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Aging and Inhibitory Processes in Memory, Attentional and Motor Tasks

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The last few years have seen an increasing focus on inhibitory processes in cognition (see Dempster, 1992; Dempster & Brainerd, 1995), especially in their impairment in certain patient populations (e.g., Beech, Powell, McWilliam, & Claridge, 1989; Cohen & Servan-Schreiber, 1992), in their development during childhood (e.g., Harnishfeger, 1995), and in their decline with normal aging (e.g., McDowd, Oseas-Kreger, & Filion, 1995). In this chapter, we briefly describe the inhibition deficit hypothesis of cognitive aging before discussing some logical and methodological issues that have complicated its investigation. We then present three aging studies across the different domains of short-term memory (Maylor & Henson, 2000), visual search (Watson & Maylor, 2002) and motor control (Schlaghecken & Maylor, 2003). In each case, it is argued that inhibitory processes are responsible for the effects of interest, namely, the Ranschburg effect (Crowder, 1968; Jahnke, 1969), the preview benefit in visual search (known as visual marking; Watson & Humphreys, 1997), and the negative compatibility effect (Eimer & Schlaghecken, 1998), respectively. What these three effects have in common is that, at some level, they all occur as a result of inhibitory processes that suppress responses to stimuli that are no longer relevant to current goals. The results show mixed support for the inhibition deficit hypothesis of aging, the current status of which is finally discussed in the light of these and other data.

Cognitive aging research in the past has been dominated by “local” explanations, which assume that deficits are localized within particular stages or components of information processing. This approach tends to rely on the Age  $\times$  Treatment interaction methodology: If the age deficit is greater for a task requiring processes X and Y than for a task requiring only process X, then process Y is supposed to be age sensitive (see Salthouse, 1991, for discussion). However, Age  $\times$

Treatment interactions are so commonly observed that researchers appear to have identified almost as many age-sensitive processing components as tasks. As Maylor and Rabbitt (1994) commented, “[t]he attempt to analyze cognitive behavior into its constituent elements and then to localize the effect of old age within a particular subset of those elements has led to demonstrations of age deficits at almost every stage of information processing” (p. 224). Moreover, the age-related variance is often substantially shared across different tasks, suggesting that a small number (perhaps just one) of basic mechanisms may be responsible for cognitive aging (Park, 2000; Salthouse, 2000). Consequently, in recent years there has been a shift toward more “global” explanations, in which the effects of aging are attributed to a single factor such as reduced processing speed (see Salthouse, 1996). It is now generally accepted that there are probably both shared (global) and unique (local) effects of old age but that shared effects dominate over unique effects. Our priority as researchers should therefore be to explore shared age-related influences because they explain more of the age-related variance (see chapters in Perfect & Maylor, 2000b, for discussion). One such single-factor explanation of cognitive aging that has been the subject of much recent research is the reduced inhibition hypothesis proposed by Hasher and Zacks (1988; see also Hasher, Zacks, & May, 1999).

#### *Inhibition Deficit Hypothesis of Aging*

Early evidence that older adults are particularly susceptible to interference (e.g., Rabbitt, 1965) led Hasher and Zacks (1988) to suggest that much of what we view as age-related decline in cognition occurs as a result of age-related decline in the efficiency of inhibitory mechanisms. Their theory was originally proposed to explain age differences in working memory capacity, which is “widely thought to be an index of the general capacity available for mental work” (p. 276, Zacks & Hasher, 1997).

They identified two consequences of impaired inhibitory processes. First, there is a failure to prevent information that is irrelevant to current goals from entering working memory. For example, studies in which people are asked to read a text while ignoring material interspersed within the target text (e.g., Connelly, Hasher, & Zacks, 1991) or to listen to target speech while ignoring a competing speaker in the background (e.g., Tun, O’Kane, & Wingfield, 2002) show that older adults are more impaired by the distracting information than are young adults. Second, with reduced inhibition, there is also a failure to prevent information from remaining in working memory when no longer relevant to current goals. For example, if an ambiguous word is presented (*bank*) that is then disambiguated by the context (*money*), there is evidence that for older adults, both meanings remain activated (*river bank* and *money bank*), whereas young adults suppress the no-longer relevant meaning (e.g., Hartman & Hasher, 1991).

