Aging, Neuropsychology, and Cognition, 13:435–457, 2006
Copyright © Taylor & Francis Group, LLC
ISSN: 1382-5585/05 print; 1744-4128 online
DOI: 10.1080/138255890969564

Psychology Press
Taylor & Francis Group

Aging and Comparative Search for Feature Differences

LAWRENCE R. GOTTLOB
University of Kentucky, Lexington, Kentucky

ABSTRACT

In a comparative visual search experiment, two halves of a display contained visual primitives of various shapes and colors. These halves were identical (50% of trials) or contained a non-matching pair (50% of trials). Response time (RT), accuracy, and eye movements were measured in both young and older adults. There were Age Group × Display Size interactions found for RT, with older adult RT affected more than younger adult RT by increases in display size. This interaction was consistent with predictions generated by sequential-sampling models for RT. There were age group main effects on fixation number and fixation duration, but no age group main effects on accuracy, saccade amplitude, or measures of scan-path efficiency; this indicated that search strategies were similar across age groups. Overall, the results showed no special age group deficits for comparative visual search.

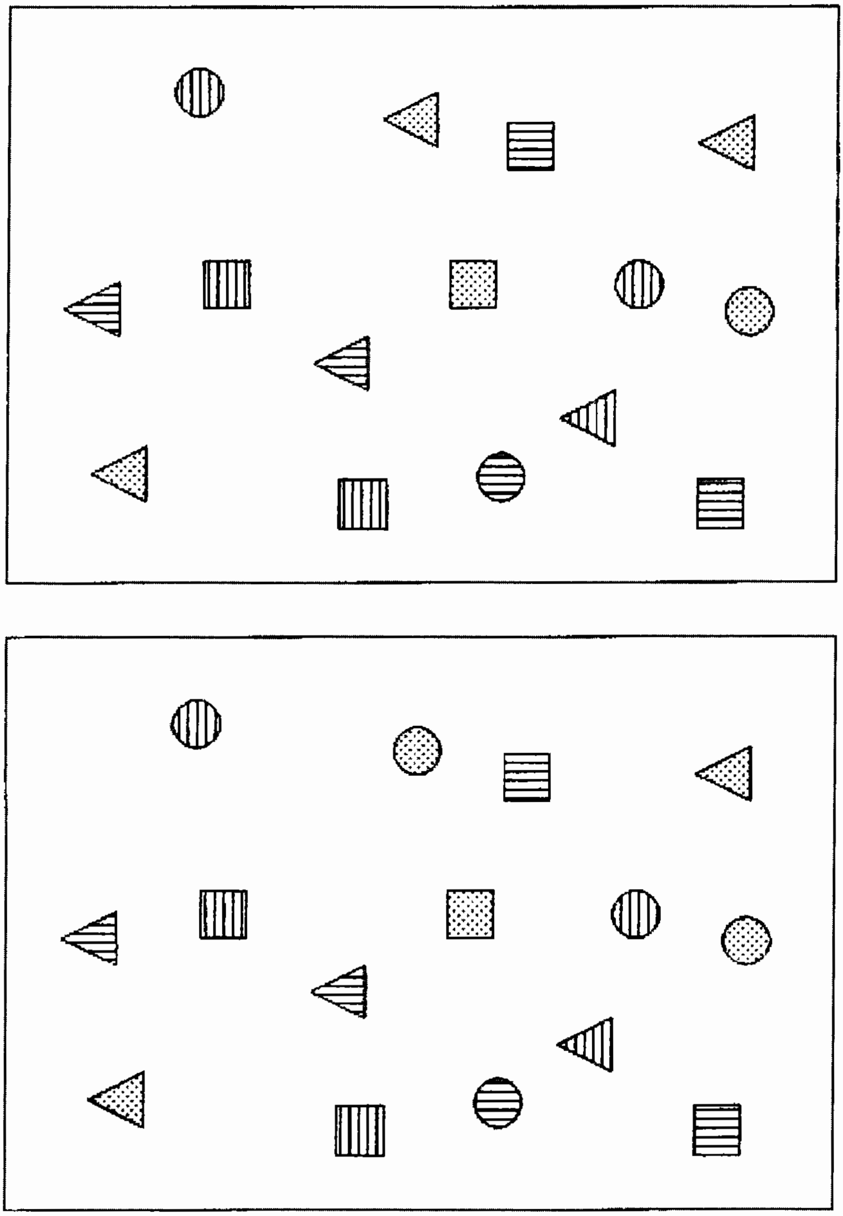
Comparative visual search (Pomplun et al., 2001a, 2001b) is a new paradigm that requires observers to compare two halves of a display containing small shapes of various colors, in order to detect a single pair of targets that are mismatched (Figure 1). This task requires observers to sample, store, and compare corresponding portions of the two display halves, which engages processes such as visual search, eye movements, and visual working memory (Luck & Vogel, 1997). Output measures include accuracy and response time (RT), as well as fixation duration, saccade length, and length of scan path. Pomplun et al. (2001a, 2001b) measured these output variables and found that (young) observers were sensitive to factors such as item density and heterogeneity, and the presence of a concurrent task.

Comparative visual search differs from simple (single target) visual search in one important dimension. In traditional visual search, bottom-up

---

Address correspondence to: Lawrence R. Gottlob, 201 Kastle Hall, Lexington, KY 40506-0044. E-mail: gottlob@uky.edu

FIGURE 1. Schematic view of stimuli in comparative visual search. Targets (red, green, and blue) are presented on a black background. On 50% of trials, a single corresponding pair of items differ in color, shape, or both.



(physical) differences between the target and distractors serve to define the target; either these differences are preattentively apparent as in feature search, or require a minimal set of computations as in conjunction search

(Wolfe, 1994). In contrast, comparative search contains a pair of targets that are defined "on the fly"; they possess no predefined bottom-up information that differentiates them from the distractors. The targets, if they are present, are defined by a lack of correspondence across the two halves of the display. Thus, this task requires a number of components not demanded by the typical visual search paradigm; among them are storage of a collection of objects or features in visual working memory, eye movements to load corresponding "snapshots" for the purposes of comparison, and a "comparator mechanism" to signal when corresponding items differ in shape and/or color. The memory demands of visual search are believed to be small, at least as they relate to memory of the scan path (Horowitz & Wolfe (1998) found no memory requirements; McCarley et al. (2003) found a memory of 3 to 4 search locations), and visual search would not require that item labels or tokens be held in memory once they are rejected as targets. It can be claimed, therefore, that comparative search taxes visual working memory much more than visual search for features or conjunctions.

