, the manipulation of display size, as well as the contrast of feature and conjunction searches, speaks to the issue of inhibitory efficiency: Interactions of age group with display size, or with search type, favoring young adults would support an inhibition viewpoint. To be more precise in our interpretation of inhibitory efficiency, we also compared performance in a simple RT task with performance in the simplest two-item search condition to assess the effects of distraction and inhibitory efficiency. If inhibitory efficiency rises and falls as a function of age, we should observe substantial age interactions with distraction at both ends of the life span.

As for evaluating the cognitive speed hypothesis, we used simple RT as a measure of general information-processing speed and used it as a covariate in our statistical analyses. If individual differences in speed of processing account for differences in visual search performance, then we should observe a considerable reduction of age effects after covarying out speed. In addition, analyses using logRT were used to address disproportionately long response latencies as another way of examining the role of slowing.

As in previous life span investigations (e.g., Cepeda et al., 2001), we also considered the presence of other search effects that might be more specific to visual search (i.e., task-specific effects). To this end, we considered variables such as the ratios of performance under target-present and target-absent conditions (Lobaugh et al., 1998) to evaluate whether search strategy would be self-terminating or more similar to guided search. We also evaluated the effects of target eccentricity (the differences between central and peripheral targets) given that the ability to detect peripheral targets appears to vary with age (e.g., Akhtar, 1990; Ball, Beard, Roenker, Miller, & Griggs, 1988; A. B. Sekuler, Bennett, & Mamelak, 2000). In addition, given that visual acuity is known to change across the life span, particularly in the latter portion (e.g., Kline & Scheiber, 1985), we incorporated a composite measure of visual acuity in our analyses as a covariate measure.

Method

Participants

The visual search task studied here was part of a large multisession, multivariate study on life span differences in the organization of intellectual abilities and underlying basic cognitive and sensory processes (S.-C. Li et al., 2004). The study assessed individuals' performance regarding intelligence, basic information processing, and sensory functioning with over 30 tests and tasks across four 1-hour measurement sessions. The visual search task was administered in one of these sessions. To obtain a representative population-based life span sample, the parent sample of the study was randomly drawn from a list of 1,920 individuals (ages ranged from 6 to 89 years), which was provided by the Berlin City Registry. The sample was stratified by age. Because of rapid changes in cognitive development from ages 6 to 15, 1-year age bins were used for this range. In view of the developmental stability that is manifested in late adolescence and adulthood, 11 four-year age bins were used for the age range from 16 to 59. Finally, in light of data showing age-related declines in many domains of cognitive functioning, 10 three-year age bins were used for the age range from 60 to 89. To recruit participants, we sent a total of 1,873 invitation letters, and a total of 356 individuals agreed to participate in the study. Hence, the participation rate for the entire sample was 19%. It was highest for individuals in the age range from childhood to early adolescence (45.7%), followed by individuals in the range from late adolescence to middle adulthood (19.9%), and was lowest for individuals in the old adulthood range (10.5%). Of the 356 participants who initially agreed to participate, some missed two or more measurement sessions, and 1 participant reported multiple medical histories of head injury and unconsciousness in a self-report questionnaire about general physical and psychological conditions. No participants in our sample reported a diagnosis of attention-deficit/hyperactivity disorder. After we excluded these participants and those for whom some or all data from the visual search task were missing, the effective sample in our analyses included 298 participants in 31 age bins. The excluded individuals were evenly distributed across the different life periods. With the exception of three bins, all had equal (or close to equal) numbers of males and females. These participants were further subdivided into 10 age groups, which reflected a compromise between theoretically reasonable age ranges and comparable group sizes. The re-

Table 1

Reaction Time Medians (in Milliseconds), Standard Deviations, and Percentages of Errors (in Milliseconds) as a Function of Age Group, Simple Reaction-Time Task, and Search Task, Set Size, and Target Present or Absent

Age group	Age (years)	n	Simple response	Feature search						Conjunction search					
				Set size 2		Set size 8		Set size 14		Set size 2		Set size 8		Set size 14	
				Present	Absent	Present	Absent	Present	Absent	Present	Absent	Present	Absent	Present	Absent
1	6-8	29													
	<i>Mdn</i>		519	1,155	1,168	1,192	1,154	1,188	1,209	1,312	1,479	1,408	1,542	1,509	1,788
	<i>SD</i>		147	410	407	409	376	359	394	441	475	392	459	415	555
	Error (%)		0.00	2.05	0.99	0.80	0.77	1.27	1.08	2.62	2.19	2.85	1.44	5.40	0.61
2	9-11	30													
	<i>Mdn</i>		362	862	825	864	819	880	851	997	1,090	1,081	1,168	1,164	1,376
	<i>SD</i>		90	245	239	250	245	276	240	352	341	317	359	364	439
	Error (%)		0.00	1.34	1.61	0.86	0.96	1.05	0.58	1.64	1.50	3.15	1.85	4.47	2.25
3	12-14	30													
	<i>Mdn</i>		324	706	684	712	699	724	710	832	888	909	968	960	1,160
	<i>SD</i>		84	180	189	202	178	188	216	248	243	228	250	249	316
	Error (%)		0.00	0.77	0.96	1.04	0.00	1.22	0.39	2.06	1.69	2.16	0.97	3.96	0.68
4	15-22	27													
	<i>Mdn</i>		317	620	615	632	642	651	655	705	776	793	934	848	1,064
	<i>SD</i>		66	175	155	147	180	137	161	193	210	208	246	230	290
	Error (%)		0.02	0.65	0.64	0.97	0.31	0.96	0.44	1.29	1.34	2.00	0.86	2.84	0.44
5	23-33	27													
	<i>Mdn</i>		295	552	553	578	564	585	594	587	684	676	787	721	990
	<i>SD</i>		87	116	100	116	117	118	121	151	154	156	162	167	217
	Error (%)		0.2	1.09	0.44	0.86	0.31	0.64	0.42	0.54	1.48	1.25	0.83	3.06	0.62
6	34-44	28													
	<i>Mdn</i>		316	593	596	598	622	623	658	653	748	721	872	782	1,106
	<i>SD</i>		83	115	109	103	146	108	151	166	153	156	192	204	214
	Error (%)		0.00	1.24	0.10	0.42	0.42	0.31	0.00	0.88	0.84	0.84	0.51	1.35	0.21
7	45-55	27													
	<i>Mdn</i>		318	621	636	653	668	672	736	671	789	772	1,013	876	1,295
	<i>SD</i>		61	133	120	148	126	145	145	146	155	198	188	253	264
	Error (%)		0.00	0.33	0.65	0.22	0.00	0.31	0.11	0.84	0.86	1.68	0.22	3.21	0.11
8	56-66	32													
	<i>Mdn</i>		355	658	713	692	762	707	834	701	919	830	1,107	937	1,410
	<i>SD</i>		91	130	156	130	141	121	181	151	201	187	209	256	245
	Error (%)		0.00	0.55	0.64	0.61	0.18	0.28	0.00	0.46	0.55	1.58	0.09	2.46	0.00
9	67-77	35													
	<i>Mdn</i>		379	689	744	722	780	749	826	748	970	928	1,222	1,055	1,542
	<i>SD</i>		91	132	142	127	155	130	179	198	244	229	242	321	265
	Error (%)		0.00	0.90	0.57	0.75	0.17	0.93	0.08	0.73	1.36	2.74	0.25	2.51	0.08
10	78-88	33													
	<i>Mdn</i>		397	706	772	737	849	778	909	824	1,043	1,027	1,337	1,156	1,637
	<i>SD</i>		99	180	176	156	162	142	168	228	266	293	256	364	319
	Error (%)		0.00	0.86	0.45	0.94	0.44	0.61	0.45	1.01	1.61	3.11	0.44	4.75	0.44
Total	6-88	298													
	<i>Mdn</i>		360	718	734	740	761	759	804	805	945	920	1,105	1,008	1,350
	<i>SD</i>		110	181	180	179	183	172	196	228	246	238	257	286	313
	Error (%)		0.00	0.98	0.71	0.75	0.36	0.76	0.35	1.20	1.34	2.17	0.73	3.41	0.54

sulting groups, shown in Table 1, were 6-8, 9-10, 11-14, 15-22, 23-33, 34-44, 45-55, 56-66, 67-77, and 78-88 years (mean ages = 7, 10, 13, 17, 28, 39, 50, 62, 72, and 82 years, respectively), each including 27-35 participants. All participants were screened for visual abilities (see below), and if applicable, they wore their corrective lenses during the experiment.

