Running head: AGING AND IRRELEVANT INFORMATION

Aging and the Ability to Ignore Irrelevant Information in Visual Search and Enumeration Tasks

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Abstract

A classic study by Rabbitt (1965) demonstrated that older adults are particularly impaired by irrelevant distractors in a visual categorisation task, a finding that has inspired many subsequent studies and theories of cognitive aging. In this chapter, we present some of our own recent experiments exploring age-related differences in the effects of irrelevant distractors in visual search and enumeration tasks. The first study shows that age differences in the effects of irrelevant distractors can vary depending on the perceptual load of relevant processing. The second study examines the ability to selectively facilitate the processing of new visual information by ignoring old irrelevant stimuli already present in the field (*visual marking*) and demonstrates age preservation for stationary stimuli but marked age decrements for moving stimuli. Finally, enumeration tasks again show that older adults' overall responses are disproportionately slowed by the presence of irrelevant distractors. Moreover, distractors have unexpected effects on age differences in enumeration rates that, together with investigations of eye movements, shed light on the specific task requirements of searching for versus enumerating visual stimuli.

The aim of this chapter is to illustrate Patrick Rabbitt's influence on the field of cognitive aging over the past 40 years, and on some of our own recent work, by a case study of one contribution in particular. The article we have chosen appeared in the Journal of Gerontology in 1965 and it showed an age decrement in a fundamental aspect of behaviour, namely, the ability to ignore irrelevant information. We discuss how this result has been interpreted and note its impact on subsequent theories of cognitive aging. We then present some of our own experiments exploring characteristics and boundary conditions of this age decrement. These include: (1) an investigation of the influence of perceptual load (Maylor & Lavie, 1998), (2) experiments exploring older adults' ability to ignore irrelevant information that appears prior to relevant information – an ability known as visual marking (Watson & Maylor, 2002), and (3) experiments in which the task is to enumerate multiple targets while ignoring irrelevant information (e.g., Watson, Maylor, & Manson, 2002). Finally, we return to Rabbitt (1965) to note some interesting parallels between our current explanations and Rabbitt's conclusions 40 years ago.

Ignoring Irrelevant Information (Rabbitt, 1965)

As noted by Scialfa and Joffe (1997), 1965 was "a watershed year for experimental gerontology" as it saw the publication of both "Rabbitt's seminal work in visual search and Brinley's generalized slowing analysis" (p. 227). These two articles have been cited almost identical numbers of times since 1981, and both were based on doctoral research (or shortly thereafter). However, as we shall see, their conclusions were rather different.

Rabbitt (1965) was one of the first studies of age differences in selective attention, that is, the ability to find information relevant to the current goal and to filter out all irrelevant information. A simple card-sorting task was employed in which participants were given packs of 48 visiting cards (similar in size to current credit cards) and were asked to sort them as quickly as possible into two piles according to whether there was a letter A (stencilled in india ink) on the card or a letter B. This target letter (A/B) appeared equally often in each of nine (3 x 3) possible locations on the card. There were four different packs of cards and these varied in terms of the number of irrelevant letters (chosen from the remaining letters of the alphabet) printed on each card (0, 1, 4, or 8 distractors).

The mean times to sort the 48 cards for 11 young and 11 old people (mean ages of 19 and 67 years, respectively) are shown in Figure 1. The old adults were slower than the young adults and both age groups took progressively longer as the number of irrelevant items on the cards increased. Crucially, there was also an interaction such that this increase was steeper for the old adults, a result that was taken to indicate “an age-decrement in the ability to ignore irrelevant information” (p. 233, Rabbitt, 1965).

Rabbitt’s (1965) interpretation was based on the localization approach to aging (see Salthouse, 1991, for discussion), which uses interactions between age and the treatment of interest to identify particular processes, or processing components, that are age sensitive – in this case, the ability to ignore irrelevant information. However, at least one problem with the localization approach has been that Age x Treatment interactions are so frequently observed across a wide range of cognitive tasks that, as Salthouse (1996a) noted, “either a large number of specific factors or a small number of general factors must be contributing to the age-related differences” (p. 287).

This suggests an alternative interpretation for the data in Figure 1. If they are considered in terms of the proportional increase in sorting times for old relative to young adults, this proportional increase was 1.7 for 0 irrelevant items and 1.8 for 8 irrelevant items. Thus, instead of a specific or localized age deficit in ignoring irrelevant information, this may be an example of generalized slowing (e.g., Birren, 1965; Cerella, 1985, 1990; Cerella & Hale, 1994; Salthouse, 1985). In other words, regardless of the actual cognitive processes required by the task, older people may simply be slower than young people by a constant proportion.

Brinley (1965) recognised this possibility in his comparison of young and old adults (mean ages of 24 and 71 years, respectively) across 21 tasks, some of which required the same operation to be carried out on successive trials (nonshift tasks) whereas others required a different operation (shift tasks). Brinley then plotted the mean response times for the young adults on the x-axis and the mean response times for the old adults on the y-axis for each of the 21 tasks (see Figure 2). This first *Brinley plot* revealed that the “time of response in the old is simply and accurately described as a linear function of performance time in the young group. … Consequently response times for both groups and for each type of task variation may be conceived as varying along a single dimension which might be termed ‘task difficulty’” (p. 131). In other words, the data suggest that the critical determinant of age differences in performance is how much processing is required rather than which processing components.

Thus cognitive aging research over the last 20-30 years has seen a shift from local explanations (as illustrated in Figure 3a where age affects performance across different tasks through deficits in particular components of information processing) to global explanations (see Figure 3b where the effects of aging are attributable to a single common factor). Various candidates have been proposed as the single common factor (see Park, 2000; Salthouse, 2000, for discussion). One is reduced processing speed, or generalized slowing, as advocated most strongly by Salthouse (e.g., Salthouse, 1985, 1996b). Another that has been the subject of much recent research is reduced inhibition as proposed by Hasher and Zacks (1988; see also Hasher, Zacks, & May, 1999). According to the inhibition deficit hypothesis of aging, age-related decline in cognition occurs largely as a result of age-related decline in the efficiency of inhibitory mechanisms (see Maylor, Schlaghecken, & Watson, in press, for a summary), and these would include the ability to ignore irrelevant information. Rabbitt's (1965) study has therefore been an important influence on current theories of cognitive aging and also the subject of much debate concerning how to interpret cognitive aging data. In the sections that follow, we summarise some of our own studies investigating the ability to ignore irrelevant information in young and old adults in the context of some recent models of selective attention. In doing so, we are mindful of Plude, Enns and Brodeur's (1994) conclusion that "Rabbitt's (1965) classic demonstration of an age decrement in visual search set the standard against which other visual search studies can be compared" (p. 247).

Perceptual Load Theory

The perceptual load theory of selective attention was first proposed in the mid-90s by Nilli Lavie (Lavie, 1995; Lavie & Tsal, 1994). In her model, perceptual processing is viewed as a limited resource. Perceptual processing proceeds automatically from relevant to irrelevant items until it runs out of capacity. (Perception here includes all processes that lead to stimulus identification.) If perceptual load is high (i.e., relevant processing is relatively demanding), this should consume full capacity. The result is that irrelevant information is successfully ignored simply because it is not actually perceived. On the other hand, if the perceptual load involved in processing relevant items is low, this should leave spare capacity to spill over and allow perception of irrelevant information.

Perceptual load theory has successfully resolved the early vs. late selection debate in the attention literature (Lavie & Tsal, 1994). Thus, evidence for early selection comes from studies in which perceptual load is high, whereas evidence for late selection comes from studies in which perceptual load is low. In addition, direct empirical support for the theory comes from studies in which perceptual load was experimentally manipulated (Lavie, 1995; Lavie & Cox, 1997; Lavie, Hirst, de Fockert, & Viding, 2004). Low perceptual load conditions resulted in interference from an irrelevant distractor whereas high perceptual load eliminated such interference.

Maylor and Lavie (1998) reasoned that perceptual load might also be an important factor in determining age differences in selective attention on the basis that perceptual capacity would be reduced in older adults. They therefore conducted a study in which perceptual load was manipulated as shown in Figure 4. In fact, a major component of the task was essentially a computerised version of Rabbitt (1965). Participants were instructed to press one of two keys as quickly as possible according to whether there was a letter X or a letter N present among the central items in the display, that is, those that appeared in an imaginary circle around the fixation point. The number of nontarget letters in the circle varied between trials from 0 to 5 letters (i.e., low to high perceptual load).

In addition to these central items, there was also a larger distractor letter that appeared either to the left or to the right of the main display. These critical distractors were either incompatible with the target letter (i.e., associated with the other response) or they were neutral (i.e., the letters T and L). Participants were strongly encouraged to ignore this distractor letter because it would not help their performance if they attended to it.

Maylor and Lavie (1998) made the following predictions: (1) The neutral distractor condition was expected to replicate the results of Rabbitt (1965). (2) Response times (RTs) were expected to be slower when the single irrelevant distractor was incompatible rather than neutral with respect to the target. In other words, there should be a response compatibility effect (cf. Eriksen & Eriksen, 1974), at least when perceptual load was low. (3) In contrast, when perceptual load was high (i.e., a large number of nontarget letters accompanying the target), there should be no response compatibility effect (replicating Lavie, 1995). (4) Finally, the decrease in the response compatibility effect should occur at a lower perceptual load for the old than for the young because the processing of both relevant and irrelevant information was more likely to exceed the total available capacity of old adults than of young adults.

Figure 5 displays the results for the neutral distractor condition for 15 young and 15 old adults (mean ages of 23 and 73 years, respectively). The old adults were slower than the young adults, RTs increased with the number of nontargets in the search set, and there was a significant interaction between age group and set size. Also, the proportional increase in RTs for old relative to young adults was identical for 0 and 5 nontargets at 1.4, in accordance with generalized slowing. Thus Maylor and Lavie (1998) successfully replicated Rabbitt (1965) in finding age deficits in visual search that were consistent with generalized slowing such that old adults were proportionally slower than young adults in identifying a target surrounded by nontargets.