A number of subprocesses can be assumed to operate in comparative visual search, among them visual search for features, execution of precise eye movements in order to register corresponding parts of the display, and storage and comparison processes in visual working memory. One interesting aspect of the comparative search paradigm is that minimal age-related deficits have been found for many of these subprocesses. In the investigation of whether a process is subject to age-group effects, a useful null hypothesis can be imposed by generalized slowing (Cerella, 1990), the strong version of which states that a single (slowing) factor can account for age group differences in performance across a wide variety of cognitive tasks. Age group differences can point to functions that are either spared from cognitive slowing, or especially sensitive to it. Following is a brief summary of findings related to the three ostensible components of visual comparative search: visual search, control of eye movements, and visual working memory.

Visual search has been the subject of a large number of aging studies. In general, older adults have more problems detecting targets among heterogeneous distractors and detecting targets defined by conjunctions of features, but when the search is conducted among homogeneous distractors or when the search is conducted for a target defined by a single feature, then age-related slowing is often reduced or eliminated altogether (Plude & Doussard-Roosevelt, 1989; Plude & Hoyer, 1986; Scialfa & Joffe, 1997). With a few exceptions (e.g., Madden et al., 1999; Zacks & Zacks, 1993) most aging studies of visual search use RT as a measure. When an interaction on RT is observed between age group and display size (i.e., where the RT display size function is steeper for the older adults), an age group decrement in visual search is claimed. When this interaction is not observed, age group equivalence in visual search is claimed, even though an age group main effect measured on overall RT might still be present.

The *control of eye movements* is coupled to systems controlled by visual attention; in many theories (e.g., Klein, 1980) covert movements of visual attention precede overt eye movements (saccades). In previous studies, it has been found that older observers are more influenced in their landing positions by distractors than are younger observers (Scialfa et al., 1999), that it takes older observers longer to execute a saccade to a target location (Kramer et al., 1999), and that older adults are impaired in their ability to inhibit saccades in the anti-saccade paradigm (Nieuwenhuis et al., 2000). These types of age-related decrements in eye movements were explained by both the generalized slowing hypothesis (Scialfa & Joffe, 1997) and by inhibitory deficits in older adults (Nieuwenhuis et al., 2000). Age-related changes in peripheral processes may also underlie differences in eye movements: Scialfa et al. (1994) found that useful field of view (UFOV) (Sekuler & Ball, 1986) predicted the number of eye movements executed in a visual search for targets defined by orientation. At this point it appears that older adults are impaired in their ability to execute or inhibit eye movements, but it is not clear whether the deficits are greater than that predicted by generalized slowing.

Visual working memory is another component of comparative visual search that has been examined in older adults. It has been established that verbal working memory is subject to age-related deficits (Verhaeghen et al., 1993). For visual working memory, however, age-related changes appear to be minimal. A review by Faubert (2002) notes that visual working memory for vernier acuity, luminance defined shape, and luminance-defined spatial frequency information, do not show age-related deficits. It has been demonstrated, however, that older adults are impaired in storage and retrieval of complex geometric shapes (Fahle & Daum, 1997). Visual working memory, therefore, seems to be preserved, if items to be retained do not require complex strategies for retention.

Comparative visual search, then, offers a technique for investigating performance of younger and older adults in a well-controlled experimental paradigm. Because it requires observers to engage and coordinate visual search, eye movements, and visual working memory processes, age-group differences in the individual components, which in some cases are minimal, may become magnified and cause overall performance decrements. On the other hand, it may be that older observers can successfully deploy the different processes demanded by comparative visual search. Performance in this task will be examined in terms of RT, accuracy, and eye movements.

The current task was a replication of the visual comparison task in Pomplun et al. (2001a; 2001b) with a few differences in the stimuli. Pomplun et al.'s stimuli were connected by lines drawn on the screen, and observers were instructed to start the scan from the upper left-hand corner and systematically scan downward. In the current experiment, stimuli were not connected by lines, in order to reduce constraints on search. Observers fixated a cross at the center of the screen, and were not given any specific instruction regarding scan path. Another difference from Pomplun et al. was that in their experiments, all trials contained targets, and thus all terminated with the same manual response; this design might permit observers to respond before collecting sufficient information. In the current task, *match* (no target present) trials and *mismatch* (target present) trials were randomly mixed, so that observers could not profitably adopt a response bias.

METHOD

Observers

Fourteen older adults (M age = 69; range 64–73 yrs) and 14 young adults (M age = 20; range = 18–24 yrs), recruited from the community, participated. The older adults were members of the Sanders-Brown subject registry, and the young adults were university students. Older observers were paid $10 per 1-hour session; younger observers received course credit. Observers passed a color-blindness test, and minimum visual acuity, measured at four feet, was 4/8 (equivalent to 20/40). All observers had a minimum of 12 years of education. A computerized version of the Mill-Hill vocabulary test was administered; mean scores were 18.8 (se = 1.5) and 11.6 (se = 0.9) for older and younger participants, respectively, F (1, 26) = 12.6, $p < .01$. A computerized version of the digit-symbol test was also administered; mean RTs were 1.40 sec (se = 0.06) and 1.11 sec (se = 0.05) for older and younger participants, respectively, F (1, 26) = 13.7, $p < .01$.

Apparatus

The stimulus displays were controlled by a Pentium 4 computer, connected to a 22" monitor running at 100 Hz, at a screen resolution of 1024 × 768. Stimulus displays were programmed in EPrime, which also started and stopped eye position recording. The eyetracker was an ASL model 504 (Applied Science Laboratories, Bedford, MA), connected to an eye-position camera sampling at 60 Hz. The ASL system measures eye position with precision of approximately +/– 1 deg. A chin- and head-rest fixed eye position and maintained an eye-to-screen distance of 100 cm. The room had dim natural lighting.

Stimuli

Each half of the display was a rectangle subtending 8.6 × 12.9 degrees, with a 1.1 deg separation between the halves. (For our setup, each degree corresponded to 46.5 pixels.) Corresponding items in the two halves were offset by 9.7 degrees (450 pixels) in the horizontal (X) direction. Minimum item separation was 0.5 degrees between edges. There were three display sizes used: 24, 30, and 36 items total, with half of the items on each side. Colors were blue, red, and green (adjusted by the experimenter for equal brightness); shapes were circles, squares, and triangles subtending about 0.5 deg (sized for the appearance of equal size and brightness). Luminance of the targets was 30 to 69 cd/m2, and background luminance was 3.4 cd/m2. The two halves of the display were identical, except that for half the trials, one item differed across halves. For *target-absent* trials, each side had equal numbers of each color and shape (but not necessarily equal numbers of color-shape combinations); for *target-present* trials, one item on the right side was substituted, which therefore created two targets, one on each side. The targets differed by either *shape, color*, or *combined* shape and color. *Target 1* was defined as the first target fixated, and *Target 2* was defined as the second target fixated, regardless of side. Figure 1 shows a typical display.