A recent update of the inhibitory deficit hypothesis (Hasher et al., 1999) identifies three functions of inhibition (*access*, *deletion*, and *restraint*) that together control the contents of working memory. The *access* and *deletion* functions correspond to their earlier inhibitory mechanisms of controlling access to working memory by preventing extraneous information from entering working memory, and deleting or suppressing the activation of no-longer relevant goals or information. Additionally, inhibition is thought to serve a *restraining* function by preventing prepotent candidates for response from controlling thought and action. Evidence for age-related impairments in restraint comes from tasks such as the antisaccade task (e.g., Nieuwenhuis, Ridderinkhof, de Jong, Kok, & van der Molen, 2000) in which the prepotent response of saccading to a peripheral target has to be intentionally inhibited (see later section on motor control). In summary, the proposal is that “older adults

have less inhibitory control over the current contents of working memory than younger adults” (p. 656, Hasher et al., 1999), resulting in working memory that is cluttered up with goal-irrelevant information and easily captured by a dominant response tendency.

*Some Problems with the Inhibition Deficit Hypothesis*

Although the inhibition deficit hypothesis of aging has generated much important and interesting research, there remain a number of controversies surrounding its investigation and status as a viable single-factor theory (see critical reviews by Burke, 1997; McDowd, 1997; see Zacks & Hasher, 1997, for a reply). The inhibition deficit hypothesis has been interpreted, perhaps more broadly than was originally intended, as suggesting that aging impairs all types and levels of inhibitory mechanisms. This assumption possibly accounts for the first main problem for the inhibition deficit hypothesis, which is that the evidence with respect to aging is mixed. For example, in the directed forgetting paradigm, participants are presented with items that they are then either required to remember or forget. In fact, the final memory test requires the recall of all items. Consistent with the inhibition deficit hypothesis, young adults show a larger difference between “remember” and “forget” items compared with older adults, suggesting that they were more successful in inhibiting the “forget” items than older adults (e.g., Zacks, Radvansky, & Hasher, 1996). In contrast, no evidence for the inhibition deficit hypothesis has been found from the “inhibition of return” (IOR) effect. This refers to the finding of increased response times to visual targets when they appear at locations to which attention has recently been directed, in comparison with response times to targets at new locations. In other words, IOR is an inhibitory process that acts as a bias against returning one’s attention or eyes to recently attended locations or objects in order to promote efficient

visual search behavior (see Klein, 2000, for a review). Equivalent IOR effects have been obtained for young and older adults (Faust & Balota, 1997; Hartley & Kieley, 1995; Langley, Fuentes, Hochhalter, Brandt, & Overmier, 2001), contrary to the reduced inhibition hypothesis. At the very least, such conflicting results “suggest limitations on the generality of inhibitory deficits in healthy aging” (p. 13, Faust & Balota, 1997).

A second complicating issue is that some “inhibitory” phenomena may be explained without inhibition. The obvious example here is the case of negative priming (e.g., Milliken, Joordens, Merikle, & Seiffert, 1998; Neill, 1997). Typically, in a negative priming paradigm, participants are asked to process items while ignoring irrelevant distracting information. If the target on the current trial was the distractor on the previous trial, then responses are slower than to new targets – the negative priming effect. The traditional explanation emphasizes the role of inhibitory processes such that inhibition of a response to the distractor on the previous trial slows down the processing of that item when it subsequently appears as a target (e.g., Neill, 1977; Tipper, 1985; Tipper & Cranston, 1985). Negative priming has often been reported as reduced or absent in older adults in traditional negative priming paradigms (see Verhaeghen & De Meersman, 1998a, for a meta-analysis), which has been taken as support for reduced inhibitory processes in normal aging (e.g., Hasher, Stoltzfus, Zacks, & Rypma, 1991; Tipper, 1991). However, there are alternative explanations for the negative priming effect (see reviews by Fox, 1985; May, Kane, & Hasher, 1995). For example, one explanation is based on episodic retrieval in which the appearance of the target automatically cues the retrieval of the previous processing episode. This contains the information that no response was made to that item, and because this information conflicts with the response required on the current trial,

negative priming occurs as a consequence of response competition (see Neill & Valdes, 1992; Neill, Valdes, Terry, & Gorfein, 1992). Thus, age reductions in negative priming could be attributed to well-known deficits in episodic memory rather than to impaired inhibition.<sup>1</sup>