Differences between RTs in the incompatible and neutral distractor conditions are shown in Figure 6a. As expected, participants were slower when the distractor was incompatible with the target at the three lowest levels of perceptual load but not at the highest level of perceptual load, thereby replicating Lavie (1995). Comparing the data for young and old adults, there are two findings to note. First, at the two lowest levels of perceptual load, there were larger distractor effects for the old than for the young. Second, for the young, the distractor effect did not decrease until there were 5 nontarget items, whereas it decreased significantly by 3 nontargets for the old (see Huang-Pollock, Carr, & Nigg, 2002, for a similar pattern of results in a study comparing young adults with children).

Why was the distractor effect larger for the old than for the young at low perceptual load? Obviously, one possibility is that because the old were slower overall than the young, then the RT differences would be correspondingly larger because of generalized slowing. This was tested by examining proportional rather than absolute RT differences, that is, (Incompatible RT – Neutral RT)/Neutral RT. As can be seen in Figure 6b, the data were very similar. Thus at low levels of perceptual load, the old were less able to ignore the irrelevant distractor than the young and this could not be explained by generalized slowing. Interestingly, this finding may relate to Lavie et al.'s (2004) second mechanism of selective attention. In contrast to the passive effects of perceptual load, this is an active control mechanism that reduces interference from distractors when they are perceived (i.e., at low perceptual load) and which depends on higher cognitive functions, such as working memory, to maintain current processing priorities. The data in Figure 6 are at least consistent with the possibility of an age-related impairment in this active inhibitory control mechanism such that when distractors *are* processed, they have a greater detrimental effect on the efficiency of selective attention in old than in young adults.

With increasing perceptual load, the distractor effect decreased earlier for the old than for the young, which is also contrary to generalized slowing. However, this is exactly what was predicted on the assumption of an age reduction in perceptual capacity. It can be concluded that older adults are not always less able to “ignore” irrelevant information – at least one factor that should be considered is perceptual load. Thus, when relevant processing is demanding, irrelevant information may not even be perceived by older people.

Finally, we should mention a recent study by Madden and Langley (2003) that successfully replicated the main findings of both Rabbitt (1965)[2] and Lavie (1995) but had mixed success in attempting to replicate Maylor and Lavie (1998). In their first two experiments, they made several methodological changes including the presentation of two rather than one irrelevant distractors always to the left and right of fixation and these were placed within the circle of items containing the target. In contrast to Maylor and Lavie, perceptual load effects were found to be similar for young and old adults. This could be regarded as consistent with evidence that age deficits can be minimised when the locations of irrelevant distractors are known in advance as in focused attention situations (for summaries, see Madden & Plude, 1993; Rogers, 2000).

Madden and Langley’s (2003) third experiment used identical methodology to Maylor and Lavie (1998) and showed some similarities (e.g., distractor effects were significantly larger for the old than for the young at low levels of perceptual load) but also some differences (e.g., the compatibility effect did not decrease for either age group prior to the highest level of perceptual load). In fact, there is a suggestion in their data that the young showed a compatibility effect at all levels of perceptual load (i.e., 0, 1, 3 and 5 nontargets), whereas the compatibility effect for the old decreased from 3 to 5 nontargets. Thus the results of the equivalent experiments across the two studies are at least qualitatively similar and any discrepancies may be due to some general differences in visual stimuli leading to greater distractor effects or to Madden and Langley's use of more able participants (e.g., their old adults were seven years younger on average and their young adults were Duke University students). Clearly, additional work with this paradigm is required (see Madden & Whiting, 2004, for further discussion).

Visual Marking

In many situations, a person is waiting for a target to appear such as looking out for a friend to arrive at an airport terminal. According to Watson and Humphreys (1997), visual search can be facilitated in this type of situation by actively ignoring unwanted or irrelevant information that is already present in the field via a process they termed visual marking. Thus visual marking is a mechanism for prioritising and controlling the selection of visual information over time. It operates by actively inhibiting old unwanted (previewed) information, which allows a selection advantage for new objects when they appear (termed the preview benefit). Visual marking is a top-down process that requires limited attentional resources. Because of these and other features of visual marking (see Watson, Humphreys, & Olivers, 2003, for a summary), we expected to find age-related deficits.

Visual marking can be demonstrated using a modified conjunction search (Treisman & Gelade, 1980) task in which one set of distractors (green Hs) is presented for some time (typically 1000 ms) before a second set (red As and a red H target when present) is added (see right panel of Figure 7). Participants are required to indicate the presence or absence of the target among a varying number of distractors and are told that if the target is present, it will be in the second display.

In order to assess whether observers are able to ignore the old previewed distractors, search in the preview condition is compared with two baseline conditions (see middle and left panels of Figure 7). In the conjunction (or full element) baseline, all the search elements are presented simultaneously. This condition therefore provides a measure of search performance if all the items have to be searched in the preview condition. Displays in the single feature (or half element) baseline are composed of the same number and type of stimuli presented in the second set of items from the preview condition, thus providing a measure of search performance expected if observers can restrict their search to the new (second set) items only. Accordingly, Watson and Humphreys (1997) argued that if the old unwanted information can be successfully ignored, search in the preview condition should be as efficient as that in the single feature condition. However, if the old unwanted items cannot be ignored, search in the preview condition should be equivalent to that in the conjunction condition.

Watson and Maylor (2002, Experiment 1) tested 12 young and 18 old adults (mean ages of 20 and 72 years, respectively) in these three conditions. The RT data for target present trials[3] are shown in Figure 8.[4] First, as expected from the results of Rabbitt (1965), the old adults were slower overall than the young adults and their search slopes were approximately twice as steep. Second, for both young and old, the slope for the preview condition was not significantly steeper than that of the single feature condition but was significantly flatter than that of the conjunction condition (see Figure 8 caption for search rates). That is, both age groups could successfully exclude the first set of items from further search, thus demonstrating age-related sparing of visual marking. Similar results were observed in an earlier study by Kramer and Atchley (2000) who used different stimuli and much larger display sizes to show that both young and old adults can ignore at least 15 irrelevant (previewed) items.

However, objects in the world are not always static – people in the airport terminal are usually moving – and so in two further experiments, Watson and Maylor

(2002) compared visual marking in young and old adults with moving stimuli. The procedure for one of these (Experiment 3) is illustrated in Figure 9. All the stimuli rotated smoothly and continuously clockwise around the fixation point. In this case, the target was the letter T and the distractors were letter Ls. The single feature and conjunction conditions therefore differed only in terms of the numbers of stimuli (2, 4 and 8 vs. 4, 8 and 16) but we have retained the descriptions for comparability with the previous experiment. In the preview condition, the Ls appeared for 1000 ms and rotated clockwise before the remaining stimuli (including a T if present), also rotating, were added.

The data for 18 young and 18 old adults (mean ages of 20 and 73 years, respectively) are shown in Figure 10. For the young adults, the preview search slope matched that of the single feature baseline but was significantly flatter than that of the conjunction baseline, thereby displaying a full preview benefit (see also Watson, 2001). In contrast, there was no evidence of visual marking for the old adults for whom the preview search slope matched that of the conjunction baseline and was significantly steeper than that of the single feature baseline.[5]

In summary, new items can be prioritised for selection by visual marking, that is, the top-down attentional inhibition of old items already in the field (see Watson & Humphreys, 1997). At least for the conditions explored by Kramer and Atchley (2000) and by Watson and Maylor (2002, Experiment 1), there appears to be no age-related impairment in visual marking for static stimuli. This therefore provides a further qualification to Rabbitt’s (1965) proposal of an age decrement in the ability to ignore irrelevant information. However, it is consistent with the relative sparing in old age of some other location-based inhibitory functions such as the passive inhibition of items that have already been processed (i.e., inhibition-of-return, IOR; see Faust &

Balota, 1997; Hartley & Kieley, 1995; Langley, Fuentes, Hochhalter, Brandt, & Overmier, 2001).

Visual marking of moving stimuli, in contrast, can be either feature-based (Watson & Humphreys, 1998) or object-based (Watson, 2001), and here there is a clear age-related decrement (Watson & Maylor, 2002, Experiments 2 and 3). Moreover, it cannot be explained by any simple account of generalized slowing because there is no linear transformation that can change the preview condition slope so that it matches the single feature condition in the young but the conjunction condition in the old (see Figure 10). However, there is another possibility. Generalized slowing could still account for the data if there is age-related slowing in the time course of visual marking. Thus, for static stimuli, 1000 ms between the previewed and new items may be sufficient for visual marking to be fully applied by both young and old adults even if it takes the latter twice as long (say 800 ms rather than 400). It is conceivable that visual marking of moving stimuli may take longer so that 1000 ms is still sufficient for young adults but not for old adults. To check this possibility, Watson and Maylor (2002) tested additional participants in their third experiment (see Figure 9) but with a preview duration of 2000 ms rather than 1000 ms. The old adults' data were exactly as before with mean search slopes of 30, 65 and 56 ms/item for the single feature, preview and conjunction conditions, respectively (cf. Figure 10), thereby discounting a slower time course of visual marking as an explanation for the age deficit with moving stimuli.

This apparent age-related reduction in the ability to ignore irrelevant moving objects is perhaps of some general concern. As noted earlier, objects in the real world are rarely stationary for long and it is perhaps in such complex scenes that successful time-based selection may provide the greatest utility. However, the practical impact of this particular form of inhibitory deficit on real world performance of course awaits future research.

Visual Search vs. Enumeration

The final set of studies compares age decrements in the ability to ignore irrelevant information in visual search tasks (cf. Rabbitt, 1965) and in enumeration tasks, which require the processing and keeping track of multiple targets in a display in order to determine as quickly as possible how many targets are present. Typically, RTs to enumerate items in the absence of distractors do not increase linearly as the number of items increase. Instead, RTs remain relatively flat (<100 ms/item) up to about 3-4 items after which they increase linearly with each additional item (>300 ms/item). This results in a bilinear enumeration function with a flex point at around 3 or 4 items. The fast and accurate enumeration for small numbers of items has been termed subitization and the slower and less accurate enumeration of larger numbers has been termed counting (e.g., Kaufman, Lord, Reese, & Volkman, 1949; Mandler & Shebo, 1982; Sagi & Julesz, 1984; Trick & Pylyshyn, 1993, 1994b). A number of mechanisms have been proposed to account for subitization. These range from the involvement of a pre-verbal counting system that is accurate and reliable only for small numbers of items (Gallistel & Gelman, 1992), to the use of pattern information as a cue to numerosity (Mandler & Shebo, 1982).

