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Age-Related Differences in the Processing of Redundant Visual Dimensions

Barbara Bucur and David J. Madden
Duke University Medical Center

Philip A. Allen
The University of Akron

Age differences in the redundant-signals effect and coactivation of visual dimensions were investigated in 2 experiments. In Experiment 1 the task required the conjoining of dimensions, whereas in Experiment 2 the spatial separation of dimensions was manipulated. Although coactivation was evident for both age groups when the redundant dimensions occurred at the same location, older adults showed more evidence for coactivation, perhaps because of compensation for declines in perceptual processing. When the redundant dimensions were separated, neither age group showed evidence for coactivation. These findings indicate that the coactive processing of redundant visual dimensions is spared in healthy older adults and that for both groups, attention must be focused on both dimensions for coactivation to occur.

Keywords: aging, attention, coactivation, reaction time, race model inequality

During daily activities, people often encounter situations in which they are presented with redundant information. When one is driving a car, for example, visual information regarding critical features of the environment, including spatial location and color, are combined redundantly to facilitate the decision to stop or keep driving at a traffic light (Wickens & Hollands, 2000). In the laboratory, research has consistently shown that reaction time (RT) tends to decrease as the number of targets in the display increases. For instance, when target features are defined as the letter “K” and the color purple, responses are much faster for trials containing a purple K compared with trials containing a purple G or an orange K. This facilitation of performance due to the presence of redundant information, termed *redundancy gain*, or the *redundant-signals effect* (RSE), has been investigated in a variety of paradigms involving visual search and discrimination (e.g., Feintuch & Cohen, 2002; Grice, Canham, & Gwynne, 1984; Krummenacher, Müller, & Heller, 2002; Miller, 1982; Mordkoff & Yantis, 1991, 1993). In this research, we investigated whether age-related differences occur in the way in which observers use redundant visual information. To understand the basis for these potential age differences, it is useful to consider the different theories of the RSE and coactivation that researchers have devised from younger adults’ performance.

RSE and Coactivation

Researchers have advanced two types of theories to explain the RSE: *separate-activation models* and *coactivation models*. Both types of models assume that an observer’s response to some target event is based on the degree to which an internal representation of the relevant features of the target is activated. The models also assume that the activation of multiple features can occur in parallel. Separate activation models, also called *race models*, state that the RSE results from statistical facilitation (Raab, 1962). The idea of statistical facilitation is that processing of redundant features is especially fast, compared with processing a single feature, because each feature is processed in parallel on separate information-processing channels. According to race models, facilitation occurs because the observer’s response is based on whichever channel completes processing first (Miller, 1982). Race models, however, assume that activation from multiple channels cannot combine to produce a single response; only information from the fastest channel receives further processing. Coactivation models, in contrast, assume that activation from multiple inputs, or channels, combine or summate to produce a single response. The level of activation necessary to initiate a response builds more quickly from the presentation of multiple instances of the features than from the occurrence of a single feature. Therefore, coactive processing of redundant features represents more efficient processing, because activation sums to initiate faster responding than is predicted from a race model.

Miller’s (1982) seminal work described the *race model inequality* (Equation 1) as a means of testing for separate activation versus coactivation. Violations of the inequality provide evidence for coactivation:

$$P(\mathrm{RT} < t|\mathrm{D}_1 \text{ and } \mathrm{D}_2) \leq P(\mathrm{RT} < t|\mathrm{D}_1) + P(\mathrm{RT} < t|\mathrm{D}_2). \qquad (1)$$

In Equation 1, t is the time since display onset with D_1 and D_2 representing different feature dimensions (e.g., color and shape). In a redundant-features paradigm in which targets are defined as

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Barbara Bucur and David J. Madden, Center for the Study of Aging and Human Development and Department of Psychiatry and Behavioral Sciences, Duke University Medical Center; Philip A. Allen, Department of Psychology, The University of Akron.

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Correspondence concerning this article should be addressed to Barbara Bucur, Box 2980, Duke University Medical Center, Durham, NC 27710. E-mail: bb@geri.duke.edu

the color purple and the letter K, for example, the left side of the equation represents the cumulative probability density function (CDF) for the RTs on trials with redundant target features (e.g., a purple K). The two terms on the right represent the CDF resulting from combining the RTs from the two categories of single-target trials (e.g., those on which the target was either an orange K or a purple G). This inequality requires that the RTs to redundant-target trials be no lower than the RTs for the fastest of the responses on single-target trials. In other words, the maximum amount of facilitation observed for redundant dimensions, assuming a model of separate activation, cannot represent a faster response than for the winner of the race (on each trial) between two independent channels. A test for coactivation is applied at each segment (quantile) of the CDF. If the race model inequality defined by Equation 1 is violated, and the responses to redundant-target trials are faster than what can be predicted by a separate activation model, then it is assumed that coactive processing is occurring.

The Role of Attention in Coactivation

Researchers interested in testing between models of separate activation and coactivation with stimuli from separable dimensions (e.g., color and shape) have used various versions of the redundancy gain paradigm to investigate the effects of spatial separation on coactivation (e.g., Feintuch & Cohen, 2002; Mordkoff & Yantis, 1993). In a series of experiments, Mordkoff and Yantis demonstrated that redundancy within the same dimension (e.g., color) did not lead to coactivation, whereas cross-dimensional redundancy did lead to coactivation (e.g., color and shape). In Experiment 1, these researchers obtained evidence for coactivation using a task in which a single stimulus letter (e.g., a green X) was presented. Participants responded if either one of two target dimensions, the color green and the letter X, was present in the display. Evidence for coactivation was also obtained when the two dimensions were spatially separated (Experiments 2 & 3). In Experiment 3, for example, the two dimensions were separated by presenting the color as a colored square below fixation along with a white letter above fixation. However, when using a design similar to Experiment 3, but using two stimuli within the same dimension (e.g., two letters presented above and below fixation), Mordkoff and Yantis did not obtain evidence for coactivation. On the basis of this result, these researchers concluded that coactivation occurs only when attention is divided between two different dimensions but that the spatial separation of the dimensions does not influence coactivation.

Recent research conducted by Feintuch and Cohen (2002), however, contradicts some of the findings of Mordkoff and Yantis (1993). Feintuch and Cohen obtained evidence for coactivation only with redundant dimensions at the same location. When the dimensions of color and shape were presented in different locations, coactivation did not occur, presumably because attention can only be focused on one of the dimensions. This finding raises the possibility that coactivation can occur when the target dimensions are contained in separate locations but are perceived as a single object. To test this possibility, Feintuch and Cohen presented the target dimensions in separate locations but grouped them together within an ellipse. Under these conditions, significant violations of the race model inequality did occur, providing further support for the role of attention on coactivation. Krummenacher et al. (2002) also reported that both the size of the RSE and evidence for coactivation decreased as a function of the spatial separation of redundant visual dimensions. Krummenacher et al. proposed that, at least in the context of highly efficient visual search performance (i.e., pop out of a unique target feature), coactivation represents the integration of location-specific signals. Both the Feintuch and Cohen and the Krummenacher et al. experiments yielded evidence for decreased coactivation as a function of increasing spatial separation of redundant dimensions. Other aspects of the results, however, led Feintuch and Cohen to conclude that coactivation occurs within a spatially limited focus of attention, whereas Krummenacher et al. characterized coactivation as the integration of location-specific signals prior to their effect on spatial attention.