Apparatus and Stimuli

Visual search task. The experiment was controlled by a custom-made program running on standard PCs connected to external keyboards via serial cables. Responses were performed manually by touching the left or right of two touch-sensitive metal plates with the index finger of the left or right hand, respectively. The two conditions of the visual search task were closely modeled after Foster et al.'s task (1995) except that in target-present trials we replaced one distractor by the target instead of adding it

to the display.¹ This method ensures that the total display size is always constant and thus cannot be used as a potential cue that indicates the

¹ One might argue that a two-item display does not engage the same set of feature-contrast detection mechanisms that more crowded displays do and thus that this condition is not a good baseline. And yet, it does meet a number of other, also important, requirements one would want a baseline to meet: (a) The perceptual search demands are not entirely absent but are more or less trivial; (b) the presence of at least one distractor in target-present displays ensures that some degree of response competition is established (Fournier, Bowd, & Herbert, 2000; Fournier, Eriksen, & Bowd, 1998); and (c) there is stimulus-induced uncertainty above and beyond what a simple RT task or a single-item display would measure.

presence of a target. Our stimulus arrays consisted of 2, 8, or 14 items, that is, 2, 8, or 14 distractors in target-absent trials and 1 distractor replaced by the target in target-present trials. The target was always a filled white circle 7 mm in diameter (subtending about 0.8° of visual angle from the viewing distance of approximately 50 cm) that appeared on the black screen of the computer monitor. In the feature-search condition, distractors consisted of unfilled white circles of the same size as the target. In the conjunction-search condition, distractors consisted of similar unfilled circles and filled white squares 7 mm on a side (i.e., $0.8^\circ \times 0.8^\circ$). The proportions of the two types of distractors were always equal (i.e., 1:1, 4:4, or 7:7) except that in the target-present trials, one distractor was replaced by the target. The presentation area of about $18.5 \text{ cm} \times 14.0 \text{ cm}$ ($20.7^\circ \times 15.8^\circ$) was divided into two invisible fields, an inner field of $9.25 \text{ cm} \times 7.0 \text{ cm}$ ($10.5^\circ \times 8.0^\circ$) around the screen center and an outer field covering the remaining area. Each field was further divided into four equally sized quadrants. The target was presented at a quasi-randomly determined location except that it was to appear with equal probability in (i.e., entirely within) each of the eight inner and outer quadrants. In the following sections we refer to targets appearing in the inner or outer field as inner and outer targets, respectively. Given the described setup, the center-to-center distance between the fixation point and inner targets thus varied between 0.5° and 10° on the horizontal dimension and between 0.5° and 7.5° on the vertical dimension, whereas outer targets varied between 11° and 20° on the horizontal dimension and between 8.5° and 15° on the vertical dimension. These distances roughly correspond to those investigated in the Foster et al. (1995) study. Distractors also appeared in quasi-randomly determined locations (a total of 1,008 locations were possible) except that no item was allowed to touch or overlap with any other item of the current display.

Simple RT task. In addition to the visual search task, the participants' simple RT was also measured. The participants' task was to respond by pressing the metal response plate (i.e., the same as in the visual search task) as soon as possible if any stimulus (either a square or a circle that was 1.5 cm or 1.7° in length or diameter) appeared on the center of the screen.

Both of the computerized experimental tasks were performed under conditions of corrected vision. That is, if the participants normally wore eyeglasses, they were told to wear their glasses to perform the tasks.

Visual acuity test. Visual acuity was measured in Snellen decimal units at two different distances using standard reading tables (Geigy, 1977). Distant visual acuity was assessed binocularly with reading tables presented at 7.5 meters (the letter reading table) and 5 meters (the Landolt rings). Close visual acuity was measured by a table with printed text and a table with Landolt rings at a 30-cm reading distance. The measurements were taken both with and without vision corrections. Past studies showed that corrected vision was more related to an individual's performance than uncorrected vision (e.g., Lindenberger & Baltes, 1994); therefore the analyses reported in this article were based on corrected vision. We computed a summary measure, or visual acuity index (VAI), that was based on the composite score of the participant's corrected distant vision and close vision.

Design and Procedure

Each participant contributed his or her visual search data in a single session. After receiving the instructions, participants were familiarized with the two types of search task by giving them 10 practice trials of feature and conjunction search. Then they worked through four 52-trial blocks, the first and the last blocks requiring feature search and the second and third blocks requiring conjunction search. A short break was offered after the second block. Care was taken to ensure that the test blocks were short in duration (less than 10 min) to minimize the possibility of fatigue for all age groups.

Each block consisted of four randomly determined unscored warm-up trials and 48 randomly ordered experimental trials with the possible combinations of 3 display sizes (2, 8, or 14 items), 2 conditions (target present or absent), and 8 target locations (4 inner and 4 outer quadrants, which mattered in target-present conditions only). Trials with incorrect responses

were repeated at some random trial in the remainder of the block, so that 16 valid replications were obtained for each combination of set size, condition and location. Trials began, after an intertrial interval of 1,500 ms, with the presentation of a central fixation cross for 1,000 ms. After a blank interval of 100 ms, the search display appeared and remained until a response was made or 5,000 ms had passed. Subjects indicated the presence of the target by pressing one key as quickly and accurately as possible, and they indicated the absence of a target by pressing the other key. Key mapping was fixed across all subjects. In case of a premature response ($RT < 150 \text{ ms}$), a response omission ($RT > 5,000 \text{ ms}$), or an incorrect keypress, a brief error message (two yellow question marks) was displayed on the screen for 1,000 ms.

Simple RT task. The simple RT condition was presented in one block with a total of 30 trials. Half of the trials were responded to with the left index finger, and the remaining half of the trials were responded to with the right index finger. A trial began, after an intertrial interval of 1,000 ms, with the presentation of a central fixation cross for 500 ms. The fixation cross was then followed by a random delay interval from 500 ms up to 3,499 ms, after which a stimulus was presented for 1,500 ms on the screen. Responses were valid only if made during the stimulus duration.

Results

Dependent Measures

Median RTs from correct trials and error percentages were computed for each combination of search task (feature vs. conjunction), set size, presence or absence of search target, and target location (inner vs. outer). These medians were then averaged across target location, a factor that was only considered in analyses of search slopes. Apart from logRTs, which were used as one way to check for general-slowing effects, individual search slopes and intercepts were computed for each combination of factors: task (i.e., feature and conjunction search), target presence or absence, and, in the case of target-present trials, target location. Specifically, the individual slopes and intercepts were derived from linear regressions of set size on mean RTs in the respective condition, run separately for each individual participant.² Median simple RTs were also computed and used as a covariate in RT analyses to compensate for peripheral slowing of sensory and motor processes. Finally, we used the VAI as a covariate in both RT and errors analyses to compensate for age-related or other differences in visual abilities. Table 1 provides an overview of RTs and error data, and Figure 1 shows age-group means for simple RTs and VAIs.

Overall Analyses

In our initial omnibus analyses, search RTs and error rates underwent analyses of variance (ANOVAs) with age group as a between-subjects factor, simple RT (for the RT analyses) and the VAI as covariates, and task, target presence, and set size as within-subject factors.