A third problem concerns scaling effects associated with reaction time (RT) measures (see Perfect & Maylor, 2000a; Verhaeghen, Cerella, Bopp, & Basak, this volume; for discussion). This is illustrated with hypothetical data in Figure 1. Consider, for example, the classic Stroop task in which participants are asked to name the ink color of a string of Xs as quickly as possible (baseline condition) or to name the ink color of a color word where the ink color conflicts with the color word (interference condition). As illustrated in Figure 1, RT is typically longer in the interference condition than in the baseline condition (see MacLeod, 1991, for a review). The Stroop effect can be explained in terms of the interference between two conflicting responses associated with the same input. Thus, one response is elicited by naming the ink color but another response is elicited by reading the word. The response tendency to read the word is relatively automatic – therefore this prepotent response of reading the word must be inhibited in favor of producing the nondominant response of color naming (cf. Hasher et al.'s, 1999, restraint function). Hence, participants are slower in the interference condition than in the baseline condition.

As illustrated in Figure 1, older adults are usually slower than young adults in the Stroop task, particularly in the interference condition (see Verhaeghen & De Meersman, 1998b, for examples), leading to an Age  $\times$  Treatment interaction and the conclusion that older adults are specifically impaired in inhibiting the automatic response of reading the word. However, in a comprehensive review of the evidence on aging and the Stroop effect, Verhaeghen and De Meersman (1998b) noted that

generalized slowing theories of aging (e.g., Cerella, 1985; 1990) would also predict a larger interference effect in older adults. In other words, larger age differences would be expected in the interference condition because RTs are slower than in the baseline condition. Indeed, from a meta-analysis of 20 studies, Verhaeghen and De Meersman (1998b) concluded that “the apparent age-sensitivity of the Stroop interference effect appears to be merely an artifact of general slowing” (p. 120) (but see also West & Alain, 2000). Thus, before concluding that any task provides evidence of greater interference (i.e., reduced inhibition) with aging, it is important to demonstrate that the age difference in the interference condition is greater than would be predicted on the basis of generalized slowing.

A fourth complicating factor in the investigation of the inhibition deficit hypothesis was described by Anderson (2002) as the “hidden activation peak” and is illustrated with hypothetical data in Figure 2. Differences between baseline and experimental conditions at time 2 would suggest greater inhibitory control in young adults than in older adults. However, it is conceivable that at an earlier point in time prior to the application of inhibition (time 1), initial activation was greater for older than for young adults (the hidden activation peak). Thus, if inhibitory control were measured instead by the difference between initial facilitation and subsequent inhibition, then young and older adults would not actually differ. Another possibility not shown in Figure 2 is that older adults may be slower to apply inhibitory control such that at a later point in time (time 3), older adults could show similar or even greater levels of inhibition than young adults. The point here is to suggest that it may be misleading to assess inhibitory functioning from a single time sample.

The fifth problem is that irrelevant information may not always be processed by older adults because of perceptual or capacity limitations (see, for example,

Maylor & Lavie, 1998). We could therefore be misled into concluding that inhibition was reduced by aging when in fact there simply was no initial activation of the interfering information.

### *The Present Studies*

With the above problems in mind, we now consider three recent aging studies focusing primarily on Hasher et al.'s (1999) delete function – the suppression of no-longer relevant information – across three different domains, to explore the generality of the reduced inhibition hypothesis. In each paradigm, it is argued that there is good evidence that inhibition is involved, although space does not permit exhaustive reviews. Where possible, we have attempted to rule out generalized slowing as an alternative account of the data. Anderson's (2002) recommendations for designs that trace the time course of effects have been followed so that both initial activation and subsequent inhibition are monitored. If we find reduced inhibition in older adults, we can therefore examine whether it can be explained by either increased initial activation (Anderson, 2002) or the absence of activation (Maylor & Lavie, 1998).