A relatively recent model (Trick & Pylyshyn, 1993, 1994a, 1994b) proposed that subitization occurs as a result of the visual system being able to simultaneously tag up to about 4 items that are individuated at a preattentive level of processing (Pylyshyn, 1989). These tags are called FINSTs (from FINgers of INSTantiation) and, according to FINST theory, subitization arises because small numbers of items can be enumerated by assigning FINSTs to them in parallel and then associating the number of bound FINSTs directly with number names. When the number of objects exceeds the number of FINSTs (about 4), enumeration has to proceed via a serial process of disengaging and reassigning FINSTs (and/or a single focus of attention) to the remaining items. This set of additional relatively complex operations results in a substantial and linear increase in RT as numerosity increases. In addition to accounting for subitization (and other findings), there are several reasons why an efficient visual system requires the ability to tag multiple items simultaneously. Some examples include the efficient relocation of attention around multiple relevant stimuli, the computation of spatial relationships and the integration of information across saccades (e.g., see Pylyshyn, 1989; for recent summaries see Pylyshyn, 1998, 2001). Therefore, if aging reduced the number of FINSTs or impaired the ability to assign or use FINSTs efficiently, this would have an impact on the efficiency of visual functioning in everyday tasks over and above those related to enumeration.

Trick and Pylyshyn (1993) examined enumeration of easy- and difficult-to-find targets (single-feature and conjunction defined, respectively) and found that subitization occurred only with easy-to-find targets. When target items required focussed attention for their detection, subitization did not occur and enumeration slopes were substantial and linear even for small numbers of items. This is consistent with the proposal that the FINST mechanism is located between a preattentive and serial attentive level of processing (Pylyshyn, 1989). Thus FINSTs can only be assigned in parallel to items that are represented and individuated preattentively.

Since Rabbitt (1965), a number of studies have examined aging and visual search for a single target (e.g., Foster, Behrmann, & Stuss, 1995; Gilmore, Tobias, & Royer, 1985; Hommel, Li, & Li, 2004; Humphrey & Kramer, 1997; Kramer, Martin-Emerson, Larish, & Andersen, 1996; Plude & Doussard-Roosevelt, 1989; Scialfa &

Joffe, 1997; see Kline & Scialfa, 1996, for a summary) and have shown that easy search is relatively unaffected by old age but difficult search is less efficient. In contrast, relatively few studies have assessed the effects of old age on enumeration and these have produced inconsistent results, possibly because (among other differences) some have included distractors (Kotary & Hoyer, 1995; Sliwinski, 1997) whereas others have not (Basak & Verhaeghen, 2003; Geary & Lin, 1998; Nebes, Brady, & Reynolds, 1992; Trick, Enns, & Brodeur, 1996).

Therefore, in our first study (Watson, Maylor, & Manson, 2002) we assessed the effects of age on the enumeration of 1-9 targets both with and without the presence of distractors. In the former case, there were 19-11 distractors accompanying the 1-9 targets, respectively, so that the total number of stimuli was always 20. In addition, there was a standard visual search task using the same target and distractors. Figure 11 includes illustrations of the three conditions. Participants enumerated Os (top panel), enumerated Os while ignoring Xs (middle left), and searched for the presence of a single O among variable numbers of X distractors (bottom left).[6] The third condition was included to check that there was no age deficit in single feature search. Indeed, for the 30 young and 35 old participants (mean ages of 21 and 72, respectively), RTs plotted against display size revealed search functions that were virtually flat in both age groups, indicating parallel detection of the single feature target across the visual field, as expected (e.g., see Plude & Doussard-Roosevelt, 1989).

Enumeration RTs are shown in Figure 12. Without distractors, the old were slower overall than the young but both age groups showed the classic bilinear pattern of faster subitizing (small numerosities) than counting (large numerosities). Moreover, the subitizing and counting rates were equivalent for young and old. When distractors were added, the old were slowed considerably more by their presence overall than were the young, showing again a marked deficit in their ability to ignore irrelevant information. In addition, whereas young adults continued to show evidence of subitization, old adults were unable to subitize in the presence of distractors despite evidence of parallel search for a single target among distractors. Finally, enumeration rates for large numbers of targets remained similar in young and old.

These are surprising results for at least two reasons. First, they are contrary to generalized slowing, which predicts that relatively fast and efficient processes (subitization) should be less affected by aging than slower more serial processes (counting beyond 4 items) – cf. single feature vs. conjunction search. This was not the case and (without distractors) enumeration was age equivalent across the whole range of numerosities. Second, when distractors were present, old adults were unable to subitize targets that they were nevertheless able to detect efficiently.

Watson, Maylor and Manson (2002) argued that the age selective deficit for subitization is, however, consistent with a modified FINST account in which they proposed that the assignment of a FINST results in a general reduction in the salience of other items in the field. When there are no distractors present, both young and old adults can assign remaining FINSTs efficiently, resulting in age equivalent subitization. In contrast, when distractors are present, assigning additional FINSTs onto targets is more difficult because of (a) the reduction in salience of the remaining items as a result of earlier FINST assignment, and (b) attentional competition from distractors. For young adults, the saliency of the targets remains sufficiently high to allow efficient FINST assignment even when distractors are present. However, for old adults, an age-related reduction in attentional resources, coupled with the reduced salience of the stimuli and competition from distractors, is sufficient to prevent the efficient assignment of multiple FINSTs; enumeration therefore proceeds serially at small numerosities (see Watson & Humphreys, 1999, for related arguments).

In a subsequent study, Watson, Maylor and Bruce (in press, Experiment 1) examined enumeration of Os without distractors (Figure 11, top panel), enumeration of Os while ignoring Qs (i.e., difficult-to-find targets; middle right of Figure 11), and visual search for the presence of a single O among variable numbers of Q distractors (bottom right of Figure 11). Note that search for targets defined by the absence of a feature relative to the distractors is known to produce relatively inefficient search (Treisman & Souther, 1985). The results from 34 young and 34 old adults (mean ages of 19 and 69 years, respectively) for the visual search task are shown in Figure 13 where it can be seen that, as expected, search slopes were no longer either flat or age invariant. Old adults' search rates were approximately twice as slow as those of young adults. Note also that slopes for target absent trials were approximately twice those of target present trials, consistent with a serial and self-terminating search (Treisman & Gelade, 1980; but see Humphreys & Müller, 1993; Townsend, 1972, for alternative limited capacity parallel accounts).

Figure 14 shows the enumeration data. In the absence of distractors, we replicated our previous finding of age-equivalent subitizing and counting and, further, showed formally that the span of subitization (i.e., the flex point of the bilinear function) was also age equivalent at 3.3 items for both groups. With distractors present, neither age group was able to subitize, consistent with the results of Trick and Pylyshyn (1993) with difficult-to-find targets. Importantly, because the old adults were less efficient at detecting a difficult-to-find target (Figure 13), we expected that their enumeration of such targets would be particularly inefficient. However, although the old adults' RTs were again much slower overall with distractors present, their enumeration rates were age equivalent.

One reason why counting beyond 4 items might be spared in old age is because it may require the involvement of a relatively slow but age equivalent process that is not needed either in difficult search or in subitizing single feature targets (which both show age deficits). If this process is sufficiently slow and age equivalent, it may become the rate-limiting process on performance, resulting in the same counting rates for young and old adults. Watson, Maylor and Bruce (in press, Experiment 2) tested whether numerical subvocalization (most likely necessary beyond 4 items) could be this rate-limiting process. Participants were presented with a digit from 1-9 and were asked to count subvocally from 1 up to the value of the presented digit and then press the space bar. Subvocalizing rates were found to be equivalent in young and old adults but at around 170 ms/number they were much too fast to be the slowest rate-limiting factor in enumeration beyond the subitizing range.

Eye Movements

An alternative rate-limiting process to numerical subvocalization is that enumerating beyond 4 items may require eye movements whereas subitization or visual search may not. In support of this, preventing saccades can make difficult search more efficient (Klein & Farell, 1989; Zelinsky & Sheinberg, 1997) whereas enumeration beyond 4 items can become less accurate (Atkinson, Campbell, & Francis, 1976; Simon & Vaishnavi, 1996). Methodological issues with the original work on eye movements in enumeration led us to re-examine the role of eye movements in enumeration (Watson, Maylor, & Bruce, 2004b). We measured enumeration rates (young adults only) when saccades were or were not allowed and found that preventing eye movements had no effect on subitization rates but counting rates were slowed. We also found that fixation durations were longer before saccades to previously examined locations, which demonstrates for the first time that IOR is involved in visual enumeration. Thus, preventing eye movements does not reduce the accuracy of enumeration but does make it less efficient, which is the opposite of what happens in visual search.

Why should saccades be particularly important in enumeration but not in visual search tasks? For accurate enumeration, it is crucial that each item is processed only once. One way in which old items could be prevented from being reprocessed is via IOR in which attention and eye movements are biased against returning to previously examined locations (Hooge & Frens, 2000; Klein, 2000; Klein & MacInnes, 1999). IOR may thus play a role in ensuring that items are enumerated only once (Simon & Vaishnavi, 1996) and as saccade generated IOR appears to be stronger than IOR generated from covert shifts of attention (Hooge & Frens, 2000) we would expect overt shifts to be more frequent in tasks in which it is particularly important to exclude previously examined items (e.g., enumeration). In contrast, visual search accuracy does not require that items are only processed once, and indeed there may be little memory for what has already been searched (e.g., Horowitz & Wolfe, 1998; but see also Peterson, Kramer, Wang, Irwin, & McCarley, 2001). This might be because visual search is more efficient overall if the cost involved in ensuring that old items are not reprocessed is removed.

If the above account is correct, we would expect the following: (i) subitization should produce relatively few eye movements per item, (ii) enumerating beyond 4 items should produce more fixations per item than difficult visual search, and (iii) fixation frequency should be age equivalent for enumeration beyond 4 items. We confirmed these predictions in an experiment that monitored eye movements in easy and difficult visual search and enumeration without distractors in young and old adults (Watson, Maylor, & Bruce, 2004a, Experiment 1). Both easy search and subitization resulted in low rates of eye movements that were equivalent for young and old. Old adults made twice as many fixations per item in difficult search than did young adults (see Table 1a). This is consistent with an age-related reduction in visual or attentional capacity (e.g., reduced useful-field-of-view; Ball, Beard, Roenker, Miller, & Griggs, 1988; Scialfa, Kline, & Lyman, 1987; Sekuler, Bennett, & Mamelak, 2000), which is compensated for by an increase in fixation frequency (rather than duration). In contrast, counting produced much slower and age equivalent fixation rates (Table 1a). Thus the experiment provides direct evidence that the counterintuitive age equivalence in counting rate beyond 4 items arises because of the need for both young and old adults to make eye movements. Because the process of programming and executing saccades is relatively slow and can be age invariant (Abrams, Pratt, & Chasteen, 1998), this then becomes the rate-limiting factor on enumeration.