Response latency. As shown in Figure 1, reactions took longer in conjunction search than in feature search, $F(1, 286) = 24.28$,

² Individual fits varied considerably, but overall, linear regressions provided a good description of the search functions in all age groups (mean R^2 s ranging from .62 to .92). Interestingly, there was a systematic and reliable trend for goodness of fit indices to increase with age (R^2 s = .62, .73, .79, .74, .80, .75, .88, .86, .92, and .84, respectively), $F(1, 9) = 4.06$, $p < .01$.

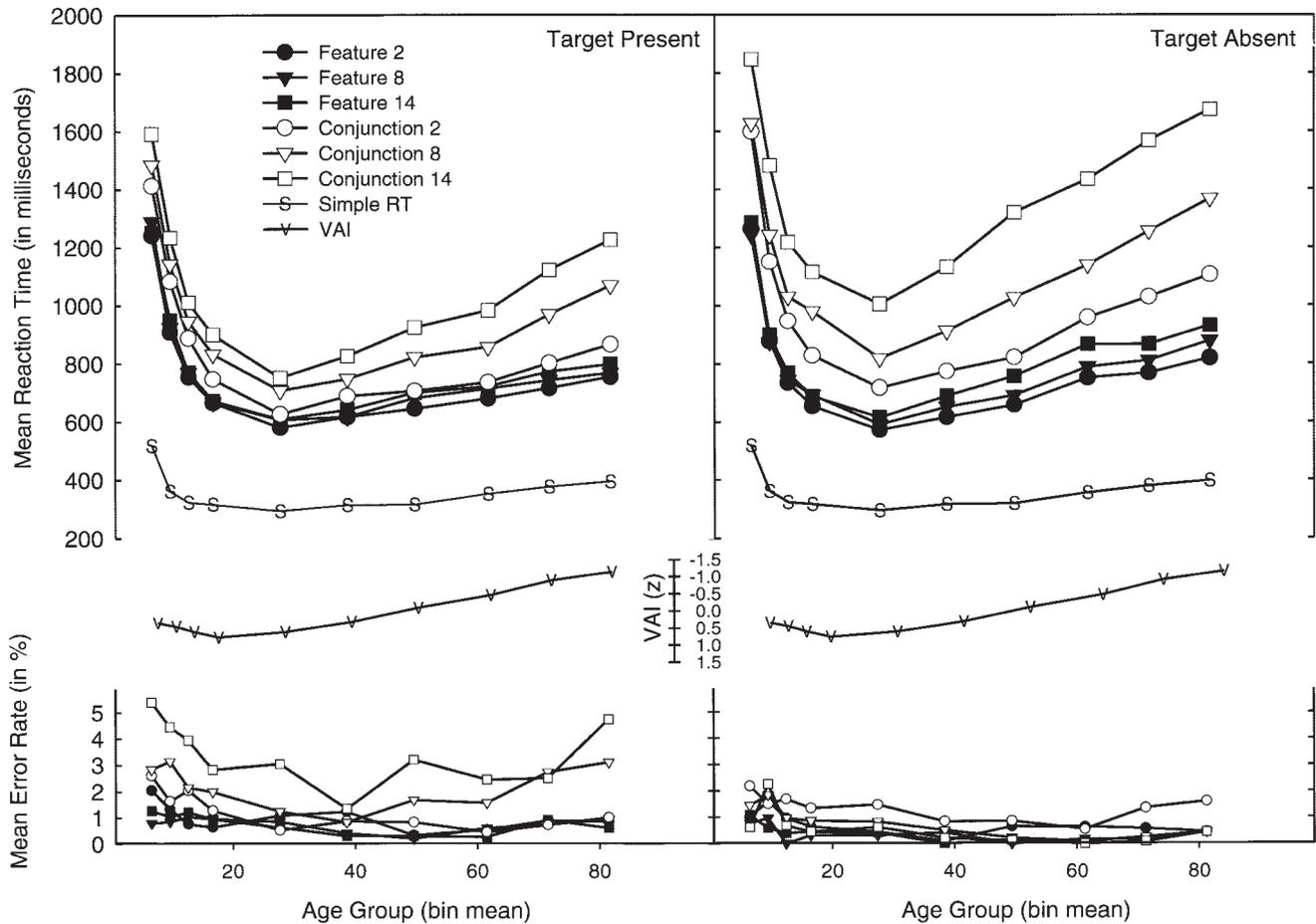


Figure 1. Mean reaction times (RTs) and error frequency by age group, search condition, set size, and target presence. For purposes of direct comparison, also shown are simple RTs and visual acuity indices (VAIs; given in standardized Z score units of the Snellen decimal points; the more negative the Z scores, the weaker the vision) by age group. As the factor of target present versus absent is not applicable for either simple RTs or VAIs, the same simple RT data and VAIs are plotted in both panels.

$p < .01$, if a target was absent than if it was present, $F(1, 286) = 13.67$, $p < .01$, and as set size increased, $F(2, 572) = 30.68$, $p < .01$. There was also a main effect of age group, $F(9, 286) = 15.58$, $p < .01$, indicating that the cross-sectional age gradients of RTs decreased with increasing age from 6 years up to 23–33 years but increased with age from there on. Interactions of task and set size, $F(2, 572) = 23.19$, $p < .01$, and of task and target presence, $F(1, 286) = 23.27$, $p < .01$, and a three-way interaction of task, set size, and target presence, $F(2, 572) = 7.82$, $p < .01$, indicated that the set-size and the presence-absence effects were both more pronounced in the conjunction-search than in the feature-search condition and that the set-size effect was most pronounced if conjunction targets were absent. All three manipulations interacted with age group: task, $F(9, 286) = 2.09$, $p < .05$, set size, $F(18, 572) = 2.04$, $p < .01$, and target presence, $F(9, 286) = 4.29$, $p < .01$.

Response accuracy. Errors were more frequent with conjunction search than feature search, $F(1, 286) = 145.44$, $p < .01$, if targets were present than if they were absent, $F(1, 286) = 147.22$, $p < .01$, and the larger the set size was, $F(2, 572) = 6.81$, $p < .01$. Note that the presence-absence effect followed a pattern opposite

from that for RTs, pointing to a speed-accuracy trade-off. The age-group effect was also significant, $F(9, 286) = 6.66$, $p < .01$, indicating that the overall error rate followed the same pattern as the RTs. Significant two-way interactions were obtained between task and set size, $F(2, 572) = 24.28$, $p < .01$, task and target presence, $F(1, 286) = 60.81$, $p < .01$, and target presence and set size, $F(2, 572) = 51.91$, $p < .01$, which were modified by a three-way interaction of task, set size, and target presence, $F(2, 572) = 45.62$, $p < .01$. The underlying pattern shows that set-size effects were most pronounced with present conjunction targets, whereas weaker and inverted set-size effects were obtained with absent targets, especially in conjunction search (see bottom curves in Figure 1). Age group interacted with task only, $F(9, 286) = 2.61$, $p < .01$, indicating that age effects were more pronounced in conjunction search than feature search.

Feature Search

A separate ANOVA on RTs from the feature-search task was computed with simple RT and the VAI scores as covariates. Apart

from the main effect of age group, $F(9, 286) = 22.09, p < .01$, the main effect of set size, $F(2, 572) = 7.92, p < .01$, and the interaction of age group and target presence, $F(9, 286) = 3.28, p < .01$, were highly significant, whereas the interaction of age group and set size, $F(18, 572) = 1.60, p < .06$, just missed the significance criterion. All four effects were significant in a corresponding ANOVA of logRTs (computed without the simple RT covariate), suggesting that they are unlikely to reflect just the generalized slowing effect.