In order to control various factors such as item density, color and shape heterogeneity, and target locations, three research assistants generated several thousand different displays with a special program, and selected the subset to be used in the experiment. Displays were rejected if distinct groupings of colors or forms seemed to be present, or if the displays appeared "unbalanced" in any way. Target location was counterbalanced across nine zones, and dependencies between target identity and location were tracked. A total of 540 (270 target-absent displays, plus 30 of each of 9 color/shape difference) displays were kept for use in the experiment. Each observer received stratified random samplings (without replacement) of 90 *target-absent* displays and 90 *target-present* displays. Manipulated factors were *target-absent/target-present display size* (24, 30, or 36 items per display), and on target-present trials, *target difference* (shape, color, or combined shape and color).

Procedure

Each observer completed a single session of the eye-tracking experiment, which began with calibration of the eye-tracker and six practice trials, followed by six blocks of 30 trials each. Each trial consisted of a central fixation point (5 sec), followed by the stimulus display. The stimulus display was terminated by the manual response which was recorded on the keyboard, with the right arrow key mapped to *target-absent* and the left arrow key mapped to *target-present*. (Response was not counterbalanced because RTs on *target-absent* and *target-present* trials were not compared in any critical tests.)

Eye movements were measured with ASL Eyewin software, which recorded a 60-HZ stream of x and y values, along with pupil diameter.

Beginnings and ends of trials were synchronized with onsets and offsets of eye-position recording. Fixations were defined according to the defaults provided by the eye-recording software: A fixation was recorded if six sequential gaze samples had a standard deviation of no more than one-half degree in the x- and y-axes. A fixation was ended if three sequential gaze samples were more than one degree from the fixation position.

RESULTS

A repeated-measures design using the generalized linear mixed model, as implemented in PROC MIXED (Littell et al., 1996), was employed. The models implemented in PROC MIXED are evaluated using likelihood functions instead of sums-of-squares as in ANOVA. In PROC MIXED, generalized F ratios are calculated using (restricted) maximum likelihood estimates of variance components and generalized least-squares estimates of treatment differences (Littell et al., 1996). In these results, least-square means are presented, with standard errors in parentheses. All multiple comparisons were adjusted using the Sidak correction (SAS Institute, 1989). For all F tests, there was a greater than .80 power at $\alpha = .05$ to detect a large effect ($f^2 = .365$).

Measures of the manual response were accuracy and RT (Table 1). Measures based on eye movements were computed from the data using the ASL Eyenal analysis program. Primary eye movement measures consisted of mean fixation time and number of fixations, as well as several other measures derived from the computations of the fixations. Secondary eye movement measures required more computations, such as the fixation-target proximity required to define a target fixation, and the determination of within-side vs. transverse saccades.

Accuracy

Target-absent accuracy (correct rejection rate) was 98% for younger adults and 99% for older adults. For target-present trials (Table 1), there was a main effect of target difference on accuracy, $F(2, 52) = 56.43$, $p < .001$, with mean hit rates of .74 (.04), .88 (.04), and .93 (.05) for the shape, color, and combined conditions, respectively. A follow-up analysis indicated that all pairwise comparisons were significant at $p < .01$. There was also a main effect of display size, $F(2, 52) = 4.98$, $p < .05$, with mean hit rates of .88 (.05), .87 (.04), and .83 (.04) for the 24-, 30-, and 36-item conditions, respectively. A follow-up analysis indicated that hit rates for the 24-item and 36-item conditions differed at $p < .05$, and the difference between 30-item and 36-item conditions was just short of significance at $p < .06$. There was no main effect of age group; $M = .87$ (.05) and $M = .86$ (.05) for younger and older adults, respectively, and there was no interaction involving age group.

TABLE 1. Primary Response and Eye Movement Measures

	Target Present			
	Target Difference			
Condition	shape	color	combined	Target Absent
Young accuracy (%)				
24	76 (6)	86 (4)	94 (3)	99 (1)
30	76 (4)	89 (4)	94 (3)	98 (1)
36	60 (7)	86 (4)	89 (3)	98 (1)
Older Accuracy (%)				
24	76 (3)	85 (5)	95 (2)	99 (1)
30	76 (4)	85 (5)	89 (3)	99 (1)
36	70 (5)	86 (2)	88 (4)	98 (1)
Young RT (sec)[1]				
24	4.21 (.29)	3.99 (.15)	3.89 (.22)	5.65 (.28)
30	4.27 (.23)	4.61 (.27)	4.53 (.17)	6.78 (.35)
36	4.88 (.39)	5.41 (.30)	4.83 (.30)	7.91 (.41)
Older RT (sec)[1]				
24	4.94 (.25)	5.09 (.24)	4.92 (.27)	7.51 (.36)
30	5.80 (.25)	5.80 (.28)	5.58 (.22)	9.01 (.43)
36	6.76 (.32)	7.06 (.47)	6.38 (.38)	10.79 (.55)
Young numbers of fixations[1]				
24	15.2 (.12)	13.9 (.06)	13.6 (.07)	20.5 (.01)
30	14.7 (.08)	16.0 (.10)	16.0 (.07)	24.5 (.12)
36	16.7 (.15)	16.7 (.10)	17.0 (.10)	26.5 (.15)
Older numbers of fixations[1]				
24	15.9 (.10)	16.6 (.11)	15.5 (.09)	26.3 (.14)
30	18.7 (.11)	18.9 (.09)	18.0 (.08)	30.4 (.16)
36	22.0 (.12)	22.8 (.16)	20.2 (.14)	36.4 (.19)
Young fixation duration (sec)[1]				
24	0.24 (.005)	0.25 (.005)	0.25 (.006)	0.23 (.006)
30	0.25 (.005)	0.25 (.005)	0.25 (.005)	0.24 (.005)
36	0.26 (.01)	0.25 (.005)	0.25 (.005)	0.24 (.006)
Older fixation duration (sec)[1]				
24	0.28 (.01)	0.28 (.01)	0.28 (.01)	0.25 (.007)
30	0.28 (.01)	0.27 (.008)	0.27 (.008)	0.26 (.007)
36	0.28 (.008)	0.28 (.01)	0.29 (.01)	0.26 (.008)

Note: Terms in parentheses are standard errors.

[1] Correct trials only (hits and correct rejections).

Planned tests on hit rate for each age group and display size were performed. For younger adults, at each level of display size, there was an effect of target difference, $F(2, 52) > 8.30$, $p < .001$ across the three tests. Pairwise comparisons indicated that for display size 24, all target type conditions differed ($p < .05$). For display sizes 30 and 36, color and combined conditions were the only pairwise comparisons that did not differ ($p < .01$) with the shape condition the lowest in accuracy. For older adults, there was also an effect of difference type at each level of display size, $F(2, 52) > 4.73$, $p < .05$ across the three tests. The results of the pairwise comparisons mirrored those for the younger adults.