Several models have been proposed to account for the findings from these studies. These models share the general assumption that an identification response is based on evidence accumulated in a master map of features activated by the display. Activity within this map is determined by the local differences among the features in the display (bottom-up activations) along with how closely the features match the observers' internal representation of the target properties (top-down activations). Both bottom-up and top-down activations of the features guide the gating of information for further processing (Wolfe, 1998). Models of the activation process differ with regard to whether or not spatial location is represented in the master map of features. The different accounts can be characterized as *dimension-weighting*, *response-based*, and *dimension-action* models.

Krummenacher et al. (2002), for example, proposed that their results fit within a dimension-weighting model of activation, which assumes that saliency maps are specific for individual perceptual dimensions (e.g., color, orientation) as well as for spatial location. This account assumes further that coactivation of features within the master map occurs relatively early in perceptual processing. As a result, dimension-weighting models predict decreases in coactivation with increases in spatial separation. The results of Mordkoff and Yantis (1993), in contrast, fit within a response-based account of activation, which specifies that featural activation is directly linked to associated mechanisms for responding (e.g., Cohen & Shoup, 2000). In response-based models, activations are pooled across feature maps independent of spatial information. Thus, response-based accounts predict no difference in coactivation as a function of spatial separation, as Mordkoff and Yantis (1993) observed. Finally, Feintuch and Cohen (2002) discussed their results in terms of a dimension-action model of target activation. In this model, information from each dimension is also segregated preattentively, as in dimension-weighting models. In the dimension-action model, however, multiple response decisions can be made simultaneously, allowing attention to serve as a gating mechanism, so that only information within the focus of attention receives further processing.

Although the role of attention in coactivation is not entirely clear because of these divergent findings, this research does suggest that coactivation models provide the best explanation for the benefit due to redundancy using cross-dimensional, visual stimuli, at least in younger adults. Although some research with older adults has been conducted in this area using bimodal stimuli (Bucur, Allen, Sanders, Ruthruff, & Murphy, 2005), the current research represents the first investigation of potential age-related differences in the processing of redundant dimensions within the visual modality.

Redundancy Gain and Coactivation in Older Adults

Age-related decline in visual tasks tends to be most pronounced when some division of attention is required. This decline is most clearly evident when participants are required to switch unpredictably between two different types of tasks (i.e., global task switching; Mayr, 2001), but it is also evident when attention is switched between items within a task (i.e., local task switching; Kramer, Hahn, & Gopher, 1999). In addition, in visual search tasks, the effect of the number of display items on RT (i.e., the display size effect) is typically greater for older adults than for younger adults (e.g., Plude & Hoyer, 1986). These and other instances of divided-attention deficits have been attributed to a limitation in the amount or availability of an internal (cognitive) processing resource necessary for task performance (for reviews, see Madden & Whiting, 2004; McDowd & Shaw, 2000; Salthouse, 1991, chap. 8). Maylor and Lavie (1998), for example, reported that one measure of resource limitation (the display size at which an irrelevant distractor no longer interfered with performance) suggested that fewer attentional resources were available for older adults than for younger adults.

Generalizing these results to the division of attention between stimulus dimensions, one expression of an age-related decline in attentional capacity may be a reduction in coactivation of visual signals. Indeed, age-related reductions in attentional resources may be especially relevant to our predictions because of the proposed locus of coactivation. In fact, Miller (1982) proposed that coactivation occurs late in processing, “after the point at which signals are identified and their task relevance is discerned” (p. 270). Attention occurring after stimulus identification tends to require more processing resources (e.g., Deutsch & Deutsch, 1963); therefore, age-related reductions in processing resources may reduce or eliminate coactive processing in older adults. Further, we hypothesized that this age-related decline in coactivation would be especially pronounced under conditions that require the division of attention between spatially separated redundant dimensions.

Research conducted by Allen and colleagues suggests that older adults do benefit from the presence of redundancy and that the magnitude of the RSE for older adults may actually be greater than for younger adults (Allen, Groth, Weber, & Madden, 1993; Allen, Madden, Groth, & Crozier, 1992; Allen, Weber, & Madden, 1994). Using a two-choice task in which either one instance or two instances of the target letter K or N were presented, Allen et al. (1994) concluded that the significantly larger RSE for older adults was due to an age-related reduction in attentional capacity at the identification stage of processing. These authors assumed that older adults extract less information from the presentation of a single target, compared with younger adults, over a given period of time due to these reductions. Thus, the presentation of an additional target on redundant trials is of greater benefit to older adults than to younger adults.

To further investigate the significantly larger RSE in older adults, Allen et al. (1992) used log-transformed RT analyses to test for one form of age-related slowing: a proportional age-related increase in the RSE. The results indicated that the RSE in the condition containing target letters without any distractor letters was not disproportionately greater for older adults than for younger adults. When distractor letters were present in the display, however, the RSE was disproportionately increased for older adults, suggesting an age-related decline in attending selectively to the target(s), beyond what can be expected from proportional age-related slowing. Although these studies yielded important information regarding the processing of redundant targets by older adults, Allen and colleagues did not test for coactivation in any of these experiments.

In the first investigation of coactivation in older adults, Bucur et al. (2005) used a go/no-go bimodal detection task, in which participants made the same keypress response either when they saw an asterisk, when they heard a tone, or when both stimuli occurred simultaneously. Consistent with Allen et al. (1992, 1993, 1994, Bucur et al. also found evidence for an age-related increase in the absolute magnitude of the RSE. The Age Group × Redundancy interaction, however, did not remain significant after correcting for generalized slowing. Important to note, older adults did exhibit significant violations of the race model inequality, indicating the preservation of parallel, coactive processing of auditory and visual features. Thus, although an age-related decline in coactivation would be expected on the basis of divided-attention research, Bucur et al. concluded that the coactivation of auditory and visual features did not vary significantly as a function of adult age. In the present experiments we investigated age-related differences in coactivation within the visual modality.

The Present Experiments

The first goal of the current studies was to investigate age-related differences in the RSE, within one modality (vision), using two separate dimensions (color and letter). Although previous research has indicated some age-related increase in the RSE, it is not clear if this increase is greater than would be expected on the basis of generalized age-related slowing (i.e., a disproportionate change). The previous finding of a disproportionate age-related increase in the RSE used a relatively complex, multi-item display (Allen et al., 1992, target-plus-distractors condition), whereas experiments exhibiting a proportionately constant RSE for younger and older adults have used single-item displays (Allen et al., 1992, target-only condition; Bucur et al., 2005). The complexity of the detection task may be a critical variable. Research on age-related differences in visual target detection and search suggests that tasks requiring the integration of features (e.g., detecting a red horizontal line among red vertical and green horizontal distractors) may be particularly problematic for older adults (Humphrey & Kramer, 1997; Plude & Doussard-Roosevelt, 1989). In the present experiments, we therefore used a complex task, either defining the target by a conjunction of features (Experiment 1) or requiring the division of attention between spatial locations (Experiment 2), to determine whether the RSE would increase disproportionately for older adults.