To further explore the set-size-related effects within the feature-search conditions, we conducted an ANOVA on target-present search slopes with age group and target location (inner vs. outer target) as independent variables and the VAI as a covariate. Although slopes were steeper with outer targets than with inner targets, $F(1, 287) = 5.45, p < .05$, neither the age effect nor the interaction was significant. An analysis of target-absent slopes revealed no age effect ($p > .2$). Slope means in all age groups were clearly smaller than 10 ms/item; that is, search was very efficient even in the most difficult trials (see Figure 2). The ratio between slopes in target-present and target-absent trials was 1.5 on average—interestingly, exactly the same ratio as in conjunction search (see below).

Effects related to the presence or absence of the target were further decomposed in two ways. First, RT intercepts were analyzed as a function of age group and presence of target, with the VAI as a covariate. Main effects were obtained for age group, $F(9, 287) = 36.79, p < .01$, and target presence, $F(1, 287) = 220.28, p < .01$, and the interaction term was also reliable, $F(9, 287) = 3.98, p < .01$. Separate t tests of the presence-absence effect in each age group revealed reliable effects in the three oldest groups only. Indeed, as shown in Figure 3, RT intercepts for present and absent targets were in the same ballpark between 6 and 55 years of age but clearly diverged at older ages. As a comparison of the child developmental and aging portions of the curves shows, the presence-absence effect is not associated with the general RT level, which speaks against an account only in terms of generalized slowing. Moreover, the error rates in target-present and target-absent trials of the two-item condition—a relatively pure estimate of set-size-independent performance—do not show a pattern that would support an account in terms of a speed-accuracy trade-off.

A second method we used to decompose target-related effects was to compute absence:presence ratios for inner and outer targets (see corresponding group means in Figure 2).³ These ratios were then used as the dependent measure in an ANOVA with age group as a between-subjects factor and target eccentricity as a within-subject factor. The only finding was a not-quite-reliable main effect of age group, $F(9, 287) = 1.85, p < .06$, suggesting that what impairs feature-search performance in late life is the absence of a target, not how peripherally or centrally it is presented.

A final interesting observation concerns the relationship between performance in the simple RT task and performance in the two-item feature-search condition. Compare the respective age functions in Figure 1 (i.e., the two lowermost RT curves in the target-present panel). In Groups 1–4 (ages 6–22), the difference between the two curves varies strongly with age. This implies that the relative difficulty of finding a target among two items over detecting an awaited target is greater in children than in adults.⁴ However, from early adulthood on, there is no further indication of any change in relative difficulty; that is, the two curves very much run parallel to each other. Indeed, an overall ANOVA on simple

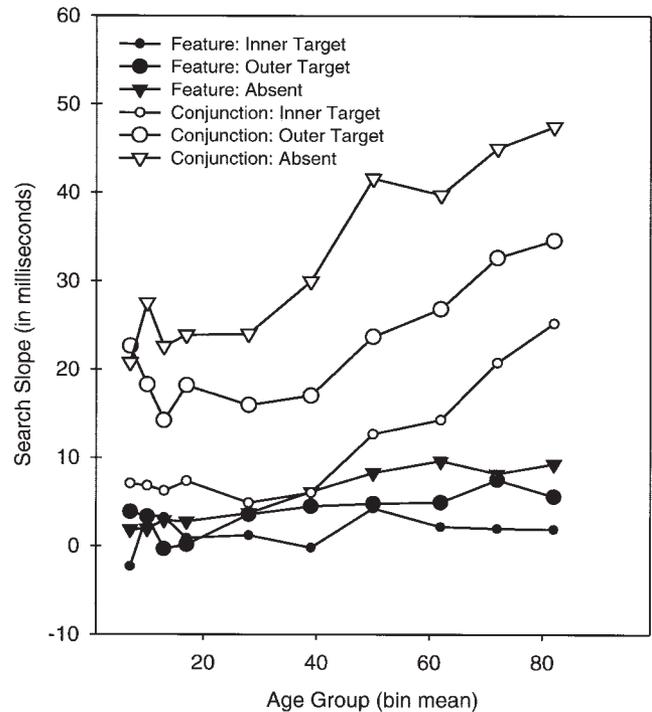


Figure 2. Mean search slopes (in milliseconds/item) by age group, search condition, target presence, and eccentricity.

RT and RT in the two-item inner-target-present condition of feature search, with the VAI as a covariate, produced a clear interaction of task and age group, $F(9, 287) = 14.37, p < .01$, that was entirely gone when Groups 1–4 were excluded ($p > .7$).

Conjunction Search

A separate ANOVA on RTs from conjunction search was computed with simple RT and the VAI as covariates. Main effects were obtained for age group, $F(9, 286) = 10.77, p < .01$, set size, $F(2, 572) = 31.33, p < .01$, and target presence, $F(1, 286) = 22.48, p < .01$. These were modified by two-way interactions of age group and target presence, $F(9, 286) = 3.23, p < .01$, and of set size and target presence, $F(2, 572) = 5.93, p < .01$, whereas the interaction of age group and set size just missed the significance

³ As the distinction between inner and outer does not apply to absent trials, we randomly divided the individual target-absent RTs into two dummy categories, the mean of one serving to compute the absent/present-inner ratio and the mean of the other serving to compute the absent/present-outer ratio. This procedure equated the number of RTs going into numerators and denominators and thus minimized possible differences in terms of distribution and variance.

⁴ Note that the target for the simple RT task was somewhat larger than the search target. Given the known negative correlation between signal intensity and RT (Kohfeld, 1971), this might explain part of the main difference between the RTs in the two tasks. However, intensity-related RT effects of 300 ms or more are rather uncommon and until now have been observed only with much more drastic variations in intensity than the differences between the sizes of our targets would imply (for overviews, see Luce, 1986; Teichner & Krebs, 1972).

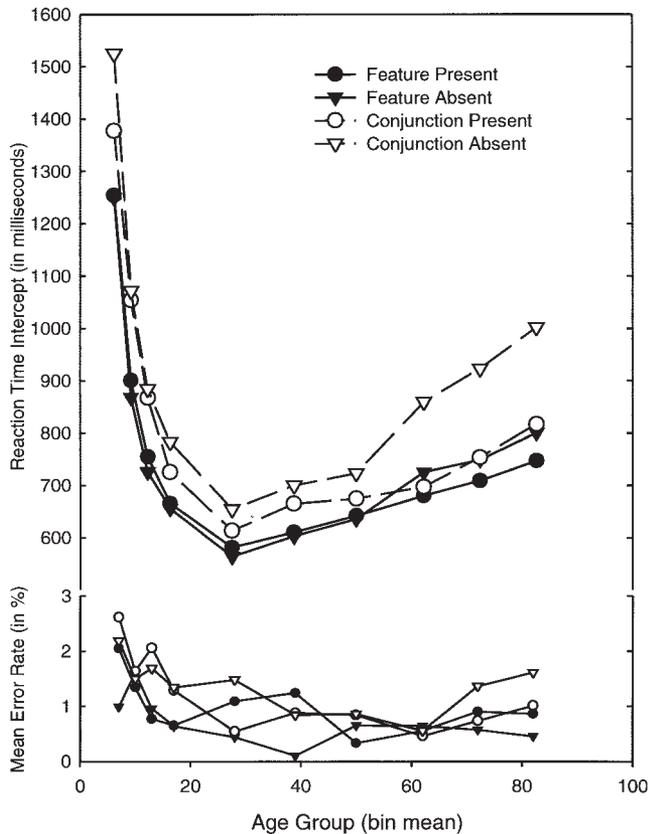


Figure 3. Mean search intercepts and error rates by age group, search condition, and target presence.

criterion, $F(18, 572) = 1.60, p < .06$. Again, all effects remained (or became) reliable in a corresponding ANOVA of logRTs, which speaks against an account strictly in terms of generalized slowing.