Mean hit rate for the shape condition was 74% across all display sizes, and was especially low in the display size 36 condition (60% for younger and 70% for older adults, where chance performance is 50%). It will be seen below that mean RT for this condition was not different from mean RT for the other difference conditions; this indicated that observers had trouble with shape mismatch detection. Because shape is a computed attribute, it appears to pose difficulties to processes responsible for storing and comparing information, although Luck and Vogel (1997) found that objects can be stored in visual working memory as integrated representations without reductions in capacity. It was possible that the deficit was due to perceptual difficulties in recognizing shape, although the older observers did not have more trouble with the shape condition than the younger observers.

Response Time

Correct RTs were compared between target-absent and target-present trials. There were main effects of target presence, display size, and age group, as well as Age Group × Target Presence and Age Group × Display Size interactions, $F > 7.77$, $p < .01$. (These effects were not analyzed further because it would not be informative to lump target-present and target-absent trials together). There was also a Target Presence × Display Size interaction, $F(2, 52) = 40.98$, $p < .001$. For target-absent trials, the search slope was 231 ms/item, and for target-present trials, the search slope was 117 ms/item. This approximately 2:1 search ratio is consistent with a self-terminating search. Response time for misses did not differ from RT for correct rejections, $p > .5$, which, combined with the low false alarm rate, indicates that misses were simply a result of passing over the targets without registering the mismatch.

For RTs on hits (Table 1), there was a main effect of age group, $F(1, 26) = 24.60$, $p < .001$, with M = 4.50 sec (0.19) for younger adults and M = 5.83 sec (0.19) for older adults. There was also a main effect of display size, $F(2,52) = 24.60$, $p < .001$, with M = 4.48 (0.11), 5.11 (0.15), and 5.91 (0.20) sec for 24-, 30-, and 36-item displays. In addition, there was an Age Group × Display Size interaction, $F(2, 52) = 3.52$, $p < .05$; this was manifested in a display size—RT slope of 88 ms/item for younger observers and a slope of 150 ms/item for older observers, computed on the total display size (24, 30, and 36 items). The age-group ratio of search slopes was 1.7.

There was no effect of target difference type on RT. Although, as seen above, there was a high error rate for shape-different trials, RT on hit trials for shape differences did not differ from those in color or combined difference conditions, so it appears that "hit" trials were the same across target difference conditions. Therefore, eye movements will be analyzed in the shape condition along with the other conditions.

The summary of the accuracy and RT measures was that there were no age group differences in accuracy on target-present trials, but there was an age group main effect, and an Age Group × Display Size interaction, in correct RT for target-present trials. The search slope ratio for older/younger was approximately 1.7. These results indicate that comparative search for older adults is slower than for younger adults, but just as accurate. The next analyses concern the eye fixations of younger and older observers.

Primary Eye Fixation Measures

Primary measures (fixation durations and number of fixations; Table 1) were computed according to the Eyenal algorithms as described above. For mean fixation duration on hits (Table 1), there was a main effect of age group, F(1, 26) = 7.37, $p < .05$. Mean fixation duration was 0.25 (0.008) sec and 0.28 (0.008) sec for younger and older adults, respectively. The fixation durations for both age groups were similar to those in previous visual search studies (e.g., Maltz & Shinar, 1999; Scialfa & Joffe, 1997). There was no effect of display size, and the Age Group × Display Size interaction was just short of significance, F (2, 52) = 3.16, $p < .052$.

In a parallel analysis to that performed on RT, the number of fixations on correct trials (target-absent vs. target-present) were analyzed. There was a Target Presence × Display Size interaction, F(2, 52) = 35.10, $p < .001$. For target absent trials, the search slope was 0.75 fixations/item, and for target-present trials, the search slope was 0.38 fixations/item. As with the RT analysis, this approximately 2:1 search ratio is consistent with a serial self-terminating search. The number of fixations for misses (26.8, se = 1.0) was lower than that for correct rejections (27.8, se = 1.0), F (1, 26) = 9.90, $p < .01$. Fixations were also compared across hits and misses. Numbers of fixations were greater for misses (26.8, se = 1.0) than for hits (M = 17.2, se = 0.60), F (1, 26) = 328.59, $p < .001$. These results, as for the RT analysis, indicate that misses were due to passing over the targets without registering their presence.

For numbers of fixations on hit trials, there was a main effect of age group, F (1, 26) = 8.71, $p < .01$, with M = 15.71 (0.74) and M = 18.78 (0.74) for younger and older adults, respectively. There was also a main effect of display size, F(2, 52) = 50.58, $p < .001$, with M = 15.0 (0.58), 17.1 (0.58), and 19.7 (0.59) for display sizes of 24, 30, and 36, respectively. There were significant differences for all pairwise comparisons of display size. There was no Age Group × Display size interaction, F (2, 52) = 2.45, $p < .097$, which indicated that older adults were not differentially impaired by increases in item number or density.

Next, fixations on the targets were measured (Table 2). On each target-present trial, there was one target on each side, with identical Y-coordinates and X-coordinates exactly 450 pixels apart. A target was considered to be fixated if the x-y coordinates of the measured fixation point were within 3 deg (140 pixels) of that target; this distance was based on an analysis of target fixations vs. hit rate. Target 1 and Target 2 were defined as, respectively, the first and second targets fixated, regardless of side. A number of analyses related to fixations on Targets 1 and 2 for hits only are summarized in Table 2. All of the measures showed significant age group main effects; all but two (duration of first fixation on Targets 1 and 2) showed a main effect of display size. None (except for the number of fixations on Target 1) showed an Age Group × Display Size interaction. The age group effects on target fixation time and number of target fixations, on both Target 1 and Target 2, indicated that older adults required more processing time on both targets.

Secondary Eye Movement Measures

Next, some derived measures of search behavior were analyzed. Search in the early stages should consist of fixations in which two visual working memory processes, loading of information and comparison, predominate. This kind of search continues until noncorresponding items are registered, when a more active comparison process should ensue. Pomplun et al. called these two stages *search and comparison*, and *detection and verification*. In the current study, the dividing line between these two stages was defined as the first fixation of Target 2, because at the end of that fixation, sufficient information may have been gathered for a "detect" response.