The second goal was to investigate potential age-related differences in the coactivation of two different visual dimensions. As noted previously, Bucur et al. (2005) reported evidence for coactive processing, by both younger and older adults, of redundant information across different modalities (visual and auditory), but it is not known whether older adults will exhibit coactivation within a single modality—in this case, vision. Indeed, the task used by Bucur et al. was a relatively simple task in which participants simply responded to the presence of any stimulus and did not need to make decisions between target and nontarget items. In our current tasks, coactivation may be evident only for younger adults and not for older adults, especially if coactivation is a resource-consuming process that requires the division of attention between stimulus dimensions (Mordkoff & Yantis, 1993). On the other hand, Bucur et al. observed an age constancy in coactivation for visual and auditory stimuli, and this pattern may also hold within the visual modality. Despite the age-related deficits that have been found on a variety of cognitive tasks, older adults tend to perform at least as well as younger adults on many attentional tasks, such as using top-down attention or conceptual knowledge to guide search (e.g., Madden, Whiting, Spaniol, & Bucur, 2005; Whiting, Madden, Pierce, & Allen, 2005). Indeed, some research suggests (e.g., Allen et al., 2002) that older adults often compensate for declines in perceptual processing by becoming more efficient during later stages of processing, especially in highly practiced tasks such as word or letter identification. Thus, coactivation may be an attentional component that is relatively preserved as a function of age.

The final goal was to investigate the role of the division of spatial attention in the RSE and coactivation, by comparing conditions presenting redundant information in either the same location or different locations (Experiment 2). Therefore, we modified the procedures used by Mordkoff and Yantis (1993) to allow a clearer examination of this issue. As did Mordkoff and Yantis, we used a go/no-go task in which participants pressed a key whenever target dimensions were presented. The design features in the Mordkoff and Yantis (1993) study that may affect the focus of attention include display size (which varied between their Experiments 1 and 2) and the spatial predictability of the target dimension (the letter dimension was always in the upper position in their Experiment 3). Our modifications included using a consistent display size and varying the spatial positions of the stimulus dimensions (upper vs. lower). Using this design, we expected to obtain evidence for more coactivation and a larger RSE, for both age groups, with redundant dimensions within the same location compared with when these dimensions are spatially separated. That is, by reducing some of the sources of variability in the Mordkoff and Yantis (1993) methodology in Experiment 2, we expected to obtain results more in line with those of Feintuch and Cohen (2002) and Krummenacher et al. (2002). The effect of spatial separation may well interact with age-related differences in sensory function and/or dividing attention, however, leading to an age-related decline in coactivation for spatially separated dimensions. As a result, age differences in redundancy gain and coactivation may be more pronounced in the separate-location condition compared with the same-location condition.

Experiment 1

In Experiment 1, we modified the task used by Mordkoff and Yantis (1993, Experiment 1) so that a correct response required the integration of different visual dimensions—color, orientation, and letter identity. Each display contained a single colored letter that was tilted 45° either left or right. We used a go/no-go paradigm in which participants responded only when the display contained a particular conjunction of target features. These were the letter K in a specified orientation (regardless of its color) and the letter G when both colored purple and in the specified orientation. Using this method, participants needed to use a conjunction of orientation and color (i.e., tilted in the specified orientation plus purple) or a conjunction of orientation and letter identity (i.e., G or K plus the specified orientation) to make a response. Thus, simply relying on either color, orientation, or letter identity alone was not sufficient for a correct response.

In view of the results of Allen et al. (1992), we predicted that, because of increased complexity, older adults would show a disproportional benefit due to the presentation of redundant dimensions. We had mixed predictions in terms of coactivation. Although we expect to obtain evidence for coactivation in younger adults, one view of cognitive aging suggests that older adults may not show evidence for coactivation because of age-related deficits in dividing attention between two stimulus dimensions. However, coactive processing may be a form of attention that remains relatively preserved as a function of increased adult age (e.g., Bucur et al., 2005); therefore, both age groups may show evidence for coactivation.

Method

Participants. Twenty older adults (10 female and 10 male) between the ages of 60 and 85 years of age ($M = 68.7$ years) and 20 younger adults (10 female and 10 male) between the ages of 18 and 22 years of age ($M = 19.0$ years) participated in both experiments. The 20 younger adults were drawn from the Department of Psychology participant pool at Duke University and received course credit for their participation. The 20 healthy older adults were community-dwelling individuals recruited from the Duke Aging Center Subject Registry and received compensation of $30.00 for their participation. All participants had near visual acuity of at least 20/40, had normal color vision (Dvorine, 1963), and scored at least 27 on the Mini-Mental State Exam (Folstein, Folstein, & McHugh, 1975). Participants were excluded if they indicated the use of any psychotropic medications and/or major medical conditions (e.g., a recent stroke, Parkinson's disease, etc.). All participants provided written, informed consent. All participants completed both Experiments 1 and 2 during separate sessions at least 1 day apart. The order in which they completed the experiments was counterbalanced over participants. Table 1 presents the means and standard deviations for all participant variables.

Stimuli, design, and procedure. Stimuli were presented using a 2.0-GHz-processor, Pentium 4 microcomputer with a 19-in. (48.26-cm), flat panel LCD. The task was a go/no-go version of single-target detection. Each display consisted of one colored letter on a black background. The letters were rotated 45° either to the left or to the right. Stimuli were the letters K, G, and J and the colors orange (red, green, and blue [RGB] = 205, 70, 0), purple (RGB = 214, 0, 214), and green (RGB = 0, 148, 0). Luminance of the display items was 36.66 cd/m^2 at a viewing distance of 60 cm. The letters subtended 0.95° of visual angle. Figure 1 contains examples of the displays.

The target dimensions were the letter K and the color purple. In addition, to qualify as a target, the stimuli also had to be presented in the specified orientation (either left or right, depending on counterbalancing assignment). The redundant-target stimuli consisted of a purple K in the specified orientation, whereas the single targets were a purple G in the specified orientation and an orange K in the specified orientation. Nontargets were

Table 1
Participant Variables by Age Group: Experiments 1 and 2 ($n = 20$ per Group)

Variable	Mean		Standard deviation	
	Younger adults	Older adults	Younger adults	Older adults
Age (years)	19.00	68.70[b]	1.08	7.02
Education	12.55	15.10[b]	0.89	2.38
Acuity	15.50	31.00[b]	1.54	10.95
Color Vision	13.90	13.30[b]	0.31	0.73
Vocabulary	63.90	63.85	4.05	3.79
Digit Symbol accuracy	96.25	97.50	3.06	2.32
Digit Symbol RT	1,288.20	1,969.20[b]	224.19	347.59
MMSE	29.55	28.85[b]	0.60	0.99

Note. Acuity = denominator of the Snellen fraction for corrected near vision; Color Vision = raw score (maximum of 14) on the Dvorine color plates (Dvorine, 1963); Vocabulary = raw score (maximum of 70) on the Wechsler Adult Intelligence Scale—Revised (Wechsler, 1981); Digit Symbol accuracy and Digit Symbol RT = accuracy (%) correct and response time (in milliseconds) on the computer test of digit–symbol coding (Salthouse, 1992); MMSE = raw score on the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975).