Set-size-related effects were further analyzed by means of an ANOVA on search slopes with age group and target location (inner vs. outer target) as independent variables and the VAI as a covariate. Again, main effects of both age group, $F(9, 287) = 1.93, p < .05$, and target location, $F(1, 287) = 78.79, p < .01$, were significant, but the interaction was not. As Figure 2 shows, performance was relatively age invariant within the five younger age groups, with very shallow (< 10 ms/item) slopes for inner targets, steeper (~ 20 ms/item) slopes for outer targets, and the steepest (~ 25 ms/item) slopes for absent targets. The five older groups produced slopes in the same order; yet overall the slopes were steeper, and their steepness increased continuously with age, up to about 50 ms/item in the oldest group. Interestingly, however, the relationship between slopes for inner and outer targets was constant across age, suggesting that the deficits of visual search in late life are not due to factors depending on target eccentricity. Also of interest, both target-absent slopes and the ratio of target-absent to target-present slopes did not vary much, or systematically, across age (1.2, 1.6, 1.6, 1.5, 1.6, 1.7, 1.6, 1.5, 1.4, 1.3, for Groups 1 through 10, respectively). The mean ratio of 1.5 was identical to that observed in feature search.

Analysis of the intercepts for target-present and target-absent conditions, with the VAI as a covariate, produced significant main

effects of age group, $F(9, 287) = 33.59, p < .01$, and target presence, $F(1, 287) = 81.40, p < .01$, and an interaction, $F(1, 287) = 3.69, p < .01$. Separate t tests produced reliable presence-absence effects in all but Groups 2, 3, and 6. To see how the sizes of the present-absent effect differ between age groups while taking into account group differences in baseline RT, we calculated effect proportions by dividing the effect size (target-absent RT intercept – target-present RT intercept) by the RT level (mean of the target-present and target-absent RT intercepts). The group means for the 10 groups were 9.4%, 2.7%, 2.0%, 7.6%, 6.1%, 5.0%, 6.7%, 20.8%, 19.8%, and 20.0%. In an ANOVA analyzing these percentages, with the VAI as a covariate, age group still produced a significant effect, $F(9, 287) = 4.01, p < .01$. However, this effect was due to the oldest three groups, and indeed, the effect was eliminated when the analysis was rerun using Groups 1–7 only ($p > .5$). The analysis of absence:presence ratios for inner and outer targets did not reveal any main effect or interaction, which provides further evidence that impairments of conjunction search in old age do not reflect particular problems with more peripheral targets.

Discussion

The main purpose of this study was to determine if the processes and mechanisms that improve visual search performance during child development are also those responsible for declining search performance in old age and whether there are aspects that are specific to different parts of the life span, commonalities notwithstanding. We found scant evidence for a correspondence between the effects observed at the two ends of the life span. In both feature search and conjunction search, the age functions we obtained were asymmetrical, and children and older adults exhibited substantially different performance patterns, results similar to those from other life span studies of attention (Cepeda et al., 2001; Trick & Enns, 1998; Williams et al., 1999). We consider first the evidence related to the two general-factor models, and then we discuss the more specific age asymmetries that were revealed in our analyses of feature- and conjunction-search conditions separately.

Comparison With General-Factor Models

The ability to search for a simple feature or a feature conjunction improves during childhood and adolescence and then worsens with increasing age, thereby describing a (somewhat tilted) inverted U-shaped life span performance function. However, our findings do not suggest that the rise and fall reflect comparable, mirror-symmetric developments, and thus they suggest that specific mechanisms other than just the general speed of information processing (e.g., Kail & Salthouse, 1994) are necessary to account for life span differences in visual search. In childhood, searching for a simple feature among just two items took three times as long as performing a simple RT task, yet performance indicative of attentional control proper, shown by search slope or target present-absent ratios, was indiscriminable from that of adults. In stark contrast, older adults exhibited no more of an increase from a simple RT task to feature search than did young adults, yet they showed pronounced deficits in attentional control parameters. Thus, although slow response latencies in the younger half of the life span may be attributed to developments in cognitive speed, we

do not see how the total pattern of gains and losses can be modeled exclusively in such terms.

Our findings also argue against a unitary inhibition model of cognitive development and aging (cf. Dempster, 1992; Harnishfeger, 1995). Certainly, many age-related effects can be described in inhibition terms: Search slopes may reflect the need to inhibit distractors, absent trials may require the inhibition of distractor-induced activation, and so forth. However, although previous research has revealed quite a number of inhibition-related deficits in young children (e.g., Décarry & Richer, 1995; Gerstadt, Hong, & Diamond, 1994; Livesey & Morgan, 1991; Mischel & Mischel, 1983; Williams et al., 1999), we did not obtain much evidence of cognitive impairments in search performance. The only exception may be the substantial increase of RTs from the simple RT task to the two-item feature-search task in the youngest age groups. As the difference between these tasks is mainly the presence of a distractor in feature search, this increase may at least partly reflect the inability to ignore that distractor and, hence, may indicate inhibitory mechanisms that are not yet fully developed. However, given the lack of any comparable effect in older participants, it seems clear that elderly adults do not share the problems that children exhibit. Rather, the problems the elderly have, as expressed in search slopes and in performance on target-absent trials, are not shared by children, young adults, or middle-aged adults. Thus, if the difficulties observed in children and older subjects have something to do with specific inhibitory processes, these processes are unlikely to be the same (Plude et al., 1994).

Although speed and inhibition together do account for some aspects of performance, neither processing speed nor selective inhibition *alone* is sufficient to account for age differences both in the improvement of and the decline in visual search performance across the life span. We next consider the findings in more detail with respect to specific effects of task, distractibility, search strategy, and target eccentricity, in relation to previous work.

Feature Search

When analyzing feature-search performance, we were able to replicate the improvement of search performance from childhood to adulthood reported in the available studies (e.g., Ruskin & Kaye, 1990) as well as the previously observed decrease shown in cognitive aging research (e.g., Plude & Doussard-Roosevelt, 1989). Although the general relation of feature-search RT to age was indeed U-shaped as expected, our detailed analyses suggested differences in more specific mechanisms.

Susceptibility to distraction. First, the relation between performance in the simple RT condition and performance in the easiest search condition indicates that the presence of just a single distractor impaired the performance of children up to adolescence but did not similarly affect elderly participants. This observation is consistent with the inhibitory approaches to child cognitive development (e.g., Diamond, 1990; Gerstadt et al., 1994) that assume that young children have difficulties ignoring task-irrelevant information because the cortical systems responsible for inhibitory processes are not yet fully matured. However, inasmuch as the mere presence of distractors reflects problems with inhibiting irrelevant information, our finding that performance in old age was unaffected by distraction in a simple task context (consistent with the results of Ho & Scialfa, 2002, and Scialfa et al., 2000) does not

fit inhibition accounts of cognitive aging (i.e., Dempster, 1992; Hasher & Zacks, 1988).

Increased cautiousness. A second observation is that response latencies markedly increased if no target appeared. This effect was restricted to the three oldest age groups (lower bound: 56 years). There are indications that this pattern cannot simply be due to general slowing: For one thing, when proportional RTs were analyzed, the pattern remained robust. For another, children exhibit much longer RTs without showing evidence of any particular problem with absent targets.

A possible reason for why the absence of a target might impair performance in elderly adults is that cortical noise increases with age (e.g., S.-C. Li, Lindenberger, & Sikström, 2001; Welford, 1965). If so, the “calling signals” (Wolfe, 1994) from feature maps, which are commonly assumed to indicate the presence of a target, may be too weak or at least judged to be an inadequate basis for a response. As a consequence, older adults may spend more time sampling sensory evidence to achieve a reliable signal-to-noise ratio and/or to make sure that the signal actually belongs to the target object. In case the target is absent, either they may check all items, though this is less likely given that we did not obtain disproportionate set-size interactions with age group, or they may check at least those signals that are strong enough to represent possible targets, consequently increasing RTs. Hence, older adults may be more cautious (Rush, Panek, & Russell, 1986) when or before saying no (e.g., Ho & Scialfa, 2002). Notably, Scialfa, Thomas, and Joffe (1994) found that older adults did not make significantly more regressive eye movements than did younger adults, which suggests that the increased search times do not reflect more rechecking per se (see also Ho & Scialfa, 2002, regarding conjunction search).