Two possible measures of search efficiency are the time difference and the number of fixations between fixating the first and second targets. On target-present trials, there is a discrepant item (target) on each side, either of which may be fixated first. If a search is executed systematically, then a single transverse saccade should link the two targets. The time differences and number of fixations between the first target fixation (left or right side; T1) and the first fixation of the second target (T2) were measured for hit trials only. A target was considered to be fixated if the x-y coordinates of the measured fixation point were within 3 deg (140 pixels) of the target. A total of 8.7% of hit trials were excluded from this analysis because both targets were not fixated within three degrees before the response was recorded. For time difference, there was a significant effect of age group, $F(1, 26) = 6.26$, $p < .05$, with M = 0.76 sec (SE = .05) and M = 0.93 sec (SE = 0.05) for younger and older adults. There was also a main effect of display size, $F(2, 52) = 8.13$, $p < .001$, with mean intervals of 0.74 (0.05) sec, 0.82 (0.04) sec, and 0.97 (0.06) sec for display sizes of 24, 30, and 36 items. A follow-up analysis found that all pairwise display size comparisons were significant ($p < .05$)

Table 2. Target 1 and Target 2 Measures for Younger and Older Adults (Hits Only)

		Young Adults		Older Adults		Age Group Effect	Display Size Effect	Age Group × Display Size Interaction
		Mean	SE	Mean	SE	F (1, 26)	F(2, 52)	F(2, 52)
Target fixation time (sec)	Target 1	0.84	0.04	1.07	0.04	17.88**	15.54**	Ns
	Target 2	0.66	0.03	0.92	0.03	36.22**	9.15**	Ns
Number of fixations	Target 1	3.23	0.42	3.7	0.52	4.81*	17.94**	4.47*
	Target 2	2.47	0.36	2.93	0.47	6.89*	13.12**	ns
Number of rechecks after T2	Target 1	1.68	0.36	2.08	0.47	4.33e*	12.62**	ns
	Target 2	1.47	0.36	1.93	0.47	6.89*	13.12**	ns
Duration of first fixation	Target 1	0.22	0.03	0.24	0.03	7.1*	ns	ns
	Target 2	0.28	0.03	0.32	0.05	4.64*	ns	ns

Note: After T2 refers to events after Target 2 is fixated for the first time (within +/– 3 degrees).
$*p < .05$.
$**p < .01$.

except for that between sizes 24 and 30. There was no effect of difference type and no interactions. The lack of an Age Group × Display Size interaction in this measure again indicated that older adults were not differentially affected by display size in their ability to fixate both targets.

For the number of fixations between T1 and T2, there was no significant effect of age group ($p > .05$), with M = 2.91 (0.15) and M = 3.28 (0.15) for younger and older adults. According to a perfectly efficient search, the number of fixations between the first on T1 and the first on T2 would be 0. There was a main effect of display size, F (2, 52) = 6.25, $p < .01$, with mean fixation numbers of 2.94 (SE = 0.15), 3.13 (SE = 0.15), and 3.21 (SE = 0.14) for display sizes of 24, 30, and 36 items. A follow-up analysis found that pairwise comparisons were significant between display sizes 24 and 36, and 30 and 36, $p < .01$. Thus, although there was a greater time gap between target fixations for older adults than for younger adults, in terms of numbers of fixations, there was no age group difference. Both age groups were fairly far from the "perfectly efficient" performance level of 0 inter-target fixations.

The time interval between the first fixation of Target 2 and the manual response was also analyzed. There was a main effect of age group, F (1, 26) = 15.64, $p < .001$, with mean intervals of 1.27 sec (SE = 0.12) and 1.95 sec (SE = 0.12) for younger and older adults. There was also a main effect of display size, F (2, 52) = 7.15, $p < .01$, with mean intervals of 1.49 (0.10), 1.58 (0.10), and 1.77 (0.09) for display sizes of 24, 30, and 36 items, respectively. Follow-up comparisons using the Sidak correction indicated that the interval at Display Size 36 differed from the other two, but that Display Sizes 24 and 30 did not differ from each other ($p < .05$). There was no main effect of target type and there were no interactions.

Measures related to search path are summarized in Table 3. Most of the measures resulted in a main effect of display size, but only three resulted in age group main effects. Amplitude of both transverse and within-side saccades did not differ across age group. The number of within-side saccades was greater for older adults than for younger adults, but the number of transverse saccades was not. This result indicated that older adults tended to recheck or shift their gaze to nearby locations more often than younger adults. This age-group difference in behavior was further revealed in the number of within-side saccades measured after the first fixation of Target 2; older adults rechecked nearby locations more than younger adults. These findings are comparable to a slightly greater tendency for older adults to recheck locations in visual search, primarily when heterogeneous displays are used (Plude & Doussard-Roosevelt, 1989; Scialfa et al., 1994).

The last three measures in Table 3 were derived from observers' gross search behavior. The total scan path is simply the number of pixels covered from the beginning of the trial to the response. There was an approximately 509 pixel difference in scan-path length between older and younger observers, which was consistent with the finding that the number of fixations was greater for older than for younger observers. Some of this extra scan-path distance must have come from revisiting parts of the display, as the number of rechecks of both targets was higher for older adults (Table 2). However, two more direct measures of scan path efficiency did not show age group main effects. Y-axis monotonicity is measured by the extent to which the Y-coordinates either increase or decrease monotonically, as quantified by the absolute value of Kendall's tau. Kendall's tau would have a value of 1 (or −1) when each fixation's Y-coordinate is greater (or smaller) than the previous fixation's. Although observers were not instructed to begin their search in a specific location such as the upper left-hand corner of the screen, a shortest-path search would be expected to begin at the top (or bottom) of the screen and proceed down (or up). Kendall's tau measures indicated that older adults were just as systematic as younger adults in their search.

The other measure of search efficiency was based on the accuracy of transverse saccades. For efficient search, corresponding areas of each side should be compared; this would require the execution of transverse saccades that would minimize the Euclidian distance between (x_1, y_1) and (x_2+/−450, y_2). The degree of matching between these two (x, y) pairs did not show any main effects, which indicated that both age groups engaged in similar search strategies.

DISCUSSION

General Findings

In this paradigm, a number of activities are probably taking place: an item or multiple items are fixated and stored in visual working memory, saccades are executed in order to bring new parts of the display into view, and an item or multiple items in the "new" fixation are compared to the contents of visual working memory. The steps are repeated until a mismatch is detected, whereupon rechecking processes, and eventually a response, are executed. The RT, accuracy, and eye movement data indicated that observers of both age groups conducted the search in approximately the same fashion. I will discuss the general findings first, and then the effects specific to age group differences. In the current section, young and older group data are reported separately if age group differences are relevant.

TABLE 3. Measures of Scan Path for Younger and Older Adults, on Hits

	Younger Adults		Older Adults		Age Group Effect F (1, 26)	Display Size Effect F (2, 52)	Age Group × Display Size Interaction F (2, 52)
	Mean	SE	Mean	SE			
Transverse saccade amplitude (pixels)	401.4	13.60	409.4	18.84	Ns	6.62**	Ns
Within-side saccade amplitude (pixels)	115.9	10.16	118.4	14.40	Ns	3.22*	ns
Number of transverse saccades	7.58	1.09	7.99	1.25	Ns	18.48**	ns
Number of within-side saccades	7.34	1.26	9.78	1.64	14.91**	39.85**	4.03*
Number of transverse saccades after T2	2.53	0.49	2.99	0.62	Ns	4.99*	ns
Number of within-side saccades after T2	2.40	0.51	3.56	0.82	10.81**	6.23**	ns
Total scan path length [pixels]	3162.70	72.58	3761.72	69.87	25.89**	ns	ns
Y-axis monotonicity of scan path (Kendall's T) measure	0.57***	0.03	0.62***	0.03	ns	ns	ns
Matching of transverse saccade landing spots (pixels)	4.37	0.03	4.44	0.03	ns	ns	ns

Note: After T2 refers to events after Target 2 is fixated for the first time (within +/–3 degrees). Total scan path length had top 1% of observations (within age-group) trimmed before analysis.