#### *(1) Short-term Memory: The Ranschburg Effect*

Reduced efficiency of Hasher and Zacks's (1988) deletion function with aging allows irrelevant information to remain in working memory, leading to increased competition at retrieval. A paradigm that enables this to be readily studied is serially ordered recall from short-term memory. Maylor and Henson (2000) argued that during serial recall, items already recalled from the current list are no longer relevant to the task of recalling the rest of the list and should therefore be inhibited. Such *response suppression*, whereby once an action has been performed it is temporarily inhibited so that it is unlikely to be performed again in the immediate future, is evident across a range of serial behaviors including speech production (MacKay,

1987; Vousden, Brown, & Harley, 2000), typing (Rumelhart & Norman, 1982), goal sequencing (Li, Lindenberger, Rüniger, & Frensch, 2000), and serial recall (Duncan & Lewandowsky, in press; Henson, 1998a). Indeed, a crucial feature of recent computational models of serial behavior that provide accurate fits to detailed patterns of human errors is a response suppression component to prevent perseverative responses (e.g., Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Farrell & Lewandowsky, 2002; Henson, 1998b; Lewandowsky, 1999; Page & Norris, 1998).

In serial recall tasks, such short-lived postoutput inhibitory processes are supported by the common observation that repetition errors, where items are erroneously recalled more than once, are relatively infrequent (e.g., Henson, Norris, Page, & Baddeley, 1996). When they do occur, the distance between the repeated outputs is usually quite large (Conrad, 1965). Also consistent with response suppression is the finding of impaired recall of repeated items in comparison with the recall of nonrepeated items (e.g., Crowder, 1968), a phenomenon known as the *Ranschburg effect* (Jahnke, 1969), after the Hungarian psychologist Paul Ranschburg (1870-1945) who discovered the effect and also published on the psychology of aging (see p. 333 of Birren & Schroots, 2000). The Ranschburg effect has been most extensively investigated recently by Henson (1998a), who developed improved methodology and analysis for examining the effects of repeated items on serial recall. For lists with nonadjacent repeated items, he observed *repetition inhibition* (i.e., the Ranschburg effect) such that recall of both repeated items was inferior to the recall of two nonrepeated items at the corresponding serial positions in control lists. This was attributed to the automatic process of response suppression, which not only causes the temporary failure to retrieve an item more than once but also prevents previous responses from coming to mind if guessing is necessary.

Maylor and Henson (2000) therefore proposed the Ranschburg effect as a useful testing ground for Hasher and Zacks's (1988) inhibition deficit hypothesis of aging. Serial recall was expected to be lower overall for older than for young adults (e.g., Maylor, Vousden, & Brown, 1999). However, the interesting prediction was that reduced response suppression in older adults would lead to a reduced Ranschburg effect, that is, older adults would actually be better able to recall repeated items, relative to nonrepeated items, than young adults.

In Maylor and Henson's (2000) first experiment, there were 36 young adults and 37 older adults, with mean ages of 20 and 72, respectively. Forty-eight experimental lists of six letters were presented to participants on a computer screen at a rate of one letter per second.<sup>2</sup> Immediately following the presentation of each list, participants were required to recall the items in correct serial order by writing their responses in six boxes strictly from left to right. If they were unable to recall an item, they were asked to place a line through the corresponding box. Participants were informed in advance that lists could contain repeated items.

The letters in each list were chosen from the following set of phonologically confusable consonants: *B, D, G, P, T, V*. Our earlier work (Maylor et al., 1999) suggested that six-item lists of phonologically confusable consonants would produce appropriate overall levels of performance in both age groups. Table 1 summarizes the composition of the 48 lists: Half were control lists with no repeated items, and half were repetition lists with one repeated item. For repetition lists, the positions of the repeated items varied across lists in eight different formats, with repeated elements between one and four positions apart.

The main dependent measure of interest was the conjoint probability of recalling both repeated elements in repetition lists or both corresponding control

elements in control lists, regardless of correct positioning. As expected, overall recall was significantly higher for young (0.78) than for older adults (0.57). Figure 3 shows the differences on this measure between repeated and control lists as a function of repetition separation for each age group. Consistent with previous studies of the Ranschburg effect, there was substantial repetition inhibition (i.e., repeated less than control) for nonadjacent repetitions (separations 2-4), attributable to a failure to recall a repeated item more than once. However, it can be seen from Figure 3 that, contrary to expectation, this Ranschburg effect was at least as large for older as for young adults, a result that was replicated in Maylor and Henson's (2000) second experiment with 30 young and 29 older adults.