In previous work, it has been argued that older adults attempt to compensate, sometimes perhaps even to overcompensate, for bodily and cognitive deficits by becoming more cautious (e.g., Rush et al., 1986), a strategy less likely to play a role in children’s performance. That this pattern of findings did not lead to a substantial speed–accuracy trade-off (i.e., longer RTs were accompanied by more errors) suggests that older adults were demonstrating true cognitive and attentional difficulties, which led to more cautious performance.

Conjunction Search

As expected, conjunction search not only increased RTs and error rates compared with feature search, it also did so more in the very young and the very old than in middle-aged adults. This pattern nicely replicates both the positive age correlation of conjunction-search performance reported in child developmental studies and the negative age correlation observed in cognitive aging studies (e.g., Plude et al., 1994; Trick & Enns, 1998). However, as in feature search, further analyses of more specific aspects did not reveal identical processing difficulties at the two ends of the life span.

Search slopes. First, although there was little decrease in search slopes from childhood to adolescence, we observed a steady increase in the steepness of search slopes from early adulthood to old age. In fact, although children responded more slowly and were more susceptible to the mere presence of distractors overall (i.e., when performance in the set-size 2 condition is compared with simple RT performance), the conjunction-search slopes did

not vary much across age groups during development. When averaged across location, search slopes hardly varied numerically until adulthood (15, 13, 10, 13, and 10 ms/item for Groups 1–5, respectively), and even a separate test of target-present slopes in the younger half of the sample did not reveal any effect of age ($p > .3$). This result is inconsistent with previous studies that showed decreasing conjunction-search slopes across childhood. For instance, Ruskin and Kaye (1990) observed a decrease from 14 to 7 ms/item between 5- to 6-year-olds and 11- to 12-year-olds. Lobaugh et al. (1998) found a decrease from 26 to 15 ms/item between 7- to 8-year-olds and adults. Similarly, Trick and Enns (1998) found a decrease from 32 to 9 ms/item between 6-year-olds and 22-year-olds. With respect to adults, our findings (10 ms/item in 23- to 33-year-olds) compare well with the observations reported in these earlier studies, which rules out the possibility that our task version might have been special somehow or simply too easy to be sensitive to age differences. The pronounced increase of slopes in older adults' performance demonstrates that our task was sufficiently sensitive to pick up age effects. Indeed, a comparison with the results of Foster et al. (1995), after whose study our task version was modeled, shows a nearly perfect replication of their findings. Foster et al. investigated the four age groups of 18–30, 56–65, 66–75, and 76–85 years, which produced conjunction-search slopes of 9, 19, 21, and 29 ms/item, respectively. If we regroup our subjects accordingly, we obtain slopes of 12, 20, 27, and 25 ms/item, respectively.

We hesitate to base strong conclusions on the mere absence of an age effect in early child development, especially in the face of contrasting evidence. However, it seems clear that with respect to conjunction-search slopes, the age-related losses do not compare to the gains, which suggests that aging processes affect attentional control differently than does early child development. Importantly, this asymmetry of slope effects is associated with RT plateaus that exhibit exactly the opposite pattern; that is, RTs are much longer in children than in elderly subjects. This finding implies that any attempt to adjust the slopes for general slowing in children would have resulted in a gross distortion of the results in comparison with those of middle-aged adults (a conclusion already drawn by Tricks & Enns, 1998) as well as an underestimation of the difficulties older subjects apparently experienced.

Guided search strategy? As in our analyses of feature search, RT was largely increased when no target appeared. Here, the effect was restricted to subjects in their sixties or older and did not increase further. Given that it does not change much if expressed in terms of RT proportions and in view of the much smaller effect in children (who produced much longer RTs), it is clear that this pattern does not reflect generalized slowing. The close correspondence to the pattern obtained for feature search suggests that the processing problem that older adults face in target-absent trials is similar, albeit more pronounced in conjunction search. Inasmuch as they address this processing problem by means of a cautious search strategy, as discussed above, our findings rule out the possibility that search is serial and exhaustive. If it were, one would expect greater target absence costs with larger set sizes; yet, given the lack of an interaction between age and target in the slope analyses (see Figure 2) there is little evidence of such a relationship.

Quite to the contrary, the target-absent:target-present slope ratios were impressively independent of age, falling far below 2.

Serial models of visual search take a 2:1 ratio to indicate that before making a target-absent decision, subjects need to scan or evaluate all items of a display, whereas in target-present trials the target will be found after scanning half of the items on average (e.g., Treisman & Gelade, 1980). If so, the ratio of 1.5:1 we obtained suggests that subjects did not scan all items even on target-absent trials, but only about half of them. Presumably, our subjects focused on only one of the two target-defining dimensions (e.g., shape) and searched for the target only among the items matching it—that is, search was not blind but guided (Wolfe, 1994). That subjects are able to constrain their search to parts of the display items and produce ratios below 2 corroborates previous findings in the aging literature (e.g., Madden, Gottlob, & Allen, 1999; Madden et al., 1996). More interesting, however, is that children appeared to use a comparable search strategy, which is consistent with unpublished evidence suggestive of age invariance in search strategy when preschoolers, children, and young adults were compared (Doussard-Roosevelt, 1989, as cited by Plude et al., 1994).

Alternatively, ratios of less than 2:1 could also be consistent with a parallel search mechanism that evaluates displayed items concurrently but that needs more time to determine the absence than the presence of a target (Bundesen, 1990; Townsend, 1990). Parallel models would not require additional assumptions to account for the ratios we obtained, which would obviate our considerations regarding possible search strategies. Importantly, however, even a parallel account would need to start with the assumption that the efficiency of the mechanism responsible for ratios greater than 1:1 (e.g., the amount of cortical cross talk) does not seem to change with age.

Target eccentricity. Another interesting outcome of our study is the lack of any interaction between age and target location. Following R. Sekuler and Ball (1986), several authors have assumed that aging is accompanied by a reduction in the useful field of view. If so, this might additionally increase age-related impairments of visual search if the target appears in the visual periphery; that is, age effects on search slopes might increase with target eccentricity. However, the empirical evidence on this issue is far from clear. Although some authors have found age-related deficits to increase with more eccentric targets in feature search only (Scialfa et al., 1994, 1998), others have found such a pattern in conjunction search only (Foster et al., 1995; Plude & Doussard-Roosevelt, 1989), and still others have found no evidence of age-differential eccentricity effects at all (Madden et al., 1996; Scialfa & Joffe, 1997). Our own observations fall decidedly into the last category: Although search slopes increased with eccentricity in the conjunction task, they did so in all age groups, thus extending the available results to childhood and adolescence. Akhtar's (1990) review of developmental differences in peripheral vision concurs, though the child findings are somewhat mixed.

One reason for this failure to find an effect might be the limited range of target eccentricities and set sizes we tested: no more than 14 items spread over the range from 5° to 20°, compared with up to 47 items spread over up to 30° in the Ball et al. (1988) study, for an example. However, given that other researchers did find interactions between age and eccentricity under display conditions comparable to ours (e.g., Foster et al., 1995), there are reasons to doubt that range factors provide a sufficient explanation.

Conclusions

The present work represents an attempt to examine processes underlying the development of visual search performance across the life span. The life span conception and design are helpful for the detection of similarities and differences between the processes of cognitive child development and aging (S.-C. Li et al., 2004). In the current study, although there are some general similarities in children's and older adults' performance (e.g., search latency being longer in general and conjunction-search latency being disproportionately longer in children and in old adults), there are also indications of processes specific to each of these two life periods. Children's performance was particularly affected by the mere presence of distractors, whereas old people's search performance was particularly impaired when the target was absent and the search set size was large. As such, we doubt that a single-factor approach is able to account for the more subtle patterns observed in the life span development of visual search. Rather, our observations suggest that the problems children face when searching for targets are primarily associated with distractibility, whereas the search performance of older adults is better characterized by a combination of neurocognitive decline and a more careful search style (e.g., exhaustive search under the target-absent condition) that may be compensatory.