*$p < .05$.

**$p < .01$.

***T > 0, $p < .01$ by one-tailed test.

One notable result was the age group equivalence in accuracy; correct rejections as well as hits differed by about 1% across age groups. There were no instructions to avoid misses or false alarms, and it was made clear that 50% of the trials were "target-present," but observers in both age groups responded "target-present" on about 39% of the trials. By far, the largest source of misses was the shape mismatch trials, especially at the largest display size (Table 1). Pomplun et al. (2001a) also reported that observers had difficulty with this type of trial. Apparently, observers of both age groups were setting search criteria that did not take into account the greater difficulty of detecting shape mismatches. It might be the case that more experience (a greater number of trials) would result in fewer misses on shape mismatch trials (although there was accuracy feedback given on each trial).

Despite the large effect of target type on accuracy, there was no effect of target type on RT. Both younger and older observers appeared to engage in a self-terminating search, as indicated by the search slope of 231 ms/item for *target-absent* trials and 117 ms/item for *target-present* trials, which yielded an approximately 2:1 search ratio. Despite the large effect of target type on accuracy, there was no target-type effect on RT, which indicated that target detection was a binary event; either the target was detected without problems, or an exhaustive search resulted in a miss. The search was relatively systematic for observers in both age groups, as evidenced by the Y-axis monotonicity scores and the matching of transverse saccades (Table 3), although as stated above, observers executed approximately three fixations between the first fixations of Targets 1 and 2 (a "perfect" search would feature 0 intertarget fixations). As will be discussed below, the fixations between the first fixations of Targets 1 and 2 mostly consisted of within-side fixations.

The data were also analyzed for the types of control exerted over the search. Pomplun et al. (2001a) found that fixations were longer and saccades were shorter in high-density regions. This strategy seemed to indicate sensitivity to the number of items that could be stored and compared in visual working memory. In contrast, I found that both fixation duration and saccade length were constant across display size, indicating that the strategy employed was not sensitive to item density over the range tested.

Control over the deployment of eye movements was also examined. The strategy that would absolutely minimize visual working memory load (at the expense of increasing the search path) would be a fixation of a single item, followed by a transverse saccade and fixation of the corresponding item in the other hemifield, followed by a within-side saccade if a mismatch is not detected. This single-item fixation and comparison would be executed until all pairs are examined or until a mismatch is found. If this strategy were executed without errors, the entire search path could consist of concatenated sequences of two consecutive within-side fixations followed by a transverse saccade, and there would be one fixation per display item in the target-absent condition and .5 in the target-present condition.

Although some of the data were consistent with the single-item comparison strategy, other data were not. Numbers of fixations were consistent with a single-item comparison strategy: approximately one per display item in the target-absent condition, and approximately .5 per display item in the target-present condition (Table 1). However, instead of two consecutive within-side fixations as would be predicted by the single-item strategy, the mean number of consecutive within-side fixations was 2.43 (0.05) for younger adults and 2.59 (0.05) for older adults, F(1,26) = 4.48, $p < .05$. Thus, it appears that observers, after executing a within-side saccade, often executed one or more additional within-side saccades (with expected values of .43 and .59 for younger and older adults, respectively). These "extra" within-side saccades may have been executed in order to load more information into visual working memory before executing the transverse saccade. Older adults may have executed more extra saccades because, as previous studies have indicated, their information uptake bandwidth (UFOV) (Sekuler & Ball, 1986) is often slightly restricted compared to the younger adults.

An additional finding was that numbers of consecutive within-side fixations differed according to the stage of search. As stated above, the dividing line between the two stages was defined as the first fixation of Target 2. For the first phase, the mean number of consecutive within-side fixations was 2.50 (0.06) for young and 2.71 (0.06) for older, and for the second phase, it was 2.23 (0.06) for young and 2.41 (0.06) for older. There was a main effect of before/after, F(1,26) = 92.54, $p < .001$ (which replicated Pomplun et al.) and age group, F(1,26) = 7.13, $p < .05$, but no Age Group × Before/After interaction. The main effect of before/after indicated that observers were more likely to execute a transverse saccade after fixating Target 2, probably to check the corresponding location in the other hemifield. Consecutive transverse fixations did not differ across before Target 2 (M = 2.42, se = 0.04) and after Target 2 (M = 2.44, se = 0.04), so there was no increase in checking behavior. (It might be thought that consecutive within-side and transverse fixations would be dependent, but this is not the case.)

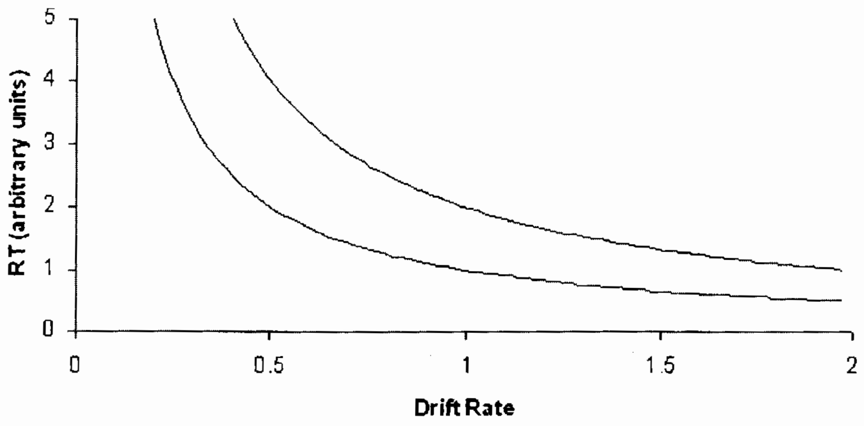
Age Effects on RT and Eye Movements

Age-group differences on "hit" trials were not consistent; they varied with respect to the type of measure. Based on the statistical results, it appeared that the effects could be divided into a three-level hierarchy. The first level consisted of three measures that exhibited age group main effects and Age Group × Display Size interactions: RT, number of fixations on Target 1 (Table 2), and number of within-side saccades (Table 3). The second level consisted of a large number of measures that exhibited age group main effects but no Age Group × Display Size interactions: fixation duration, numbers of fixations, and most of the measures relating to fixations on Targets 1 and 2 (Table 2), as well as scan path length and the number of within-side saccades after Target 2 was fixated (Table 3). The third level of measures exhibited no main effect of age group; these included most of the measures of the scan path in Table 3.