Watson, Maylor and Bruce (2004a, Experiment 2) also examined fixation frequency for enumeration of difficult-to-find targets (cf. Figure 14). This revealed that the overall RT difference was associated with many more fixations by the old than the young. In addition, their fixation enumeration slopes were slightly shallower. This shows that under conditions of high attentional competition, the old were processing the displays less efficiently (more exhaustively) than were the young adults. In addition to fixation frequency, we also examined how often locations were refixated. This indicates the extent to which observers needed to recheck locations or restart their enumeration of a display as a result of a failure to keep track of what had already been enumerated. When distractors were absent, refixations increased as a function of numerosity only beyond 4 items and there were no age differences. This finding is consistent with the memory for what has been processed being based on IOR which has been shown to be unaffected by old age (see earlier). However, the addition of distractors did cause an increase both in fixation and refixation frequency and the increase in both was greater for the old adults. This is consistent with our account as IOR has been shown to be limited to about 5 or 6 locations (Danziger, Kingstone, & Snyder, 1998; Snyder & Kingstone, 2000) and so we would expect IOR-based memory failures to increase as a function of the total fixation frequency.

In summary, the main findings from this series of experiments were that: (i) eye movements are particularly important in enumeration but not in search tasks, (ii) eye movement-based IOR is the likely basis by which old items are prevented from being enumerated more than once, (iii) the reliance of enumeration on eye movements is the reason for the counterintuitive age equivalent enumeration performance, and (iv) age equivalent subitization only holds when distractors do not also compete for attention with the target items.

Rabbitt (1965) Revisited

Briefly returning to Rabbitt (1965), there was in fact a second condition in the experiment that has received far less attention in which participants were required to sort the packs of visiting cards into eight rather than only two piles according to which of the letters from A-H appeared among the different numbers of distractors. Sorting times were obviously longer for both young and old adults in this more difficult condition but, more importantly, there was less sign of the interaction between age and the number of irrelevant items that was found in the first condition (Figure 1). Rabbitt (1965) suggested that “when young Ss search for two relevant letters they ignore irrelevant symbols more quickly because they process them in larger groups than when they search for eight relevant letters…old Ss cannot sample letters in a display in large groups in either condition” (p. 236). This is summarized in Table 1b. Interestingly, the argument is qualitatively similar to our own in relation to the comparison between search and enumeration. That is, the slower or more difficult condition in each case forces the young to adopt the same slow strategy as the old, which of course leads in both cases to violations of generalized slowing.

In summary, our aim has been to convey something of Patrick Rabbitt’s influence by taking just one article and showing how it has influenced recent theories of cognitive aging and also inspired many subsequent studies. As Scialfa and Joffe (1997) commented, “Rabbitt’s hypotheses motivated many of the attempts to find specific age-sensitive mechanisms to explain the deficits exhibited by older adults in visual search tasks” (p. 228). Madden and Whiting (2004) even describe a recent PET study of a variant of Rabbitt (1965). In the work presented here (on perceptual load, visual marking, and the comparison between search and enumeration), there was some evidence in each case of an age decrement in the ability to ignore irrelevant information. Like the Rabbitt (1965) study, the data were only partially consistent with generalized slowing. A closer look at Rabbitt’s (1965) original conclusions reveals an interesting parallel with our current interpretation of enumeration data that suggests we should always be careful to consider the involvement of task-specific factors (such as the need to make eye movements) that may become the rate-limiting process on performance. More generally, if increasing task difficulty results in the involvement of additional processes that are both relatively slow and age equivalent, then age-related differences can disappear. Thus, predictions based on a generalized slowing account will fail whenever a task requires multiple processes and one of the processes is both rate limiting and age equivalent. Determining in which situations and tasks this issue arises will be an important goal for future research.

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Footnotes

[1] From 1984-92, I worked with Patrick Rabbitt as a postdoctoral researcher at the Age and Cognitive Performance Research Centre in Manchester. Our first project concerned the cognitive effects of alcohol and fatigue on young adults (see Maylor & Rabbitt, 1993, for a summary of some of this work). However, I was inevitably captured by Pat’s enthusiasm for another factor associated with the slowing of behaviour (i.e., old age) and have continued to work in the area of cognitive aging ever since. My work has benefited considerably from Pat’s insights and encouragement over many years and so I was delighted to be asked to contribute to this volume in his honour.

[2] Madden and Langley (2003) attributed the Rabbitt (1965) effect of age on search efficiency to “general (relatively task-independent) changes in the speed of visual information processing” (p. 65).

[3] Greater emphasis is usually placed on target-present trials than on target-absent trials because when the target is absent, people tend to rely on a number of different strategies and are often more cautious (particularly old adults) in responding absent than present (e.g., Humphreys & Müller, 1993; Plude & Doussard-Roosevelt, 1989). In fact, for both experiments reported here from Watson and Maylor (2002), it can be noted that the data patterns were qualitatively similar for target-present and target-absent trials.

[4] Following Watson and Humphreys (1997), the data for the single feature condition are plotted as if there were twice as many items in the display. Thus, if search rate in the preview condition matches that of the single feature condition, then we can conclude that the previewed items have been excluded from subsequent search.

[5] Similar results were found in Experiment 2 of Watson and Maylor (2002) in which the task was identical to Experiment 1 as illustrated in Figure 7 except that all the stimuli moved smoothly and continuously down the screen (i.e., linear rather than circular motion). As in Experiment 3 (see Figure 10), visual marking was apparent for young but not for old adults.

[6] Participants responded by pressing the space bar of the computer keyboard and then entering the response (i.e., numerosity, or target present/absent) when prompted. RT was measured from the onset of the display to the press of the space bar. See Watson, Maylor and Manson (2002) for a summary of some of the advantages of this technique over other methods.

Table 1

Summary of Conclusions From (a) Watson, Maylor and Bruce (2004a) and (b) Rabbitt (1965)

	Young	Old
(a) Fixation rate (*n*/item)		
Difficult visual search*	0.09	0.18
Enumeration (> 4 items)	~1	~1
(b) Size of search set		
Condition 1 (2 targets)	large	small
Condition 2 (8 targets)	small	small

*Target present trials

Figure Captions

Figure 1. Mean times (in seconds) to sort packs of 48 cards into two piles (A/B) as a function of number of irrelevant items for young and old adults. Data from Table 1 of Rabbitt (1965), *Journal of Gerontology, 20*, 233-238. Copyright © The Gerontological Society of America. Adapted by permission of the publisher.

Figure 2. Response times of old adults as a function of response times of young adults for nonshift and shift tasks. Reproduced from Figure 2 of Brinley's (1965) chapter in A. T. Welford and J. E. Birren (Eds.), *Behavior, aging and the nervous system*. Courtesy of Charles C Thomas Publisher, Ltd., Springfield, Illinois.

Figure 3. Illustrations of (a) local and (b) global models of aging.

Figure 4. Examples of the displays used in Experiment 1 of Maylor and Lavie (1998). The target (X or N) was accompanied by 0, 1, 3, or 5 nontarget letters in a circle around fixation. In addition, a single distractor letter (X or N on incompatible trials; T or L on neutral trials) appeared either to the left or right of the central display. From Figure 1 of Maylor and Lavie (1998), *Psychology and Aging, 13*, 563-573. Copyright © 1998 by the American Psychological Association. Adapted with permission.

Figure 5. Means of median response times (RTs) for the neutral distractor condition of Experiment 1 of Maylor and Lavie (1998) as a function of the number of nontarget items in the search set for young and old adults. Data taken from Table 1 of Maylor and Lavie (1998), *Psychology and Aging, 13,* 563-573. Copyright © 1998 by the American Psychological Association. Adapted with permission.

Figure 6. (a) Mean response time (RT) differences (with standard error bars) between the incompatible and neutral conditions of Experiment 1 of Maylor and Lavie (1998) as a function of the number of nontarget items in the search set and age group. (b) Mean response time (RT) differences between the incompatible and neutral conditions

of Experiment 1 of Maylor and Lavie (1998) divided by RT in the neutral condition (with standard error bars) as a function of the number of nontarget items in the search set and age group. Data redrawn from Figures 2 and 3 of Maylor and Lavie (1998), *Psychology and Aging, 13,* 563-573. Copyright © 1998 by the American Psychological Association. Adapted with permission.

Figure 7. Examples of single feature, conjunction and preview conditions in Watson and Maylor's (2002, Experiment 1) visual marking experiment in which participants searched for a red H among red As (single feature) or among red As and green Hs (conjunction and preview). In the preview condition, the green Hs were presented for 1000 ms before the appearance of the red As and red H (if present). [Red and green letters are shown here in black and gray, respectively. The screen background and fixation point are shown with black/white reversed.]

Figure 8. Mean correct reaction times (RTs) to determine target presence for young (solid lines) and old (dashed lines) adults from Watson and Maylor (2002, Experiment 1). See Figure 7 for summary of experimental conditions. Search rates for the single feature, preview and conjunction conditions were 12, 14 and 24 ms/item, respectively, for young adults, and 29, 35 and 46 ms/item, respectively, for old adults. For both age groups, the single feature and preview search rates did not differ but each was faster than the conjunction search rate, indicating that participants were able to ignore the previewed items while searching for the target. Data taken from Figure 1 of Watson and Maylor (2002), *Psychology and Aging, 17,* 321-339. Copyright © 2002 by the American Psychological Association. Adapted with permission.

Figure 9. Examples of single feature, conjunction and preview conditions in Experiment 3 of Watson and Maylor (2002), with stimuli rotating clockwise around virtual concentric rings at a rate of 38 degrees per second. The screen background and

stimuli are shown with black/white reversed. Participants searched for a target letter T among distractor letters L, oriented randomly at 0, 90, 180 and 270 degrees.