In summary, postoutput response suppression is a fundamental inhibitory mechanism involved in serial behavior, and in short-term memory tasks is responsible for the Ranschburg effect (see Henson, 1998a). Maylor and Henson (2000) therefore regarded it as analogous to Hasher et al.'s (1999) deletion function, which during retrieval prevents information from remaining in working memory when no longer relevant to current goals. However, contrary to the reduced inhibition hypothesis, there was no evidence of a reduced Ranschburg effect in older adults, which led Maylor and Henson (2000) to conclude that "the specific process of response suppression during serial recall is not reduced by aging" (p. 657). A similar Ranschburg experiment comparing children aged 7-11 years found no developmental increase in response inhibition, despite substantial improvements in overall recall over this age range (McCormack, Brown, Vousden, & Henson, 2000, Experiment 3). Together, these findings support the view that postoutput response suppression is an inhibitory mechanism that does not follow the predicted rise and fall across the lifespan (e.g., Dempster, 1992). It seems therefore unlikely to play a significant role in

accounting for improvement in short-term memory during childhood and decline with aging.

Maylor and Henson (2000) noted the conceptual similarity between postoutput response suppression in serial recall and IOR in visual attention, which both act to avoid perseverations in serial behavior (see also Houghton & Hartley, 1995). They are also similar in being unimpaired by normal aging, thereby challenging the general inhibition deficit hypothesis. However, because both are considered relatively automatic processes (see Henson, 1998a; Taylor & Klein, 1998, respectively), the findings can be reconciled by the suggestion that whereas controlled inhibitory processes are impaired with aging, automatic inhibitory processes may be preserved (e.g., Kramer, Humphrey, Larish, Logan, & Strayer, 1994; McDowd, 1997). We therefore turn next to an effortful top-down inhibitory mechanism in visual search.

## *(2) Visual Search: The Preview Benefit*

The visual system is constantly bombarded with more information than can be dealt with at any one time, hence the need to prioritize selection. There might be two ways by which this can be done. One is to actively enhance visible targets, which will be successful only if the information is already present. In contrast, the prioritization of anticipated, newly appearing stimuli could be achieved by actively inhibiting stimuli already visible, which would decrease their competition for selection when the new stimuli arrived. This second process of deprioritization has been termed *visual marking* (Watson & Humphreys, 1997).

Visual marking was demonstrated by Watson and Humphreys (1997) using a modified color-shape conjunction visual search task as illustrated in Figure 4a. Participants were required to indicate the presence or absence of a target (a blue H) among a varying number of distractors. In the single feature condition, the distractors

were blue As. Typically, when the target differs from the distractors by the possession of a unique feature, as in this case, then RTs to find the target are not particularly affected by the number of distractors in the display and the target is said to “pop out” (e.g., Treisman & Gelade, 1980). However, if the target is defined by a conjunction of features (i.e., a blue H among blue As and green Hs), then search becomes relatively slow, with RTs increasing more steeply as a function of display size. In addition, the slope for target-absent trials is approximately twice that for target-present trials, consistent with search as serial and self-terminating – on average, only half of the items need to be searched on target-present trials (but see also Humphreys & Müller, 1993; Townsend, 1972).

Watson and Humphreys (1997) contrasted these two baseline conditions (single feature and conjunction) with a preview condition in which one set of distractors (green Hs) was presented for 1000 ms prior to the remaining items (blue As and a blue H if the target was present). Participants were instructed that when the target was present, it would be in the second display. Thus, if the old unwanted information could be successfully ignored, search in this preview condition should be more efficient than when all the items were presented simultaneously (as in the conjunction baseline). In fact, search rate should be equivalent to that of the single feature condition in which only the blue items from the preview condition were displayed. Figure 4b shows the data for target-present trials<sup>3</sup> from Experiment 1 of Watson and Humphreys (1997).<sup>4</sup> In terms of search slopes, the preview condition was indeed as efficient as the single feature baseline and significantly more efficient than the conjunction baseline (the preview benefit). This ability to exclude the previewed items from current search, termed visual marking, is an important mechanism for prioritizing and controlling the selection of visual information (see Watson &