Why did only a few measures in the current data set exhibit Age Group × Display Size interactions? In the visual search literature, conjunction and other "difficult" searches often produce Age Group × Display Size interactions, whereas feature and other "easy" searches most often do not. The tasks in which these interactions are observed are said to show age-related decrements (Humphrey & Kramer, 1997; Madden et al., 1999; Plude & Doussard-Roosevelt, 1989; Plude & Hoyer, 1986; Zacks & Zacks, 1993). Within that framework, it can be said that our results, which included Age Group × Display Size interactions in RT, indicated age group decrements in comparative search. For other measures (fixation duration, number of fixations, scan-path length, etc), based on the absence of an interaction, it can be said that there was no age group decrement. (Note that, unlike the previous studies cited, the type of search was not manipulated, but rather different measures on a single behavior were examined.) Another, closely related interpretation of these results is that older adults had a decrement in comparative visual search that was manifested in some measures but not others; i.e., some measures are more sensitive to the age group decrement. This is certainly a reasonable interpretation of the results.

However, there may be another interpretation for why only a few of the current measures show Age Group × Display Size interactions. As it has been often noted, it is difficult to interpret interactions without a model linking some internal construct to the output measure (Loftus, 1978; Salthouse, 2000); equivalently, it is difficult to interpret interactions involving groups at different levels of performance (Miller et al., 1995: Rabbitt, 2003). Loftus (1978) constructed the argument explicitly for the measure of accuracy, and stated that interactions that can be removed by monotonic transformation to an underlying variable (e.g., "resources") are uninterpretable without a model. In the current paradigm, the effects are expressed in time, but one is actually interested in measuring some construct underlying time, such as speed of processing. The goal is to examine whether older adults are disproportionately slowed by increasing the display size, i.e., whether RT for older adults increases more at large display sizes than what would be expected under generalized slowing. (Although some of the measures such as numbers of fixations are not expressed directly in time units, because fixation duration is fixed within each age group, these measures are equivalent to RT measures.)

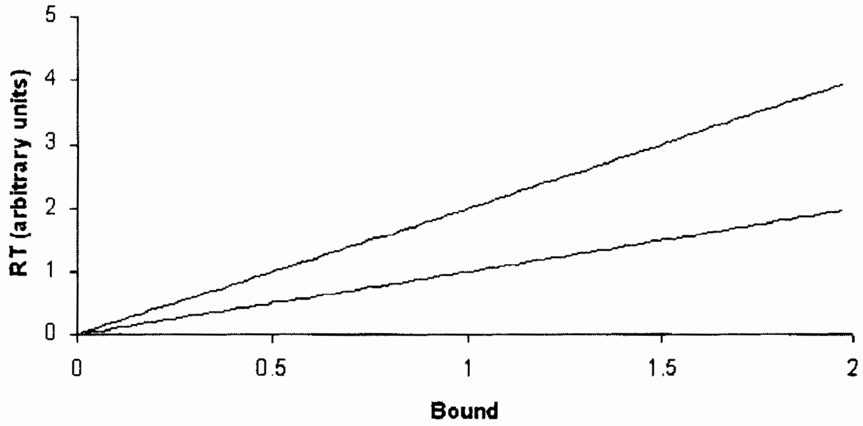
FIGURE 2. Response time (RT) as a function of drift rate in a sequential-sampling model, for boundary levels of 1 (bottom curve) and 2 (top curve). Boundary level may represent task difficulty or amount of processing required.



Although they have not been addressed in the interaction literature, various models for RT do feature explicit mappings between speed and RT (Luce, 1986). Most notably, Ratcliff and colleagues have developed a sequential-sampling model called the *diffusion model*, to explain many phenomena including age group differences in perceptual tasks (Ratcliff et al., 2001; Thapar et al., 2003). One feature of sequential sampling models is that mean RT can be expressed as a function of boundary (amount of accumulated information required for a response) and drift rate (rate of information accumulation). The relationship is isomorphic to the relationship between elapsed time, distance, and speed in classical physics and is expressed as $RT = B/D$, where B is boundary and D is drift rate (Luce, 1986). It is also important to note that this RT drift rate equation would be a first-order description of the behavior of *any* model that features an inverse relationship between speed and time. For our argument, we will allow drift rate to stand in for processing speed, i.e., the rate of approach toward a response. Figure 2 shows drift rate/RT functions for two (arbitrary) boundary levels. They both show decreasing RT as a function of drift rate, but the curves are negatively accelerated.

The next step in the argument is to recognize that display size can stand in for boundary (amount of evidence collected before a response). This leads to an expression of the relationship between boundary and RT, parameterized by drift rate or speed (Figure 3). The implication from Figure 3 is apparent: Two age groups that differ in speed (drift rate) can show a Group × Boundary (Age Group × Display Size) interaction at the output (RT) level, even though speed is constant within groups and does not differ across

FIGURE 3. Response time (RT) as a function of boundary in a sequential-sampling model, for two groups with drift rates of 2 (bottom line; young observers) and 1 (top line; older observers). This model would produce a Group × Boundary interaction as measured by RT, although drift rate is constant within group.



display size. This implies, in turn, that Age Group × Display Size interactions on RT may be completely consistent with simple (generalized) slowing, and may not indicate special age group deficits (Cerella, 1990; Salthouse, 2000).

A further implication of Figure 3 is that Age Group × Display Size interactions on RT can be found when speed-loaded processes underlie the measure. For instance, Age Group × Display interactions on RT may be produced for a conjunction search because a limited-bandwidth (serial or limited-capacity parallel) search is conducted, and a component of that process is slower for older adults. On the other hand, a feature search does not load highly on a limited-bandwidth search and so does not produce the interaction. A test of generalized slowing in the context of the RT drift rate equation could be whether an Age Group × Display Size interaction is removed by a log transformation of RT: log (RT) = log (B) – log (D), which transforms Figure 3 to parallel lines separated by log (D). This is the same transformation that Cerella (1990) recommended to test for violations of generalized slowing. The log transformation was applied to the three effects showing the interaction (RT, number of fixations on Target 1, and number of within-side saccades), and the implication was partially confirmed. For RT, the interaction was removed by the transformation; however; for the other two measures, the interactions were not removed. The interactions that were not removed by the log transformation could have had other (unidentified) components that led to the original interaction, or they may represent age group effects beyond that predicted by generalized slowing. Without a formal (model-based) representation of the processes, it is not possible to make strong inferences about the underlying processes.

Nevertheless, a first-order interpretation of the results of the current experiment can be attempted in light of the above logic. As stated above, the measures seem to sort themselves into a three-level hierarchy whose top level includes measures that resulted in Age Group × Display Size interactions. Response time shows such an interaction, probably because the measure is highly loaded on speed-dependent or limited-bandwidth processes which are affected by display size. These speed-dependent processes may include information uptake and comparison of items in working memory. Because the log transformation removes the interaction, however, the RT result is consistent with generalized slowing. The two other measures at this level, number of fixations on Target 1 and number of within-side saccades, show interactions that persist after the log transformation. Those two measures may reflect age group effects above the level predicted by generalized slowing.