Figure 10. Mean correct reaction times (RTs) to determine target presence for young (solid lines) and old (dashed lines) adults from Watson and Maylor (2002, Experiment 3). Search rates for the single feature, preview and conjunction conditions were 14, 17 and 26 ms/item, respectively, for young adults, and 36, 62 and 61 ms/item, respectively, for older adults. For young adults, the single feature and preview search rates did not differ but each was faster than the conjunction search rate. For old adults, the preview and conjunction search rates did not differ but each was slower than the single feature search rate. Data taken from Figure 3 of Watson and Maylor (2002), *Psychology and Aging*, *17*, 321-339. Copyright © 2002 by the American Psychological Association. Adapted with permission.

Figure 11. Top panel: Example stimulus display for enumeration task without distractors (how many Os?). Middle panel: Example stimulus displays for enumeration task with X (left) and Q (right) distractors. Bottom panel: Example stimulus displays for search tasks (O present/absent?) with X (left) and Q (right) distractors. Watson, Maylor and Manson (2002) used X distractors; Watson, Maylor and Bruce (in press, Experiment 1) used Q distractors. In all cases, luminance inverted (not drawn to scale).

Figure 12. Mean correct response times (RTs) as a function of numerosity and distractor absence/presence for young and old adults in the enumeration tasks from Watson, Maylor and Manson (2002). Distractors were Xs.

Figure 13. Mean correct response times (RTs) as a function of age, target absence/presence and display size for the visual search task from Experiment 1 of Watson, Maylor and Bruce (in press). Distractors were Qs. Reworked from the

original Figure 2 to appear in the *Quarterly Journal of Experimental Psychology (Section A),* published for The Experimental Psychology Society (see journal web site at http://www.psypress.co.uk/journals.asp).

Figure 14. Mean correct response times (RTs) as a function of numerosity and distractor absence/presence for young and old adults in the enumeration tasks from Experiment 1 of Watson, Maylor and Bruce (in press). Distractors were Qs. Reworked from the original Figure 3 to appear in the *Quarterly Journal of Experimental Psychology (Section A),* published for The Experimental Psychology Society (see journal web site at http://www.psypress.co.uk/journals.asp).

Figure 1

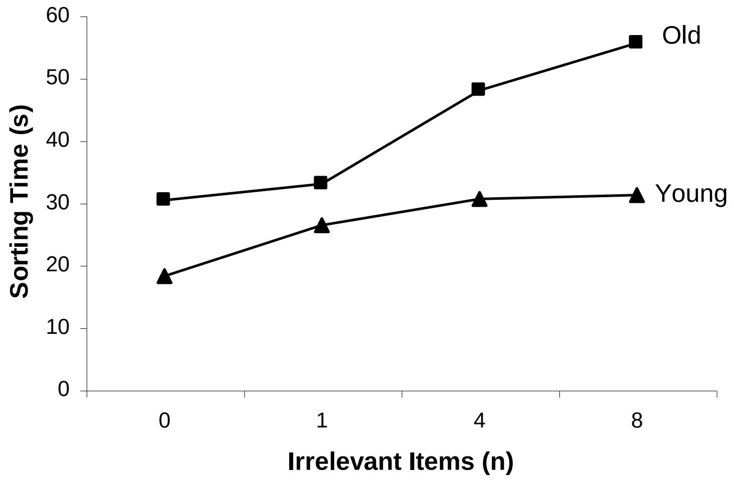

60
50
40
30
20
10
0
Sorting Time (s)
Old
Young
0
1
4
8
Irrelevant Items (n)

Figure 2

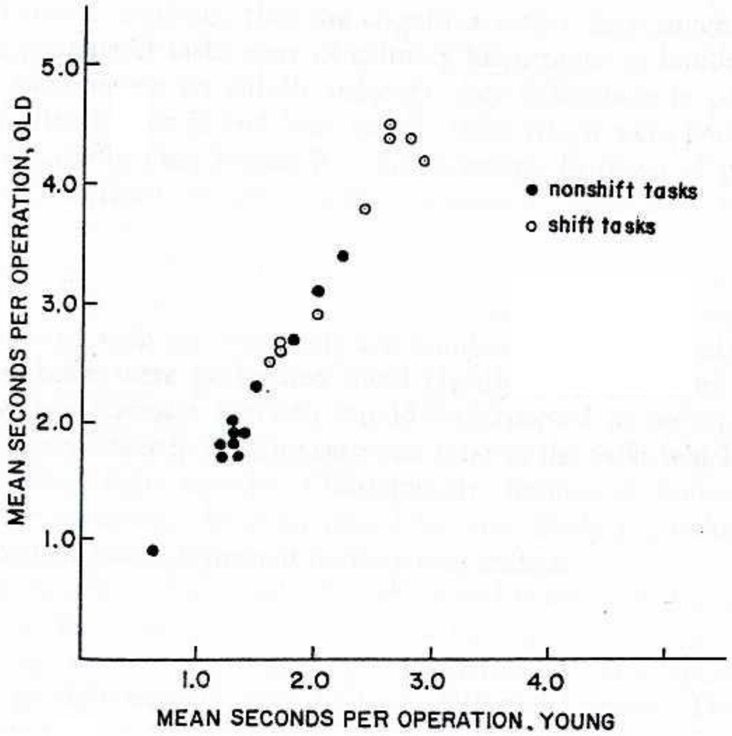

MEAN SECONDS PER OPERATION, OLD
5.0
4.0
3.0
2.0
1.0
1.0
2.0
3.0
4.0
MEAN SECONDS PER OPERATION, YOUNG
● nonshift tasks
○ shift tasks