[b] Significant age group differences within each experiment, $p < .05$.

a green G, a green J, and an orange J in both orientations and an orange K, a purple K, and a purple G in the nonspecified orientation. This arrangement resulted in three different types of targets and nine different types of distractors· Twenty-five percent of the trials were go trials, whereas the remaining 75% of the trials were no-go trials.[1]

A trial began with a 400-ms presentation of a white fixation cross in the center of the screen. After a 100-ms blank interval, the letter display appeared on the screen and remained until the participant made a response or until 1,000 ms elapsed. Responses not made within 1,400 ms of the stimulus presentation were considered errors. Participants first completed a block of 24 practice trials followed by 16 blocks of 72 experimental trials (18 go trials; 6 trials for each stimulus type in Figure 1). The first block of experimental trials was also considered practice and was not analyzed. Stimuli were presented in random order within each trial block. Half of the participants in each age group performed the task with a stimulus set in which the specified target orientation was right (as in Figure 1), and half performed the task with the same stimuli displayed in the opposite orientation, thus defining the target orientation as left.

Participants were instructed to respond by pressing the center key on the response box whenever they saw either a purple G in the specified orientation or the letter K in the specified orientation. Responses were to be withheld on all other trials. The instructions emphasized speed and accuracy equally. After each block, feedback accuracy was displayed and an opportunity for a break was provided.

Results and Discussion

Participants in both age groups performed the task with a high level of accuracy (older adults, $M = 99.0\%$; younger adults, $M = 99.5\%$). Prior to conducting the redundancy gain analyses, we removed error trials, RTs less than 100 ms, and RTs greater than 1,000 ms, resulting in the deletion of less than 0.0015% of the data. All analyses were conducted using the mean of median RTs.

Redundancy gain analyses. Using the mean of the two single-dimension conditions as the dependent variable,[2] we conducted a 2 (age group: younger vs. older) × 2 (redundancy: one dimension vs. two dimensions) split-plot analysis of variance (ANOVA), in which age group was a between-subjects variable and redundancy was a within-subjects variable. The results revealed a significant main effect of age group, $F(1, 38) = 31.01$, $MSE = 7,570.95$, $p < .0001$, partial $\eta^2 = .45$, with younger adults ($M = 458$ ms) responding more quickly than older adults ($M = 566$ ms). As predicted, the main effect of redundancy was also significant, $F(1, 38) = 296.46$, $MSE = 137.68$, $p < .001$, partial $\eta^2 = .89$, because participants responded more rapidly on the redundant-target trials ($M = 489$ ms) than on the single-target trials ($M = 535$ ms). In addition, the Age Group × Redundancy interaction was significant, $F(1, 38) = 16.55$, $MSE = 137.68$, $p < .0002$, partial $\eta^2 = .30$. Although redundancy facilitated responding in both groups,

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[1] Typically, experiments examining the RSE use an equal number of target and nontarget stimuli. Mordkoff and Yantis (1993), for example, selected their stimuli from three colors (green, cyan, purple) and three letters (X, I, O) for their stimuli. Each letter was presented in two colors resulting in two single targets, one redundant target, and three distractors. In the present experiment, the addition of the orientation dimension prevented the type of design used by Mordkoff and Yantis (1993). Our goal was to have participants attend to orientation, as well as to letter and color; therefore, we presented each letter and color combination equally often in each orientation (left and right). This method of constructing stimuli resulted in more nontarget than target stimuli. Although unusual, this method avoided introducing a bias in responding toward one type of target (single vs. redundant). Consistent with other research, each of the target stimuli were presented equally often; we simply included more nontarget trials.

[2] We also conducted analyses of the RSE using the *fixed favored dimension test* (e.g., Biederman & Checkosky, 1970; Mordkoff & Yantis, 1993). According to the logic of the fixed favored dimension test, the RSE could be the result of one of the dimensions being processed faster than the other. Therefore, the redundancy gain may occur because the "favored" dimension is present on all redundant trials, whereas on single-target trials, the favored dimension is present on only half of the trials. The fixed favored dimension test corrects for this by using the single-dimension condition leading to the faster responses. The results from this analysis were similar to those using the mean of the single-target trials. Table 2 presents the means and standard deviations from both analyses.

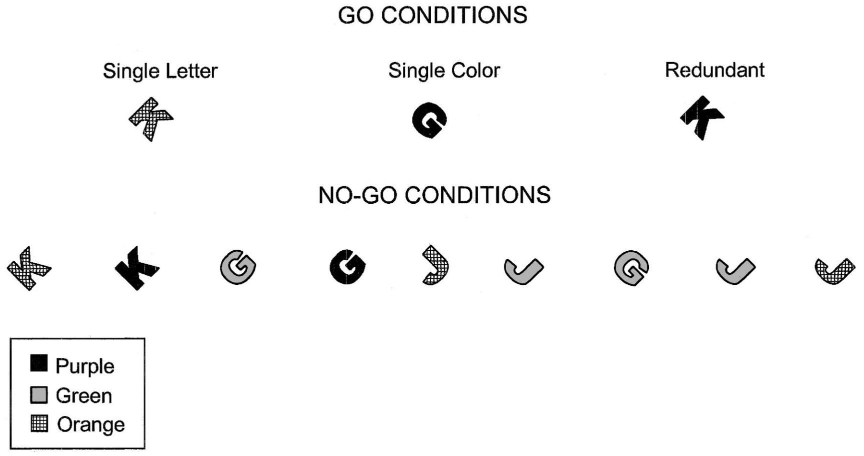

Figure 1. Stimuli used in Experiment 1.

the absolute magnitude of the RSE was greater for the older adults (M = 56 ms) than for the younger adults (M = 35 ms).

Percentage of RT. To determine whether the significant Age Group × Redundancy interaction resulted from the overall slower responses of the older adults in the single-task condition, we created a new variable representing the percentage of improvement due to redundancy, (Single-Target RT – Redundant-Target RT)/ Single-Target RT × 100. This type of relative change measure is often used to control for the effects of generalized slowing (e.g., Hartley, 1993). The results of an independent-groups t test using this variable indicate that the degree of improvement for the older adults (9.76%) was not significantly different from that for the younger adults (8.36%).

RT distribution analyses. To test for coactivation, we used the procedures outlined by Miller (1982). We first grouped the blocks into five epochs (Blocks 1–3, 4–6, 7–9, 10–12, and 13–15), which helps to reduce the effects of practice on the distribution (Miller, 1982; Mordkoff & Yantis, 1991). Each participant completed 18 redundant-dimensions trials in each epoch, so we sorted these 18 RTs in ascending order of latency to estimate 18 quantiles (with each quantile containing 5.56% of the distribution). These numbers were then averaged across epochs and participants to produce a CDF for the redundant-dimension condition. To produce the sum of the two single-dimension CDFs, we pooled together all of these trials and estimated the 18 quantiles based on only the fastest 18 of the 36 trials within each epoch for each participant. The 18 quantiles were then averaged across epochs and participants to produce a composite CDF. The race model inequality was violated if the mean RT for redundant-target trials was lower than the mean RT for the sum of the single-target trials at the corresponding quantile.