The second level of the hierarchy includes measures that result in age group and display size main effects but no interactions. The lack of an interaction found for Target 1 and 2 fixation times, for example, imply a low loading on speeded processes. For instance, if only the initial fixations involve speed-loaded processes (e.g., loading the image into visual working memory), and subsequent fixations only involve reactivating the memory representation; then one might observe a main effect of display size but no age group interaction. Thus, measures that do not result in age group interactions may load highly on top-down processes with limited speed components (which could also include goal maintenance, keeping track of the scan path, and monitoring the contents of visual working memory in order to detect a mismatch).

The third level of the hierarchy includes those measures for which no age group differences were found. These seem to reflect strategic components of the task; for instance, both transverse and within-side saccade amplitude were affected by display size, but there were no age group main effects on these measures, indicating that older adults searched in the same manner. Age group similarities in both monotonicity of search path and matching of transverse saccade landing spots were also indicators that comparative search strategies were preserved with age (Table 3).

In summary, the various measures of visual comparative search point to preservations with respect to age group. Reflecting back on the three components of visual comparative search (visual search, control of eye movements, and visual working memory) described in the introduction of this article, it appears that the older adults did not express impairments on any of the components, beyond that which would have been produced by generalized slowing. Molar measures of RT and accuracy, as well as molecular measures of eye movements, indicated that visual comparative search was accomplished with very few qualitative differences between younger and older adults.

ACKNOWLEDGMENTS

This research was supported in part by National Institute on Aging grant RO1 AG20860. The author is grateful for the helpful comments of Charles Scialfa and Robert Lorch on a previous version of this paper. Help on programming and statistics was provided by Tim Askins and Marie Gantz.

REFERENCES

Cerella, J. (1990). Age and information processing rate. In Birren, J. E., & Schaie, K. W. (Eds.), *Handbook of the Psychology of Aging* (3rd ed., pp. 201–221). San Diego: Academic Press.

Fahle, M., & Daum, I. (1997). Visual learning and memory as functions of age. *Neuropsychologia, 12*, 1583–1589.

Faubert, J. (2002). Visual perception and aging. *Canadian Journal of Experimental Psychology, 563*, 164–176.

Horowitz, T. S., & Wolfe, J. M. (1998). Visual search has no memory. *Nature, 394*, 575–577.

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.

Klein, R. (1980). Does oculomotor readiness mediate cognitive control of attention? In Nickerson, R. S. (Ed.) *Attention and Performance VIII* (pp. 259–276). Hillsdale, NJ: Erlbaum.

Kramer, A. F. Hahn, S., Irwin, D. E., & Theeuwes, J. (1999). Attentional capture and aging: Implications for visual search performance and oculomotor control. *Psychology and Aging, 14*, 135–154.

Littell, R. C., Milliken, G. A., Stroup, W. W., & Wolfinger, R. D. (1996). *SAS System for Mixed Models*. Cary, NC: SAS Institute Inc.

Loftus, G. R. (1978). On interpretation of interactions. *Memory & Cognition, 6*, 312–319.

Luce, R. D. (1986). Response times: Their role in inferring elementary mental organization. New York: Oxford University Press.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 309*, 279–281.

Madden, D. J., Gottlob, L. R., and Allen, P. A. (1999). Adult age differences in visual search accuracy: Attentional guidance and target detectability. *Psychology and Aging, 14*, 683–694.

Maltz, M., & Shinar, D. (1999). Eye movements of younger and older drivers. *Human Factors, 41*, 1–7.

McCarley, J. S., Wang, R. F., Kramer, A. F., Irwin, D. E., & Peterson, M. S. (2003). How much memory does oculomotor search have? *Psychological Science, 14*, 422–426.

Miller, M. B., Chapman, J. P., Chapman, L. J., & Collins, J. (1995) Task difficulty and cognitive deficits in schizophrenia. *Journal of Abnormal Psychology, 104*, 251–258.

Nieuwenhuis, S., Ridderinkhof, K. R., de Jong, R., Kok, A., & van der Molen, M. W. (2000). Inhibitory inefficiency and failures of intention activation: Age-related decline in the control of saccadic eye movements. *Psychology and Aging, 15*, 635–647.

Plude, D. J., & Doussard-Roosevelt, J. A. (1989). Aging, selective attention, and feature integration. *Psychology and Aging, 4*, 98–105.

Plude, D. J., and Hoyer, W. J. (1986). Age and the selectivity of visual information processing. *Journal of Psychology and Aging, 1*, 4–10.

Pomplun, M., Sichelschmidt, L., Wagner, K., Clermont, T., Rickheit, G., & Ritter, H. (2001a). Comparative visual search: A difference that makes a difference. *Cognitive Science, 25*, 3–36.

Pomplun, M., Reingold, E. M., & Shen, J. (2001b). Investigating the visual span in comparative search: The effects of task difficulty and divided attention. *Cognition, 81*, B57–B67.

Rabbitt, P. (2003), Aging and cognition. In Pashler, H., & Wixted, J. (Eds.) *Steven's Handbook of Experimental Psychology*, 3rd Ed., New York: John Wiley & Sons. Volume 4 (pp. 793–860).

Ratcliff, R., Thapar, A., & McKoon, G. (2001). The effects of aging on reaction time in a signal detection task. *Psychology and Aging. 16*, 323–341.

SAS Institute Inc (1989). *SAS/STAT User's Quide, Version 6, (4th Ed.)* Cary, NC: SAS Institute Inc.

Salthouse, T. A. (2000). Methodological assumptions in cognitive aging research. In Craik, F. I. M., & Salthouse, T. A. (Eds.), *The Handbook of Aging and Cognition* (pp. 467–498). Mahwah, NJ: Erlbaum.

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*, 736–742.

Scialfa, C. T., Hamaluk, E., Skaloud, P., & Pratt, J. (1999). Age differences in saccadic averaging. *Psychology and Aging, 14*, 695–699.

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.

Sekuler, R., & Ball, K. (1986). Visual localization: Age and practice. *Journal of the Optical Society of America A, 3*, 864–867.

Thapar, A., Ratcliff, R., & McKoon, G. (2003). A diffusion model analysis of the effects of aging on letter discrimination. *Psychology and Aging, 18*, 415–429.

Verhaeghen, P., Marcoen, A., & Goosens, L. (1993). Facts and fiction about memory aging: A quantitative integration of research findings. *Journal of Gerontology: Psychological Sciences, 48*, P157–P171.

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

Zacks, J. L., & Zacks, R. T. (1993). Visual search times assessed without reaction times: A new method and application to aging. *Journal of Experimental Psychology: Human Perception and Performance, 4*, 798–813.