Figure 3a

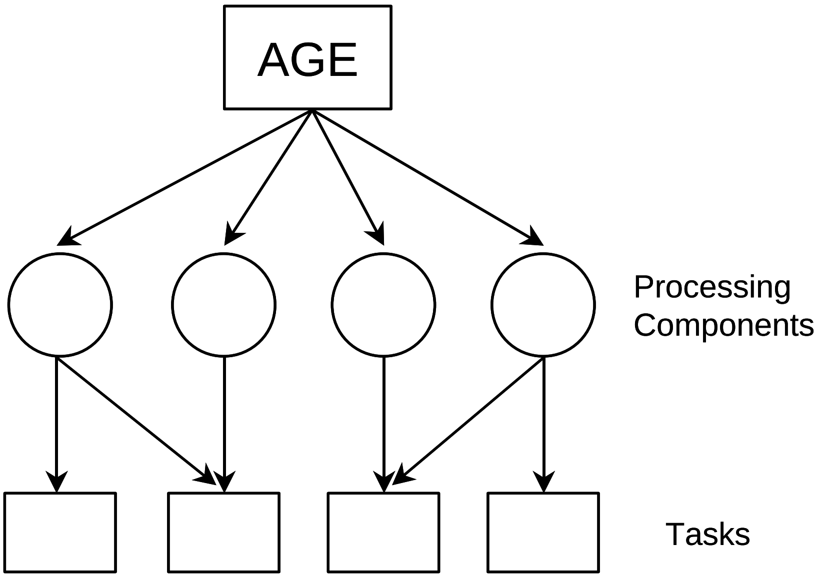


Figure 3b

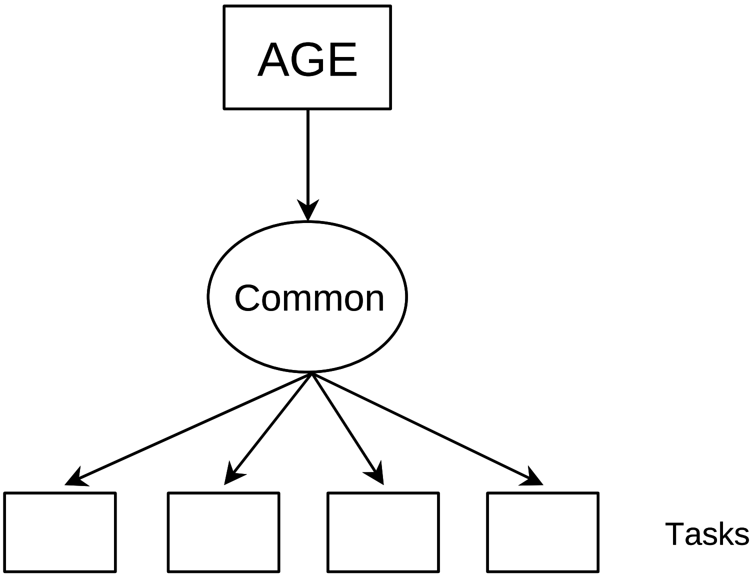


Figure 4

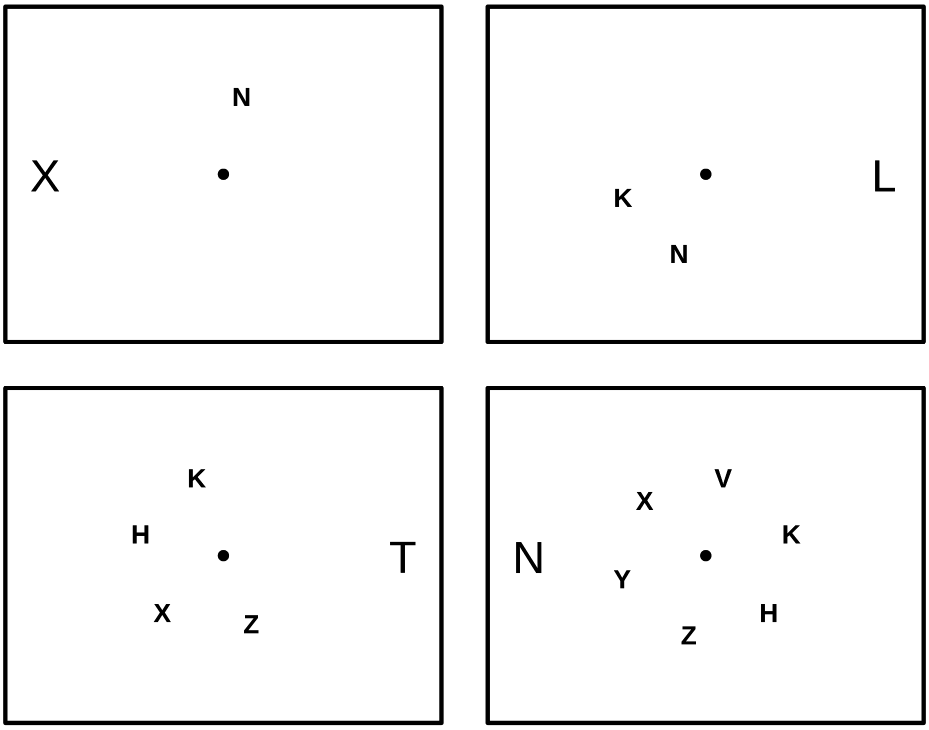


Figure 5

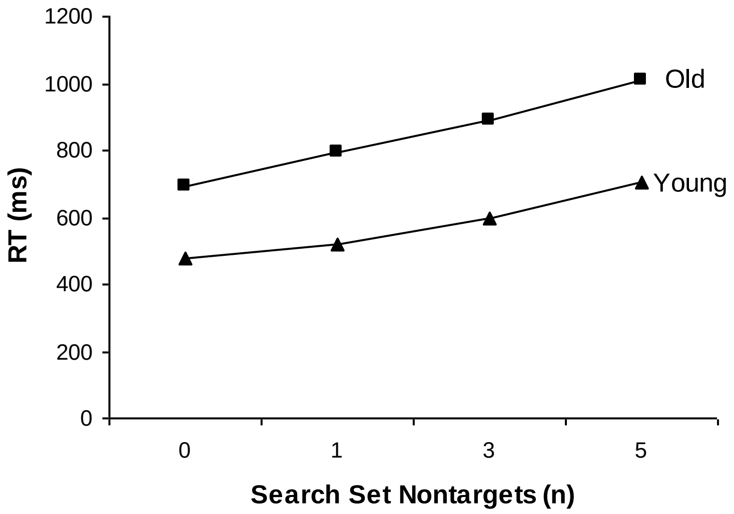

1200
1000
800
600
400
200
0
RT (ms)
Old
Young
0
1
3
5
Search Set Nontargets (n)

Figure 6a

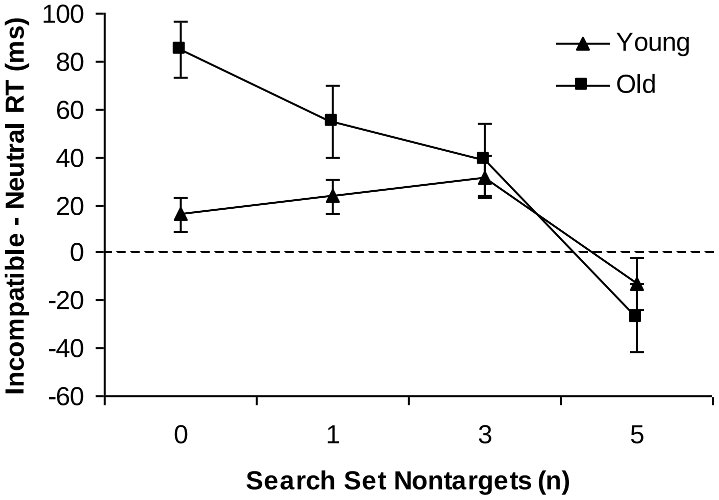


Figure 6b

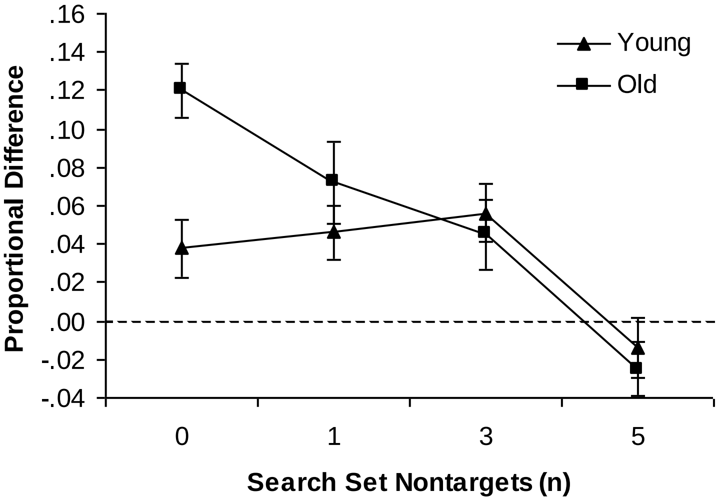


Figure 7

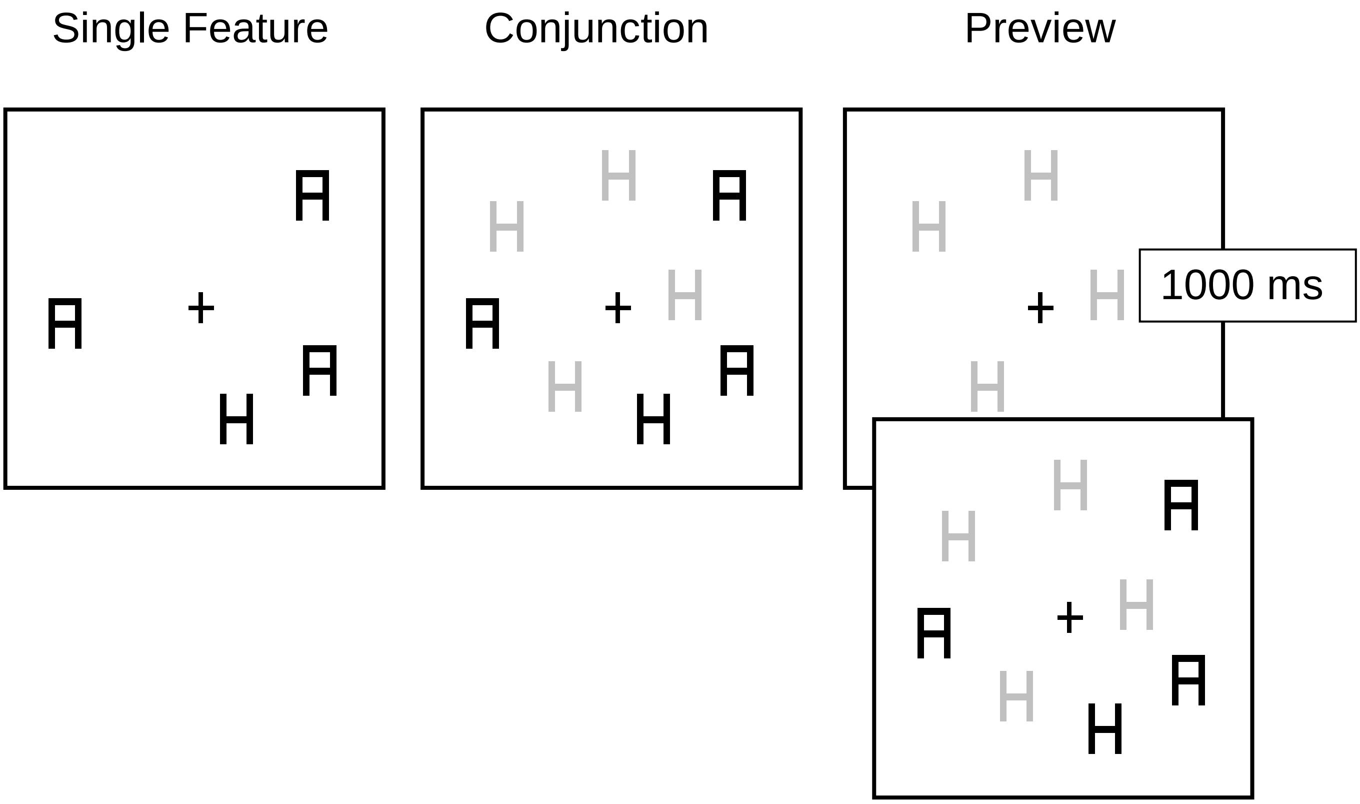


Figure 8

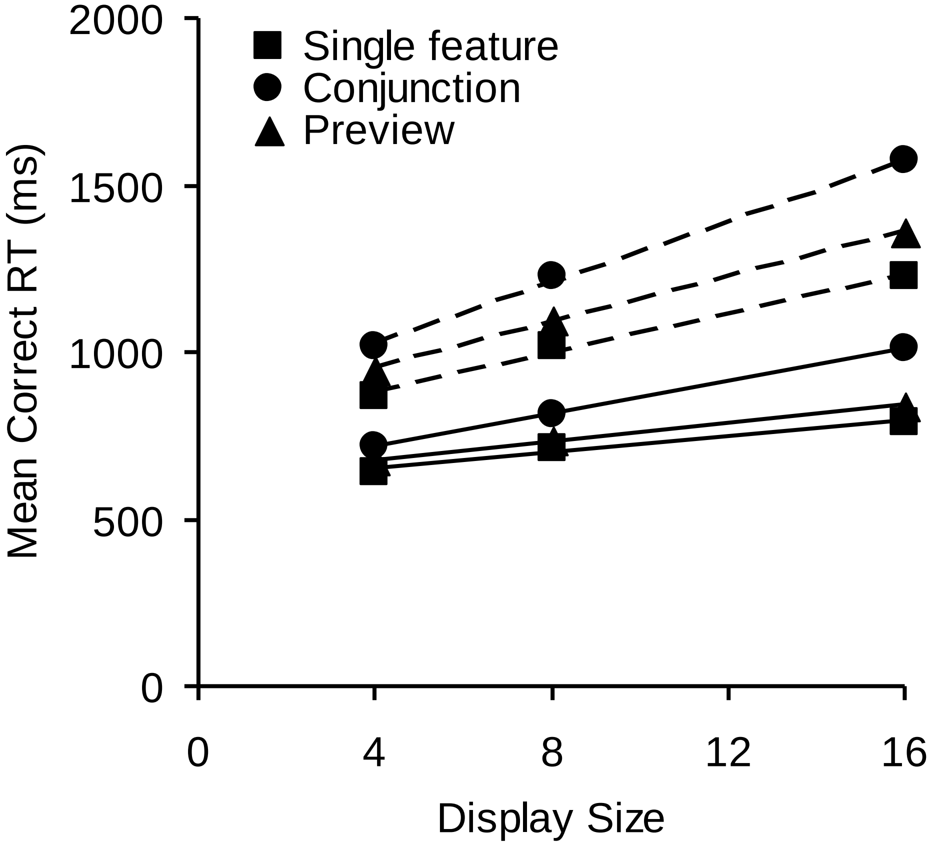

2000
1500
1000
500
0
Mean Correct RT (ms)
■ Single feature
● Conjunction
▲ Preview
0
4
8
12
16
Display Size