The CDFs for the redundant-target trials and each of the single-target trials are plotted for each age group in Figure 2. Miller's race model inequality for separate activation requires that, for data conforming to a race model, the CDF for the redundant-target trials will be to the right and below the CDF for the sum of the single targets. If the redundant-target CDF is instead to the left and above that of the single-target CDF, then the race model inequality is violated, thus providing evidence for coactivation. Because we are

Table 2
Mean Reaction Time (RT) and Results of the Redundancy Gain Analyses in Experiment 1

	Mean		Standard deviation	
Variable	Younger adults	Older adults	Younger adults	Older adults
Mean single	475.05	594.08	62.05	69.77
Fast single	470.50	590.00	52.18	69.58
Redundant	440.55	538.23	58.79	62.05
$\text{Gain}_{\text{Mean}}$	34.50	55.85	11.53	20.44
$\text{Gain}_{\text{B\&C}}$	29.95	51.77	14.99	27.02

Note. RT values are in milliseconds. Mean single = mean RT for the two single-target conditions; Fast single = mean RT for the fastest of the two single-target conditions; Redundant = mean RT for the redundant-target condition; $\text{Gain}_{\text{Mean}}$ = redundant-signals effect (RSE) calculated using mean single RT; $\text{Gain}_{\text{B\&C}}$ = RSE calculated using fast single RT (Biederman & Checkosky, 1970).

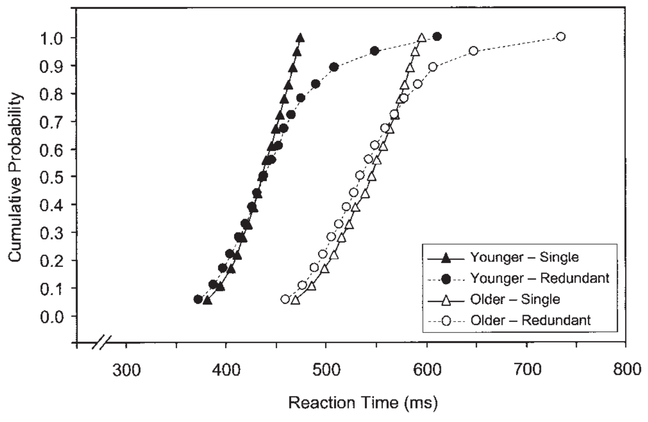

Figure 2. Cumulative probability density function (CDF) of reaction time in Experiment 1, for single- and redundant-dimension trials, as a function of age group.

testing for violations of the race model inequality (i.e., evidence for coactivation), the only relevant quantiles are those showing a mean difference favoring faster responding for redundant-target trials compared with the sum of the single-target trials at the corresponding quantile (Miller, 1982). A significant violation at any quantile allows us to reject a model of separate activation in favor of coactivation. The mean difference data indicated that there were violations of the race model inequality at 7 of the 18 quantiles (the 1st through the 7th quantiles) for the younger adults and at 12 of the 18 quantiles (the 1st through the 12th quantiles) for the older adults. To follow up on this finding, we conducted correlated-groups *t* tests on the summed single-target and redundant-target RTs at each of these bins. (All tests for coactivation used a critical *t* value of 1.73, corresponding to $p = .05$ for $df = 19$, one-tailed, because the direction of the RT difference was specified a priori.) For younger adults, four of these tests revealed significant violations, whereas for older adults, 11 of the tests were significant. That is, as illustrated in Figure 2, the CDF for the redundant-target trials is to the left and above the CDF of the sum of the single-target trials from the 1st through the 4th quantiles for younger adults and from the 1st through the 11th quantiles for older adults.[3]

An inspection of Figure 2 suggests that the size of the violations may have been larger for older adults than for younger adults. To determine quantitatively if one group produced more coactivation than the other, we conducted post hoc analyses using the procedures outlined by Miller (1986). First we calculated the area below the redundant-dimension CDF but above that of the sum of the single-dimension CDF for each participant. This area represents violations of the race model inequality and was measured as a proportion of the total area under the redundant-dimension CDF, expressed in units of 1/1,000 of the area under the redundant-target curve. We next performed an independent-groups *t* test between the mean areas for younger and older adults. As shown in Figure 3, this test revealed that the area for older adults ($M = 43.67$) was significantly larger than that for the younger adults ($M = 23.67$), $t(38) = 2.07$, $p = .05$, $d = 0.65$. Thus, older adults produced more evidence for coactivation than did the younger adults.

These results lead to two conclusions. First, consistent with previous research (Allen et al., 1992, 1993, 1994; Bucur et al., 2005), the absolute magnitude of the RSE was greater for older adults than for younger adults. However, similar to Bucur et al., when the RSE was analyzed as a percentage change in RT, the RSE was not significantly greater than would be expected on the basis of proportional age-related slowing. Apparently, although older adults often have more difficulty with tasks that require the integration of different features, these difficulties did not result in an age-related increase in the benefit due to redundancy, beyond what would be expected due to proportional age-related slowing.

The second conclusion is that both younger and older adults exhibit coactive processing of redundant features within the visual modality. The observed violations of the race model inequality allow us to reject a separate activation model, in favor of a coactivation model, for both older and younger adults. Further, although both groups show evidence for coactivation, the analysis of the area between the two CDFs provides evidence that more coactivation was produced by the older adults. In this sense, the pattern of age-related effects associated with coactivation resembles other aspects of selective attention leading to improved performance (e.g., top-down attention effects), which tend to be constant with age, and does not resemble the age-related decline that has been observed in other forms of divided attention and executive control.

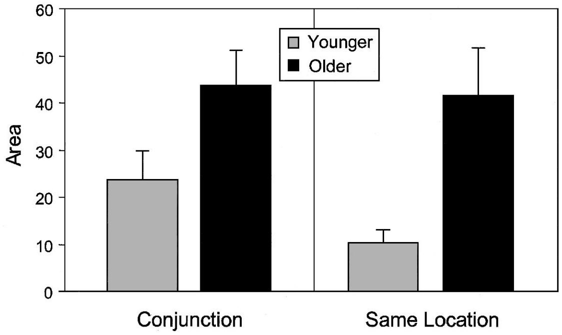

Figure 3. Area represents the degree of coactivation for redundant-dimension trials, relative to single-dimension trials, expressed as the difference between the respective cumulative probability density functions (CDFs). For the CDFs in Figure 2, for example, this difference is the area below the redundant-dimension trial CDF but above the single-trial CDF. The unit of measurement is 1/1,000th of the total area below the redundant-dimension trial CDF.

Experiment 2

In Experiment 1, the relevant visual dimensions were presented in a single object—a letter. Mordkoff and Yantis (1993, Experiment 3) found that coactivation of two separate dimensions (shape and color) could occur when the dimensions were separated spatially in two display items (a white letter positioned above a colored square), as well as when they were contained in a single display item (a colored letter). Other evidence indicates that coactivation decreases with increasing spatial separation (Feintuch & Cohen, 2002; Krummenacher et al., 2002). In Experiment 2, we used a design similar to that of Mordkoff and Yantis (1993) to examine coactivation of dimensions within the same location compared with dimensions that are spatially separated (different location). However, we modified the procedures used by Mordkoff and Yantis (1993) so that the composition of the displays in the different conditions of spatial separation would be more closely equated.