One can conceptualize these differing sources of developmental variation in terms of Baltes's (1997; Baltes, Reese & Lipsitt, 1980) life span theoretical perspective, which argues that early developmental differences are driven primarily by biological factors, or cognitive mechanics, whereas performance differences in late life, although reflective of a decline of cognitive mechanics and their underlying neurobiological processes, also reflect a greater reliance on pragmatic abilities and a compensatory strategy. For instance, it has been demonstrated that unlike basic information-processing mechanisms, culture- and experience-based pragmatic abilities remain stable even into very old age (S.-C. Li et al., 2004). Furthermore, under dual task conditions, old adults were more inclined to use compensatory strategies than were young adults (K. Z. H. Li, Lindenberger, Freund, & Baltes, 2001). Just as Plude et al. (1994), with respect to selective inhibitory control that is more directly implicated in the visual search performance under investigation, have speculated that early improvements in selective attention may reflect the myelination of neural pathways, so age-related decline during aging may reflect more experiential influences, in addition to declines in neuromodulatory mechanisms that may contribute to less robust basic information processing (e.g., K. Z. H. Li et al., 2001; S.-C. Li & Lindenberger, 1999).

We deliberately focused on general candidate mechanisms, previously identified as relevant to life span changes in cognition, but we acknowledge that other more specific factors warrant more detailed examination within a life span experimental approach (e.g., Cepeda et al., 2001; Williams et al., 1999). Although it is self-evident that trade-offs exist between theoretical parsimony and precision when conducting life span developmental research, we contend that it is important to study developmental processes in any given phenomenon by considering general mechanisms that are known to improve and decline across the life span while simultaneously examining processes that are more specific to the experimental task. Using a common test methodology across an age-continuous cross-sectional sample in the present study, we

were able to consider multiple levels of explanation in a more coherent way than previously reported (cf. Trick & Enns, 1998).

References

- Akhtar, N. (1990). Peripheral vision in young children: Implications for the study of visual attention. In J. T. Enns (Ed.), *The development of attention: Research and theory* (pp. 245–262). Amsterdam: Elsevier Science.
- Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America*, *5*, 2210–2219.
- Baltes, P. B. (1997). On the incomplete architecture of human ontogenesis: Selection, optimization, and compensation as a foundation of developmental theory. *American Psychologist*, *52*, 366–380.
- Baltes, P. B., Reese, H. W., & Lipsitt, P. (1980). Life-span developmental psychology. *Annual Review of Psychology*, *31*, 65–110.
- Belmont, J. (1996). Commentary: The “inverted-U” shapedness of mental development. *Journal of Russian and East European Psychology*, *34*, 12–15.
- Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*, 523–547.
- Cave, K. R., & Wolfe, J. M. (1990). Modeling the role of parallel processing in visual search. *Cognitive Psychology*, *22*, 225–271.
- Cepeda, N. J., Kramer, A. F., & Gonzalez de Sather, J. C. M. (2001). Changes in executive control across the life span: Examination of task-switching performance. *Developmental Psychology*, *37*, 715–730.
- Cerella, J. (1985). Information-processing rates in the elderly. *Psychological Bulletin*, *98*, 67–83.
- Cerella, J., & Hale, S. (1994). The rise and fall in information processing rates over the life span. *Acta Psychologica*, *86*, 109–197.
- Comalli, P. E., Wapner, S., & Werner, H. (1962). Interference effects of the Stroop color-word test in children, adulthood, and aging. *Journal of Genetic Psychology*, *100*, 47–53.
- Décary, A., & Richer, F. (1995). Response selection deficits in frontal excisions. *Neuropsychologia*, *33*, 1243–1253.
- Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review*, *12*, 45–75.
- Diamond, A. (1990). The developmental and neural bases of memory functions as indexed by the AB and delayed response tasks in human infants and infant monkeys. *Annals of the New York Academy of Sciences*, *608*, 267–317.
- Doussard-Roosevelt, J. A. (1989). *Feature integration theory and the development of selective attention*. Unpublished doctoral dissertation, University of Maryland, College Park.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*, 433–458.
- Folk, C. L., & Lincourt, A. E. (1996). The effects of age on guided conjunction search. *Experimental Aging Research*, *22*, 99–118.
- Foster, J. K., Behrmann, M., & Stuss, D. T. (1995). Aging and visual search: Generalized cognitive slowing or selective deficit in attention? *Aging and Cognition*, *2*, 279–299.
- Fournier, L. R., Bowd, C., & Herbert, R. J. (2000). Interference from multi-dimensional objects during feature and conjunction discriminations. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *53A*, 191–209.
- Fournier, L. R., Eriksen, C. W., & Bowd, C. (1998). Multiple-feature discrimination faster than single-feature discrimination within the same object? *Perception & Psychophysics*, *60*, 1384–1405.
- Geigy, J. R. (1977). *Wissenschaftliche Tabellen* [Scientific tables]. Basel, Switzerland: J. R. Geigy AG.
- Gerstadt, C. L., Hong, Y. J., & Diamond, A. (1994). The relationship between cognition and action: Performance of children 3½–7 years old on a Stroop-like day-night test. *Cognition*, *53*, 129–153.