Figure 9

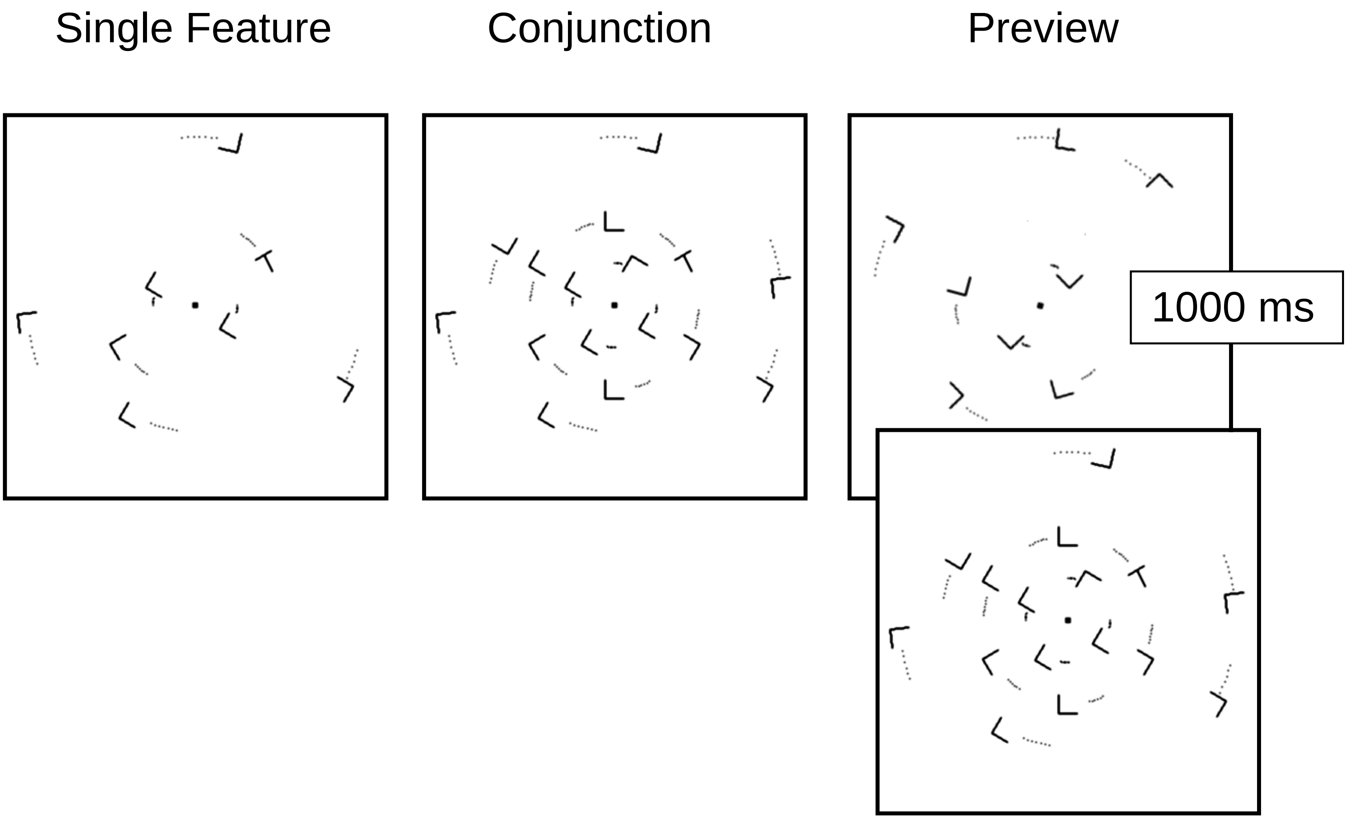


Figure 10

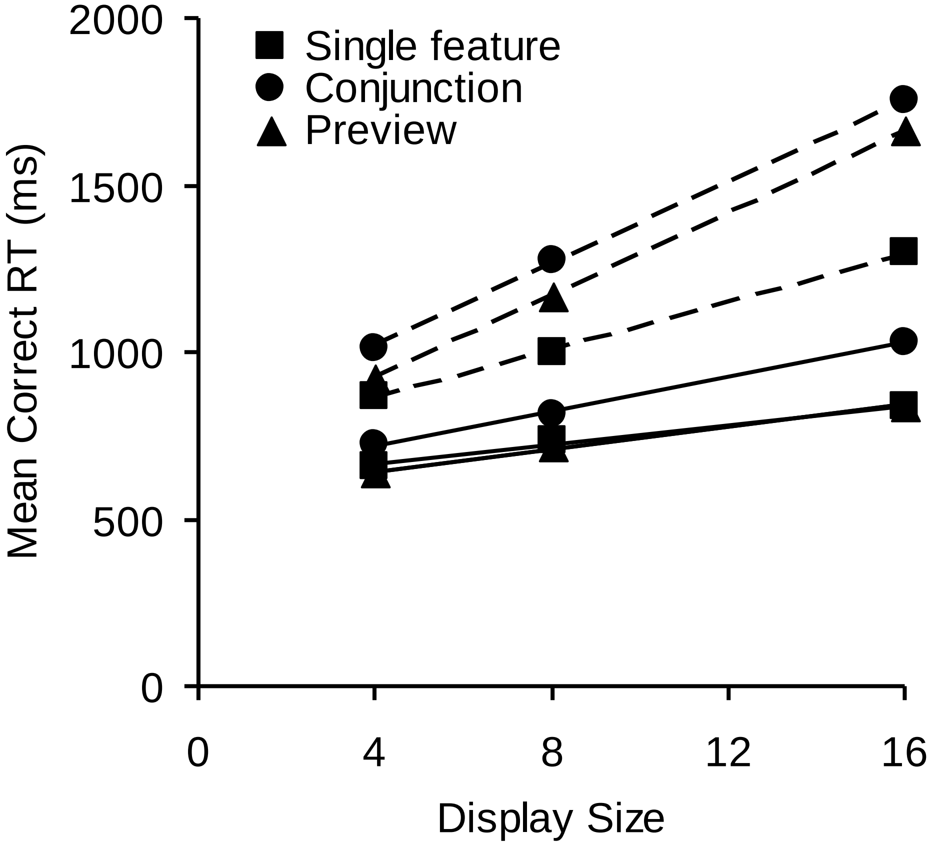

2000
1500
1000
500
0
Mean Correct RT (ms)
■ Single feature
● Conjunction
▲ Preview
0
4
8
12
16
Display Size