In each spatial separation condition of Experiment 2, all of the displays contained two items, a letter and a square. In the same-location condition, the letter was colored and the square was white. In the different-location condition, the letter was white and the

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[3] According to Miller (1982), because we are comparing all of the redundant dimension trials to only half of the single-dimension trials (those containing the fastest responses), the race model inequality can be violated only with relatively small values of *t*, for the reason that the sum of the single-dimension CDF reaches a maximum of 2.0 on the *y*-axis whereas the redundant dimension CDF reaches a maximum of 1.0. Thus, at larger values of *t*, the sum of the single-dimension CDF will certainly be above that of the redundant dimension CDF.

square was colored (see Figure 4). Thus, in the same-location condition, the white square was an irrelevant distractor, in that it never contained either of the target dimensions. We further modified the stimuli so that color and shape were presented equally often, and unpredictably, in the upper and lower display positions. In contrast to this, Mordkoff and Yantis (1993) always presented the letter in the upper position and the colored square in the lower position. Presenting the stimuli in predictable locations provided a top-down source of information that may have made it easier for participants to focus attention on both objects simultaneously. By equating the number of display items (two) in the same- and different-locations conditions, combined with varying the positions of each dimension (upper vs. lower), we were able to measure the effect of spatial separation on coactivation independent of the influence of the predictability of the spatial location of the dimensions.

Following Mordkoff and Yantis (1993), we predicted that the RSE would be evident for both age groups, in both the same-location and different-location conditions. However, in view of the Feintuch and Cohen (2002) and Krummenacher et al. (2002) findings, it is also likely that the RSE will be larger when the dimensions are contained at the same location, relative to different locations. Consistent with Allen et al. (1992, 1993, 1994) and Bucur et al. (2005), we also expected that the absolute magnitude of the RSE would be greater for older adults than for younger adults. The decrease in the magnitude of the RSE reported by Feintuch and Cohen and by Krummenacher et al. was also associated with decreasing evidence for coactivation. We therefore predicted that, for both age groups, more evidence for coactivation would be obtained in the same-location condition compared with the different-location condition. Because of age-related differences in dividing attention and processing speed, we expected that this pattern of change in coactivation as a function of spatial separation would be more pronounced for older adults than for younger adults.

Method

Experiment 2 was also a go/no-go, single-target detection task, and the methods for Experiment 2 were similar to those of Experiment 1. All of the participants in Experiment 1 also completed Experiment 2, during a separate session on a different day.

We used a 2 (age group: younger vs. older) × 2 (redundancy: one dimension vs. two dimensions) × 2 (location: same location vs. different locations) design, with age group as the between-subjects variable and redundancy and location as the within-subjects variable. The stimulus letters and colors were the same as those used in Experiment 1. However, in this experiment, the display consisted of a letter and a square presented in the center of the monitor. The character space for the letter was 0.67° × 0.67°, and the square was 0.76° × 0.76°. In both the same- and different-location conditions, the physical distance between the letter and square was 0.57°. In the same-location condition, the letter was colored and the square was white. In the different-location condition, the letter was white and the square was colored. Thus, the same- versus different-location condition referred to whether the relevant target dimensions were located on the same object (the letter) or separated spatially on different objects. The dimensions of color and shape were presented equally often in both positions (upper and lower). The entire display subtended 0.76° × 1.9° visual angle.

The target dimensions were the letter K and the color purple. The redundant-target item was a purple K, whereas the single targets were a purple G and an orange K. Nontargets consisted of a green G, a green J, and an orange J. There were consequently three different targets (go trials; 50% of total) and three different distractors (no-go trials; 50% of total). Participants first completed a block of 24 practice trials followed by 16 blocks of 72 experimental trials (6 trials for each stimulus type in each location condition). Thus, participants could not anticipate the location of the relevant dimensions and had to prepare, on each trial, to divide attention between the locations. The first block of experimental trials was also considered practice and was not analyzed. The different types of trials were presented in a pseudorandom order within each block with the constraint that no more than four of each trial type occurred sequentially.

Results and Discussion

Participants were also very accurate in performing this task, and mean accuracy was greater than 99% for each age group. Prior to

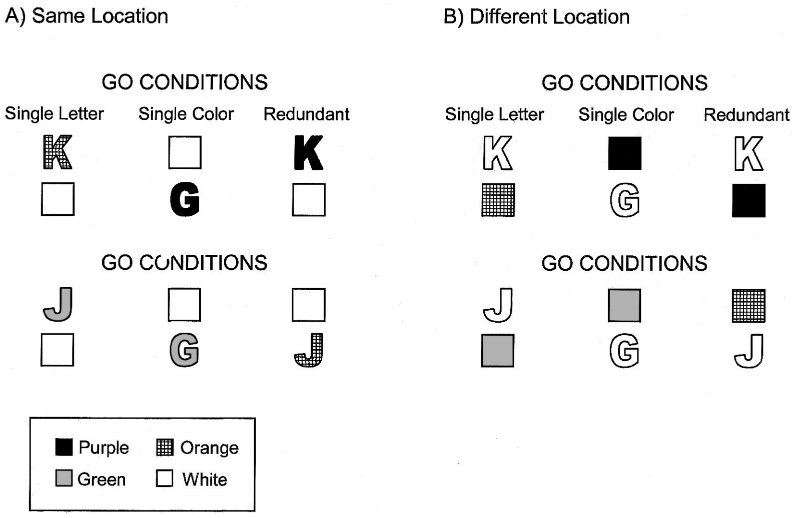

Figure 4. Stimuli used in Experiment 2 for the same-location (A) and different-location (B) conditions.

conducting the analyses, we removed incorrect response trials and trials with RTs either less than 100 ms or greater than 1,000 ms (less than 0.72% of the data). All analyses were conducted using the mean of median RTs on the go trials.

Redundancy gain analyses. We conducted a 2 (age group: younger vs. older) × 2 (redundancy: one dimension vs. two dimensions) × 2 (location: same vs. different) split-plot ANOVA, in which age group was a between-subjects variable and redundancy and location were within-subjects variables. (The data for the one-dimension condition were the mean of the two types of single-dimension trials, color and letter.) The main effects of age group, $F(1, 38) = 22.59$, $MSE = 11{,}852.08$, $p < .0001$, partial $\eta^2 = .37$, and redundancy $F(1, 38) = 370.59$, $MSE = 126.20$, $p < .0001$, partial $\eta^2 = .91$, were significant, as was the Age Group × Redundancy interaction, $F(1, 38) = 14.41$, $MSE = 126.20$, $p < .0005$, partial $\eta^2 = .28$, reflecting a larger RSE for older adults (41 ms) than for younger adults (27 ms). Although the main effect of location was not significant, the Age Group × Location interaction was significant, $F(1, 38) = 12.85$, $MSE = 69.70$, $p < .0009$, partial $\eta^2 = .25$, because older adults were 7 ms faster in the same-location condition than in the different-location condition, whereas younger adults were 2 ms faster in the different-location condition than in the same-location condition. The Redundancy × Location and Age Group × Redundancy × Location interactions were not significant. Direct comparison of the two single-dimension conditions indicated that responses to the two dimensions did not differ significantly. Therefore, the dimension with lowest mean RT, for each age group, was used for the fixed favored dimension test. The results from this latter analysis were similar to that using the mean of both types of single-target trials, with the exception that the main effect of location was significant, $F(1, 38) = 7.72$, $MSE = 97.79$, $p = .0084$, partial $\eta^2 = .17$, as a result of slightly faster responses in the same-location condition ($M = 440$ ms) compared with the different-location condition ($M = 444$ ms).