- Harnishfeger, K. K. (1995). The development of cognitive inhibition: Theories, definitions, and research evidence. In F. N. Dempster (Ed.), *Interference and inhibition in cognition* (pp. 175–204). London: Academic Press.
- Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). New York: Academic Press.
- Ho, G., & Scialfa, C. T. (2002). Age, skill transfer, and conjunction search. *Journals of Gerontology: Psychological Sciences*, 57B, P277–P287.
- Humphrey, D. G., & Kramer, A. F. (1997). Age differences in visual search for feature, conjunction, and triple-conjunction targets. *Psychology and Aging*, 12, 704–717.
- Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin*, 109, 490–501.
- Kail, R., & Salthouse, T. A. (1994). Processing speed as a mental capacity. *Acta Psychologica*, 86, 199–225.
- Kline, D. W., & Scheiber, W. (1985). Vision and aging. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (pp. 296–331). New York: Van Nostrand Reinhold.
- Kohfeld, D. L. (1971). Simple reaction time as a function of stimulus intensity in decibels of light and sound. *Journal of Experimental Psychology*, 88, 251–257.
- Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibition processing in attention. *Psychology and Aging*, 4, 491–512.
- Kramer, A. F., Martin-Emerson, R., Larish, J. F., & Andersen, G. J. (1996). Aging and filtering by movement in visual search. *Journal of Gerontology: Psychological Sciences*, 51B, P201–P216.
- Li, K. Z. H., Lindenberger, U., Freund, A. M., & Baltes, P. B. (2001). Walking while memorizing: A SOC study of age-related differences in compensatory behavior under dual-task conditions. *Psychological Science*, 12, 230–237.
- Li, S.-C., & Lindenberger, U. (1999). Cross-level unification: A computational exploration of the link between deterioration of neurotransmitter systems and dedifferentiation of cognitive abilities in old age. In L.-G. Nilsson & H. Markowitsch (Eds.), *Cognitive neuroscience of memory* (pp. 103–146). Toronto, Ontario, Canada: Hogrefe & Huber.
- Li, S.-C., Lindenberger, U., Hommel, B., Aschersleben, G., Prinz, W., & Baltes, P. B. (2004). Life span transformations in the couplings among intellectual abilities and constituent cognitive processes. *Psychological Science*, 15, 155–163.
- Li, S.-C., Lindenberger, U., & Sikström, S. (2001). Aging cognition: From neuromodulation to representation. *Trends in Cognitive Sciences*, 5, 479–486.
- Light, L. L. (1991). Memory and aging: Four hypotheses in search of data. *Annual Review of Psychology*, 42, 333–376.
- Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychology and Aging*, 9, 339–355.
- Livesey, D. J., & Morgan, G. A. (1991). The development of response inhibition in 4- and 5-year-old children. *Australian Journal of Psychology*, 43, 133–137.
- Lobaugh, N. J., Cole, S., & Rovet, J. F. (1998). Visual search for features and conjunctions in development. *Canadian Journal of Experimental Psychology*, 52, 201–211.
- Luce, R. D. (1986). *Response times: Their role in inferring elementary mental organization*. New York: Oxford University Press.
- Madden, D. J., Gottlob, L. R., & Allen, P. A. (1999). Adult age differences in visual search accuracy: Attentional guidance and target detectability. *Psychology and Aging*, 14, 683–694.
- Madden, D. J., Pierce, T. W., & Allen, P. A. (1996). Adult age differences in the use of distractor homogeneity during visual search. *Psychology and Aging*, 11, 454–474.
- Mischel, H. N. & Mischel, W. (1983). The development of children's knowledge of self-control strategies. *Child Development*, 54, 603–619.
- Oken, B. S., Kishiyama, S. S., & Kaye, J. A. (1994). Age-related differences in visual search task performance: Relative stability of parallel but not serial search. *Journal of Geriatric Psychiatry and Neurology*, 7, 163–168.
- Plude, D. J., & Doussard-Roosevelt, J. A. (1989). Aging, selective attention, and feature integration. *Psychology and Aging*, 4, 98–105.
- Plude, D. J., Enns, J. T., & Brodeur, D. (1994). The development of selective attention: A life-span overview. *Acta Psychologica*, 86, 227–272.
- Plude, D. J., & Hoyer, W. J. (1981). Adult age differences in visual search as a function of stimulus mapping and information load. *Journal of Gerontology*, 36, 598–604.
- Plude, D. J., & Hoyer, W. J. (1985). Attention and performance: Identifying and localizing age deficits. In N. Charness (Ed.), *Aging and human performance* (pp. 47–99). London: Wiley.
- Rabbitt, P. (1965). An age decrement in the ability to ignore irrelevant information. *Journal of Gerontology*, 20, 233–237.
- Rush, M., Panek, P., & Russell, J. (1986). Cautiousness and visual selective attention performance among older adults. *Journal of Genetic Psychology*, 148, 225–235.
- Ruskin, E. M., & Kaye, D. B. (1990). Developmental differences in visual processing: Strategy versus structure. *Journal of Experimental Child Psychology*, 50, 1–24.
- Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, 103, 403–428.
- Scialfa, C. T., Esau, S. P., & Joffe, K. M. (1998). Age, target-distractor similarity, and visual search. *Experimental Aging Research*, 24, 337–358.
- Scialfa, C. T., Jenkins, L., Hamaluk, E., & Skaloud, P. (2000). Aging and the development of automaticity in conjunction search. *Journals of Gerontology: Psychological Sciences*, 55B, P27–P46.
- Scialfa, C. T., & Joffe, K. M. (1997). Age differences in feature and conjunction search: Implications for theories of visual search and generalized slowing. *Aging, Neuropsychology, and Cognition*, 4, 227–246.
- Scialfa, C. T., & Joffe, K. M. (1998). Response times and eye movements in feature and conjunction search as a function of target eccentricity. *Perception & Psychophysics*, 60, 1067–1082.
- Scialfa, C. T., Thomas, D. M., & Joffe, K. M. (1994). Age differences in the useful field of view: An eye movement analysis. *Optometry and Vision Science*, 71, 1–7.
- Sekuler, A. B., Bennett, P. J., & Mamelak, M. (2000). Effects of aging on the useful field of view. *Experimental Aging Research*, 26, 103–120.
- Sekuler, R., & Ball, K. (1986). Visual localisation: Age and practice. *Journal of the Optical Society of America A: Optics, Image Science and Vision*, 3, 864–867.
- Teichner, W. H., & Krebs, M. J. (1972). Laws of the simple visual reaction time. *Psychological Review*, 79, 344–358.
- Theeuwes, J., & Kooi, F. L. (1994). Parallel search for a conjunction of shape and contrast polarity. *Vision Research*, 34, 3013–3016.
- Thompson, L. A., & Massaro, D. W. (1989). Before you see it, you see its parts: Evidence for feature encoding in pre-school children and adults. *Cognitive Psychology*, 21, 334–362.
- Tipper, S. P. (1991). Less attentional selectivity as a result of declining inhibition in older adults. *Bulletin of the Psychonomic Society*, 29, 45–47.
- Townsend, J. T. (1990). Serial and parallel processing: Sometimes they look like Tweedledum and Tweedledee but they can (and should) be distinguished. *Psychological Science*, 1, 46–54.
- Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 97–136.
- Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, 95, 15–48.
- Treisman, A., & Sato, S. (1990). Conjunction search revisited. *Journal of*

Experimental Psychology: Human Perception and Performance, 16, 459–478.

Trick, L., & Enns, J. (1998). Life span changes in attention: The visual search task. *Cognitive Development*, 13, 369–386.

Welford, A. T. (1965). Performance, biological mechanisms and age: A theoretical sketch. In A. T. Welford & J. E. Birren (Eds.), *Behavior, aging, and the nervous system* (pp. 3–20). Springfield, IL: Charles C Thomas.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, 120, 272–292.

Williams, B., Ponesse, J., Schachar, R., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology*, 25, 205–213.

Wolfe, J. M. (1994). Guided search 2.0. A revised model of visual search. *Psychonomic Bulletin & Review*, 1, 202–238.

Wolfe, J. M. (1998). Visual search. In H. Pashler (Ed.), *Attention* (pp. 13–73). Hove, England: Erlbaum.

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 419–433.

Zacks, R. T., Hasher, L., & Li, K. Z. H. (2000). Human memory. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed., pp. 293–357). Mahwah, NJ: Erlbaum.

Zacks, J. L., & Zacks, R. T. (1993). Visual search times assessed without reaction times: A new method and an application to aging. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 798–813.

Received October 2, 2002
 Revision received January 15, 2004
 Accepted February 25, 2004 ■



**AMERICAN PSYCHOLOGICAL ASSOCIATION
 SUBSCRIPTION CLAIMS INFORMATION**

Today's Date: _____

We provide this form to assist members, institutions, and nonmember individuals with any subscription problems. With the appropriate information we can begin a resolution. If you use the services of an agent, please do **NOT** duplicate claims through them and directly to us. **PLEASE PRINT CLEARLY AND IN INK IF POSSIBLE.**

PRINT FULL NAME OR KEY NAME OF INSTITUTION _____		MEMBER OR CUSTOMER NUMBER (MAY BE FOUND ON ANY PAST ISSUE LABEL) _____
ADDRESS _____		DATE YOUR ORDER WAS MAILED (OR PHONED) _____
CITY _____	STATE/COUNTRY _____	ZIP _____
YOUR NAME AND PHONE NUMBER _____		PREPAID _____ CHECK _____ CHARGE _____ CHECK/CARD CLEARED DATE: _____
TITLE _____		VOLUME OR YEAR _____
_____		NUMBER OR MONTH _____
_____		_____
_____		_____

(If possible, send a copy, front and back, of your cancelled check to help us in our research of your claim.)

ISSUES: ___ MISSING ___ DAMAGED

Thank you. Once a claim is received and resolved, delivery of replacement issues routinely takes 4–6 weeks.

(TO BE FILLED OUT BY APA STAFF)

DATE RECEIVED: _____	DATE OF ACTION: _____
ACTION TAKEN: _____	INV. NO. & DATE: _____
STAFF NAME: _____	LABEL NO. & DATE: _____

Send this form to APA Subscription Claims, 750 First Street, NE, Washington, DC 20002-4242

PLEASE DO NOT REMOVE. A PHOTOCOPY MAY BE USED.