Humphreys, 1997; Watson, Humphreys, & Olivers, 2003). It can be distinguished from other inhibitory mechanisms such as the passive inhibition of previously attended objects or locations (i.e., IOR) or the inhibition of previous rejected distractors (i.e., negative priming). Watson and Humphreys (1997) proposed that the preview benefit resulted from the active inhibition of old information, which allows a selection advantage for new stimuli that subsequently appear, and is a top-down process that requires the commitment of limited attentional resources (see Humphreys, Watson, & Jolicoeur, 2002; Watson & Humphreys, 1997, 2000, for evidence).

In view of these characteristics, one would expect older adults to show substantial decrements in visual marking tasks. We conducted a series of experiments (Watson & Maylor, 2002) to explore age-related differences in the preview benefit, comparing young and older adults with mean ages of approximately 21 and 71 years, respectively. The first experiment was essentially as already described (see Figure 4a), the main difference being that there were fewer display sizes. The results for target-present trials are shown in Figure 5. As expected from previous aging studies (e.g., Humphrey & Kramer, 1997; Plude & Doussard-Roosevelt, 1989), young adults were faster than older adults overall and their searches were conducted approximately twice as quickly (see Figure 5 caption for search rates). Crucially, however, the two age groups did not differ in terms of their ability to visually mark the previewed items as evidenced by the finding that the search rate for the preview condition matched that of the single feature baseline rather than that of the conjunction baseline for young and older adults alike. Experiment 1 therefore replicated the results from a study of visual marking in old age by Kramer and Atchley (2000), who used different stimuli and much larger display sizes, suggesting that older as well as young adults can

successfully ignore at least 15 previewed items. Together, they “provide yet another demonstration of age-related sparing in an inhibitory process” (p. 295, Kramer & Atchley, 2000).

Watson and Humphreys (1997) demonstrated that for stationary stimuli, previewed items are marked by inhibition applied to their locations (see also Olivers, Watson, & Humphreys, 1999; but see also Olivers & Humphreys, 2002, and Braithwaite & Humphreys, 2003, for evidence of feature-based effects with stationary stimuli). Visual marking appears intact in older adults for stationary stimuli, consistent with other work showing preserved location-based inhibitory processes (e.g., Faust & Balota, 1997; Hartley & Kieley, 1995). But clearly objects in the real world are not always static. Watson and Humphreys (1998) explored displays in which all the items moved linearly down the screen at a constant speed. Their young participants still showed evidence of visual marking; that is, they could successfully ignore the previewed items even though they were continuously moving. However, it was shown that visual marking was not in this case location-based but was instead feature-based – in other words, it operated by the inhibition of a whole feature map (i.e., color) (see also Kunar, Humphreys, & Smith, 2003).

In our second experiment (Watson & Maylor, 2002), we compared feature-based visual marking of moving stimuli in young and older adults. The single feature, conjunction and preview conditions were as before except that all the stimuli moved continuously down the screen as illustrated in Figure 6a, scrolling back into the top of the display as they reached the bottom. The data for young adults presented in Figure 6b successfully replicated those of Watson and Humphreys (1998) in showing visual marking of the previewed items. Thus, the preview search rate resembled that of the single feature rather than the conjunction baseline. In contrast, the older adults

showed no evidence of visual marking, with a preview search rate equivalent to that of the conjunction rather than the single feature baseline. Thus, they were unable to exclude the previewed items from their search of the subsequent display. This experiment therefore demonstrates a clear age-related impairment in feature-based visual marking of moving stimuli.

Feature-based marking of moving stimuli obviously requires there to be a unique feature (in our case, color) that distinguishes between the previewed and new items (see Figure 6a). However, if the local spatial relationships, or configuration, between the previewed items remains fixed, then visual marking of moving items can be achieved by grouping them to form a single virtual object (Watson, 2001). Such object-based marking was investigated in our third experiment (Watson & Maylor, 2002) using rotational, rather than linear, motion. This maintained the local spatial relationships between items but there was now no simple feature distinguishing the old previewed items from the new stimuli. As illustrated in Figure 7a, the stimuli rotated clockwise around the fixation point in a smooth and continuous fashion. The task was to search for the letter T, with Ls as distractors.<sup>5</sup>

The results presented in Figure 7b for the young adults replicated those of Watson (2001) in showing a full preview benefit, with the preview search rate matching that of the single feature and not the conjunction baseline. Older adults, on the other hand, again showed no evidence of a preview benefit, with the preview search rate matching that of the conjunction and not the single feature baseline. Thus, unlike young adults, older adults were not able to restrict their search to the new items alone in the preview condition.