Percentage of RT. As in Experiment 1, we conducted analyses of the percentage of improvement in RT that was due to redundancy. We conducted an Age Group × Location ANOVA of the percentage RSE measure for the same-location and different-location conditions. The results revealed a significant main effect of age group, $F(1, 38) = 5.12$, $MSE = 15.76$, $p = .03$, partial $\eta^2 = .12$, indicating that the percentage of benefit due to redundancy was greater for the older adults (9.99%) than for the younger adults (7.98%). Neither the main effect of location nor the Age Group × Location interaction was significant.

RT distribution analyses. We again used the procedure of testing for violations of Miller's race model inequality, as a method of determining whether there was evidence for coactivation in Experiment 2. This time, CDFs were formed for the sum of the single-target trials and the redundant-target trials for each condition (same location vs. different location) as well as for each age group. The CDFs are presented in Figure 5. As in Experiment 1, we tested for violations of the race model inequality by means of t tests at each quantile, with critical $t(19) = 1.73$, $p < .05$ (one-tailed). For the same-location condition, there was only one significant violation of the race model inequality for younger adults (at the 1st quantile). For the older adults' same-location data, the violations at the 3rd through the 9th quantiles were significant. We analyzed the data for the different-location condition in a comparable manner and did not obtain any significant violations of the race model inequality for either age group.

Table 3

Mean Reaction Time (RT) and Results of the Redundancy Gain Analyses in Experiment 2

Variable	Mean: Younger adults	Mean: Older adults	Standard deviation: Younger adults	Standard deviation: Older adults
Same location				
Mean single	419.63	501.20	49.54	60.41
Fast single	411.35	498.58	51.50	69.70
Redundant	388.73	461.33	42.98	59.41
$\text{Gain}_{\text{Mean}}$	30.90	39.88	15.12	13.05
$\text{Gain}_{\text{B\&C}}$	22.63	37.25	18.29	21.16
Different location				
Mean single	413.80	509.35	45.46	63.13
Fast single	412.00	508.20	43.58	67.89
Redundant	389.80	467.35	50.76	64.13
$\text{Gain}_{\text{Mean}}$	24.00	42.00	8.51	16.86
$\text{Gain}_{\text{B\&C}}$	22.20	40.85	15.92	21.98

Note. RT values are in milliseconds. Mean single = mean RT for the two single-target conditions; Fast single = mean RT for the fastest of the two single-target conditions; Redundant = mean RT for the redundant-target condition; $\text{Gain}_{\text{Mean}}$ = redundant-signals effect (RSE) calculated using mean single RT; $\text{Gain}_{\text{B\&C}}$ = RSE calculated using fast single RT (Biederman & Checkosky, 1970).

To determine whether the older adults produced significantly more coactivation than did the younger adults, we again used the procedures described in Experiment 1 to calculate the area between the two curves, for the same-location condition. As illustrated in Figure 3, the results revealed that older adults produced significantly more evidence for coactivation ($M = 41.51$) than did the younger adults ($M = 10.44$), $t(38) = 2.96$, $p = .005$, $d = 0.54$.

There were three main findings from Experiment 2. First, consistent with Experiment 1 and previous literature (e.g., Allen et al., 1992, 1993, 1994; Bucur et al., 2005), the absolute magnitude of the RSE in Experiment 2 was greater for older adults than for younger adults. Further, the age-related increase in the RSE was also significant when analyzed as a percentage change in RT, suggesting an effect beyond generalized age-related slowing. The age difference in the relative improvement in RT associated with redundancy in Experiment 2 was small in magnitude but statistically significant (10% for older adults vs. 8% for younger adults). Thus, it appears that the presence of redundant target information is more beneficial for older adults than for younger adults, beyond the effect of generalized age-related slowing, perhaps as a result of age-related decline in some aspect of visual sensory processing. The present results in addition demonstrate that feature integration (as implemented in Experiment 1) is not a necessary condition for an age-related increase in the RSE. In Experiment 2 participants could respond on the basis of the occurrence of either the letter K, the color purple, or both. Experiment 2 did, however, require participants to divide attention between two relevant display locations on each trial, which may have contributed to the age difference in the RSE.

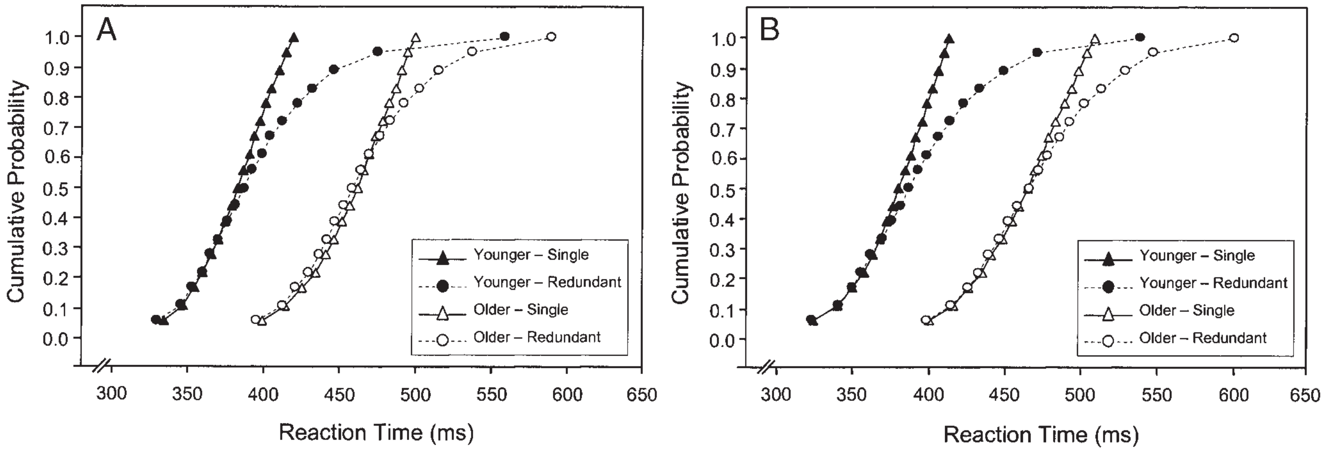

Figure 5. Cumulative probability density function (CDF) of reaction time in Experiment 2, for single- and redundant-dimension trials, as a function of age group, for the same-location (A) and different-location (B) conditions.

The second main finding is that, for both age groups, the magnitude of the RSE did not vary as a function of the location of the redundant dimensions. This result replicates the findings of Mordkoff and Yantis (1993) but is inconsistent with Feintuch and Cohen (2002) and Krummenacher et al. (2002). On the other hand, evidence for coactivation was obtained in the same-location condition but was eliminated for both age groups when the redundant dimensions were separated spatially. This latter result is consistent with those of Feintuch and Cohen and Krummenacher et al. This pattern of results—spatial separation leading to decreased coactivation but no change in the RSE—is somewhat at odds with previous research. Although the previous investigations of coactivation differ with regard to which variables are found to influence performance, the variations in the RSE and evidence for coactivation, within an experiment, tend to occur in a similar manner. In other words, when coactivation decreases as spatial separation increases, the size of the RSE decreases as well. The reason for the particular pattern we observed in Experiment 2, in which spatial separation affected coactivation but not the RSE, is unclear. It is possible that under certain conditions (e.g., spatial separation), the use of redundant signals can be accomplished by means of a race model architecture. As noted in the Introduction, researchers have advanced several models to explain spatial separation effects in the RSE and coactivation. We examine some of these within the context of our results in the General Discussion.