Figure 11

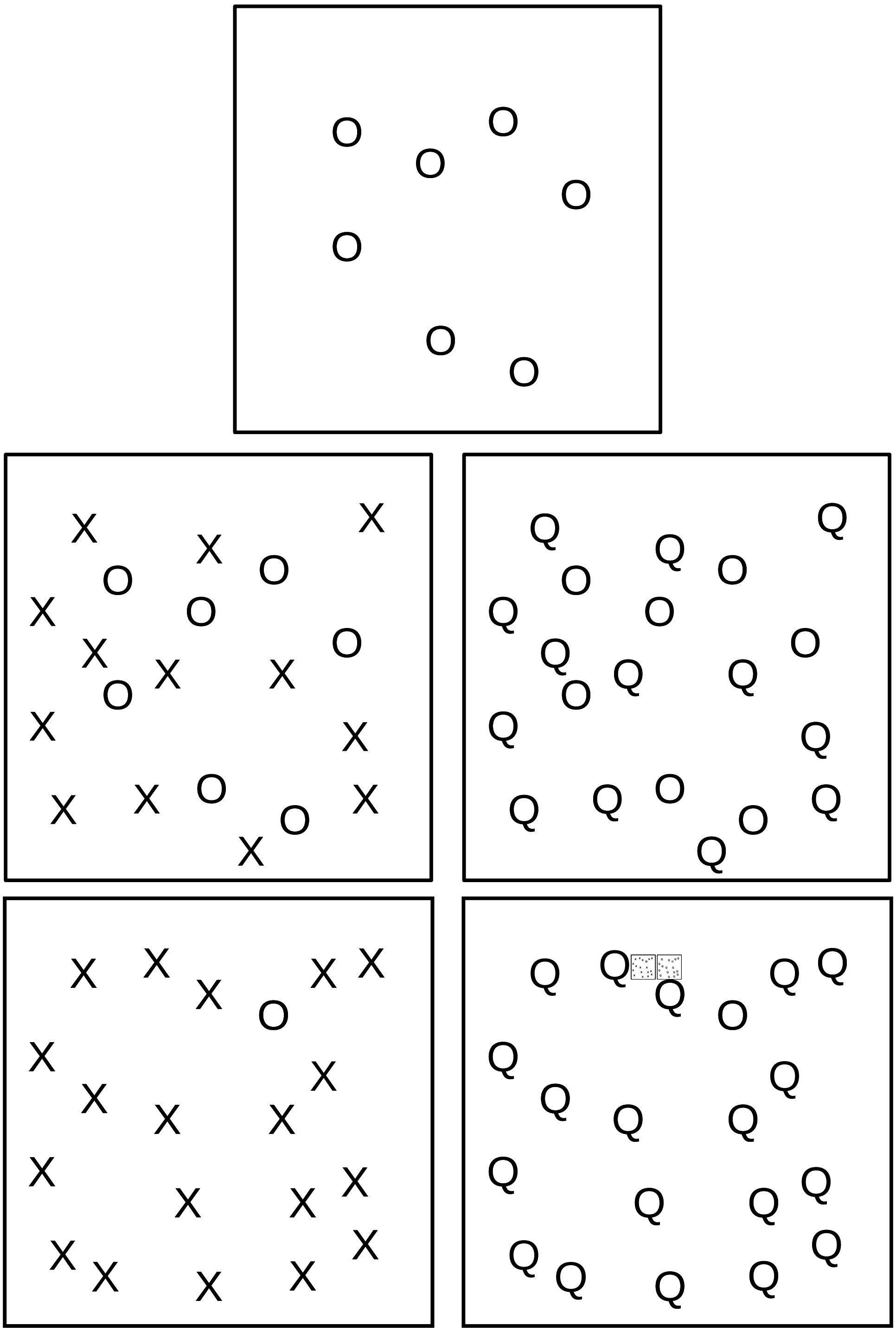


Figure 12

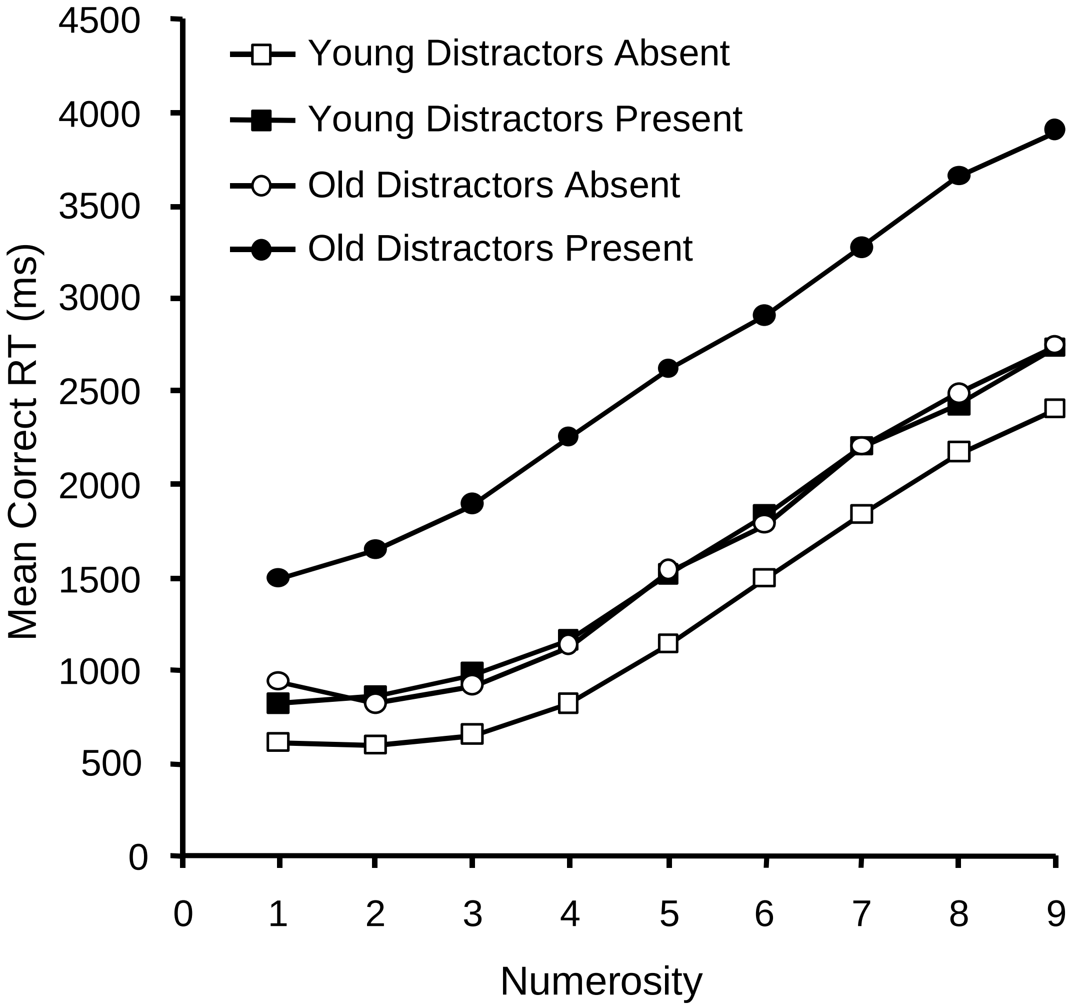
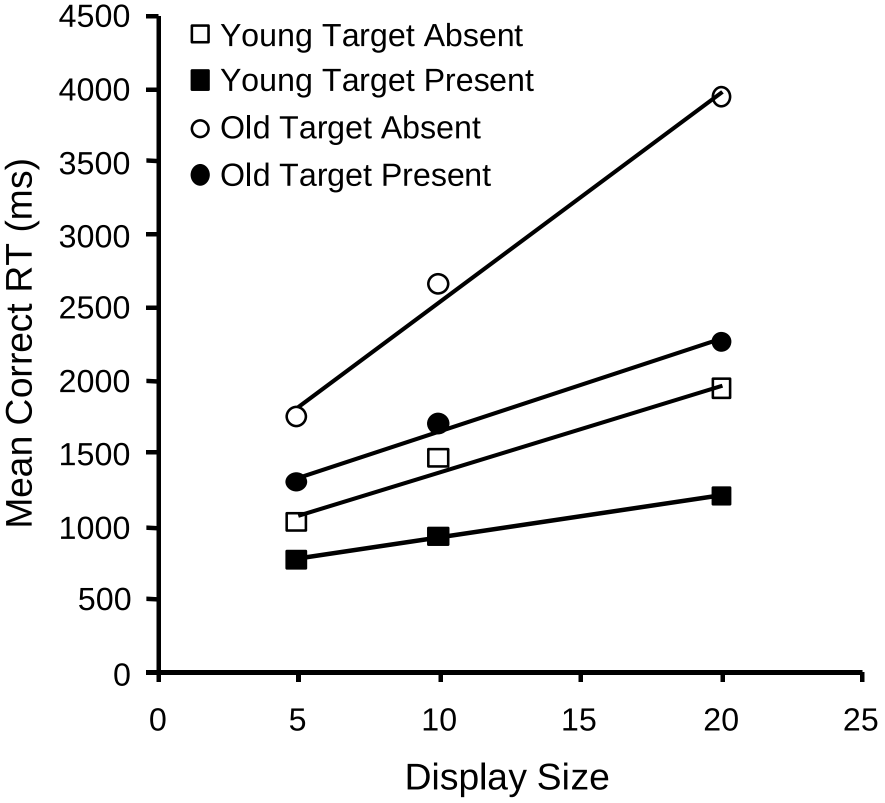
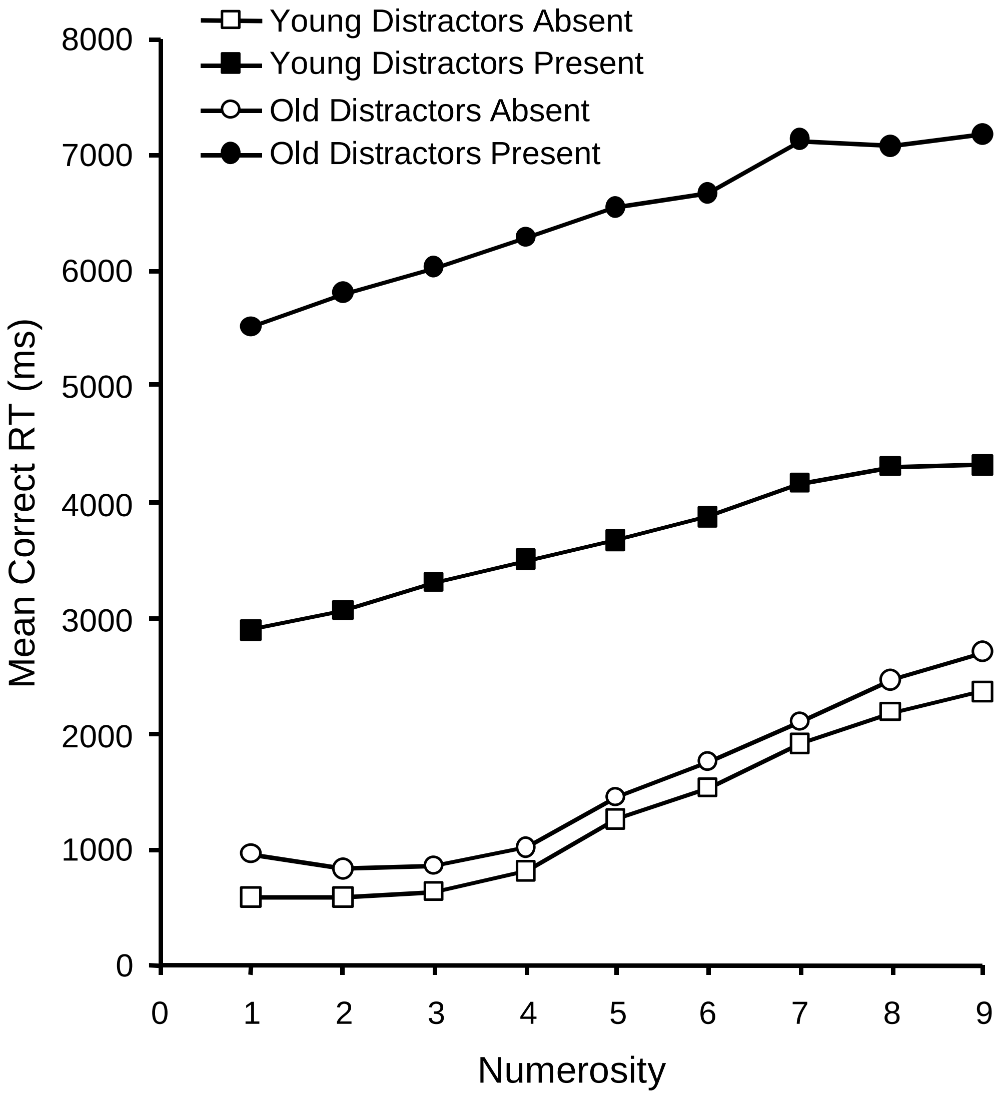

Young Distractors Absent
Young Distractors Present
Old Distractors Absent
Old Distractors Present
Mean Correct RT (ms)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
1
2
3
4
5
6
7
8
9
Numerosity

Figure 13



4500
4000
3500
3000
2500
2000
1500
1000
500
0
Mean Correct RT (ms)
0
5
10
15
20
25
Display Size
□ Young Target Absent
■ Young Target Present
○ Old Target Absent
● Old Target Present

Figure 14


Young Distractors Absent
Young Distractors Present
Old Distractors Absent
Old Distractors Present
Mean Correct RT (ms)
0
1000
2000
3000
4000
5000
6000
7000
8000
0
1
2
3
4
5
6
7
8
9
Numerosity