Although location did not affect the RSE significantly, there was some evidence for an age-related increase in the overall effect of divided attention, as evidenced by the Age Group × Location interaction. Older adults were slightly (7 ms) but significantly faster at responding to dimensions contained within the same location, as compared with dimensions that were spatially separated, whereas younger adults were slightly (2 ms) faster in responding to separated dimensions. This interaction, though small in magnitude, is consistent with previous research showing that older adults have difficulty dividing attention between different spatial locations (e.g., Maylor & Lavie, 1998; Plude & Doussard-Roosevelt, 1989; Plude & Hoyer, 1986). This age difference may, in addition, reflect an age-related reduction in the perceptual window (i.e., useful field of view) that limits the amount of display information available for processing (Schneider & Pichora-Fuller, 2000; Scialfa, 2002).

The third main finding of Experiment 2 is the absence of age-related decline in coactivation. This result is consistent with previous research on bimodal (visual–auditory) redundancy (Bucur et al., 2005) as well as with the visual redundancy investigated in Experiment 1. In fact, when the redundant dimensions in Experiment 2 were present in the same location, the evidence for coactivation was much stronger for older adults than for younger adults. When the redundant dimensions were separated spatially, neither age group exhibited coactivation. Thus, our prediction regarding age-related decline in coactivation, as a function of spatial separation, was not supported.

General Discussion

In these two experiments we investigated age-related differences in the RSE using two separate visual dimensions (color and letter). We were especially interested in whether the larger RSE usually exhibited by older adults could be interpreted independent of a proportional age-related slowing. Previous research (e.g., Allen et al., 1992) suggests that under difficult task conditions (i.e., searching for targets among distractors), older adults do exhibit a disproportional increase in the size of the RSE, whereas less demanding conditions yield age-related differences in the RSE that are consistent with generalized slowing (Allen et al., 1992, target-only condition; Bucur et al., 2005). We therefore tested participants using a complex task that required either the conjoining of target features (Experiment 1) or the division of attention between spatial locations (Experiment 2).

Consistent with our predictions and prior literature (e.g., Allen et al., 1992, 1993, 1994; Bucur et al., 2005), the absolute magnitude of the RSE was significantly larger for the older adults than for the younger adults in both of the present experiments. In Experiment 1, this difference did not remain significant after we used a proportional measure to control for the overall slower responses of the older adults. In Experiment 2, however, analyses conducted on the percentage improvement in RT associated with redundancy indicated a significantly larger effect of redundancy for older adults. Although the age-related differences were relatively modest (10% vs. 8%) this does suggest that, above some critical level of task complexity, the presence of redundant target information is differentially beneficial to older adults. Thus, redundant target information may help older adults overcome deficits in perceptual processing by increasing the amount of target activation.

The second purpose of these experiments was to investigate whether age-related differences occurred in the coactivation of redundant visual information. Although Bucur et al. (2005) found evidence that older adults use coactivation in a bimodal (visual–auditory) detection task, it was not clear whether this finding would generalize to a task using redundant dimensions within the visual modality. Both of the present experiments demonstrated that the coactivation of information (dimensions of color and letter) within the visual modality is at least as strong for older adults as for younger adults. In fact, evidence for coactivation, in terms of the size of the area between the two CDFs, was greater for older adults than for younger adults in both experiments (see Figure 3). Although we expected that older adults might show decreased evidence, or no evidence, for coactivation due to age-related deficits in divided attention, this obviously was not the case. It appears that the degree to which target identification involves the coactivation of different stimulus dimensions is at least as great for older adults as for younger adults. Thus, similar to other aspects of attentional processing, such as the use of top-down or conceptual knowledge to guide visual search (e.g., Madden et al., 2005) coactive processing is spared with increased age. As reflected in the age-related increase in coactivation observed in both of these experiments, it is possible that older adults rely more heavily on preserved aspects of attentional functioning to compensate for declines in earlier, more bottom-up stages of processing.

The final goal was to investigate the role of spatial separation in the RSE and coactivation. On the basis of previous research (e.g., Feintuch & Cohen, 2002), we predicted a decrease in the size of the RSE along with less evidence for coactivation when the redundant dimensions were separated spatially. We also predicted spatial separation to interact with age due to age-related deficits in divided attention. In Experiment 2, as was the case for other researchers (e.g., Feintuch & Cohen, 2002), coactivation varied with spatial location for younger and older adults with significant violations occurring only in the same-location condition. Mordkoff and Yantis (1993), in contrast, were able to find evidence for coactivation using a condition similar to our different-location condition. Although the task that we used is similar to that of Mordkoff and Yantis (1993), it is possible that our modifications were sufficient to produce these diverging results. As mentioned in the introduction, these changes involved using a within-subjects design, using a display size of two in each condition, and counterbalancing the location of the dimensions between the upper and lower display positions. In contrast to this, Mordkoff and Yantis (1993) used a between-subjects design and presented the stimuli in fixed locations. In the Mordkoff and Yantis (1993) study, top-down knowledge in the form of consistent stimulus arrangements, along with a between-subjects design, may have facilitated coactivation for different-location stimuli. Inconsistent with our predictions and other studies (e.g., Krummenacher et al., 2002), we did not find a relationship between spatial separation and the size of the RSE. Although we do not have an explanation for this, it is clear that further research is needed to investigate the relationship between the RSE and coactivation.

We believe that the Feintuch and Cohen (2002) dimension-action account provides the best explanation for our results as well as those of Mordkoff and Yantis (1993). As mentioned previously, the specific task characteristics used by Mordkoff and Yantis (1993), unlike the present Experiment 2, may have allowed participants to focus attention on both dimensions simultaneously. Although Krummenacher et al. (2002, Experiment 3) did not find evidence for the influences of attention on coactivation in a feature search task, performance in this type of task is highly efficient and involves minimal demands on attention. It is possible that perceptually based (i.e., dimension-weighting) accounts of coactivation provide a good explanation of performance in visual search tasks in which target features tend to pop out from among distractors, whereas dimension-action accounts explain performance in tasks in which the specific identity of the target has to be determined. With regard to aging, it appears that older adults do not exhibit age-related declines in processing redundant dimensions in separate locations as we had predicted. Indeed, neither age group showed evidence for coactivation with spatial separation. Thus, the dimension-action model provides an explanation for the older adults' as well as the younger adults' data.

Taken together, these results show that when the task involves the division of attention between spatial locations (Experiment 2), older adults benefit from the presentation of redundant visual dimensions and that this benefit is not due entirely to a proportional age-related slowing. Further, although older adults responded more slowly in both experiments, as indicated by the significant main effect of age, this slowing was not sufficient to prevent the coactivation of redundant dimensions. It appears that coactivation is a form of attention that remains preserved with increased age and possibly acts as a compensatory mechanism for a decline in earlier stages of perceptual processing. Evidence for coactivation, however, varied under conditions (e.g., spatial separation) that did not affect the overall improvement in RT associated with redundancy, and additional research is required to determine the role of processing components other than coactivation in the identification of redundant visual dimensions.

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