It appears that whether there was a feature difference between the previewed and new items (Figure 6) or whether previewed items could be grouped to form a

virtual object (Figure 7), there were striking age-related deficits in visual marking of moving stimuli. Can these inhibitory deficits be explained by generalized slowing? They are certainly incompatible with a simple account in which older RTs are a linear transformation of young RTs (e.g., Figure 1). This is because there is no linear transformation possible that can convert the young adults' RT data pattern across conditions (i.e., single feature = preview < conjunction) into the older adults' RT data pattern (i.e., single feature < preview = conjunction). Generalized slowing could nevertheless still provide an account on the basis that young adults require approximately 400 ms between the previewed and new items for full visual marking to occur with stationary items (Watson & Humphreys, 1997). Visual marking of moving items may take longer; hence, it is possible that whereas a preview display duration of 1000 ms may be sufficient for young adults across all conditions, older adults may require longer than 1000 ms to mark the previewed items when they are moving.

To examine this possibility of age-related slowing of the time course of visual marking, we conducted a further experiment with older participants only (Watson & Maylor, 2002), which was identical to the third experiment with rotating stimuli (see Figure 7a) except that the preview duration was increased from 1000 to 2000 ms. Despite this additional time, none of the older participants showed any hint of a preview benefit, with mean search slopes of 30 (single feature), 65 (preview), and 56 (conjunction) ms/item. Like the older adults with 1000 ms preview duration in Figure 7b, the preview and conjunction search rates did not differ but each was slower than the single feature search rate. Consequently, we cannot attribute the age-related deficit in visual marking of moving stimuli to insufficient time to set up and apply marking as a result of generalized slowing.

As noted earlier, it is important to consider whether there are alternative explanations for visual marking that do not involve inhibitory mechanisms. Donk and Theeuwes (2001) have recently suggested that the preview benefit might be explained instead in terms of automatic attention capture by the luminance transients (onsets) associated with the appearance of the new items. However, a number of findings argue against this alternative view (see, for example, Watson et al., 2003), including those from the present aging experiments. Kramer, Hahn, Irwin and Theeuwes (1999) demonstrated that the attentional and oculomotor processes underlying attentional capture by abrupt onsets are unimpaired by old age. If visual marking were due to the prioritization of abrupt onsets, then we would have expected older adults to have been able to selectively attend to the abruptly appearing new items, thereby displaying preview benefits. The failure to obtain this result is therefore more in line with an inhibition interpretation than with an attentional capture interpretation of visual marking.

In summary, we have argued that prioritizing the selection of new items in visual search can be achieved through visual marking, that is, the active inhibition of items already present in the visual field (Watson & Humphreys, 1997). Consistent with the inhibition deficit hypothesis of aging, both feature-based and object-based visual marking of moving stimuli were impaired in older adults (Watson & Maylor, 2002, Experiments 2 and 3, respectively). However, there was age-related sparing of location-based visual marking of stationary stimuli (Kramer & Atchley, 2000; Watson & Maylor, 2002, Experiment 1), although it would probably be a mistake to conclude that this would always be the case. Visual marking of stationary stimuli is disrupted in young adults by, for example, the addition of a demanding secondary task such as monitoring digits at fixation (e.g., Humphreys et al., 2002; Watson & Humphreys,

1997). It seems likely, therefore, that visual marking of stationary stimuli with a secondary load would be even more disrupted in older adults than in young adults based on known age-related increases in dual-task costs (e.g., Verhaeghen & Cerella, 2002; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003).

*(3) Motor Control: The Negative Compatibility Effect*

Our final case study concerns inhibitory processes in motor control, which is a relatively neglected domain with respect to normal aging. There is, nevertheless, evidence of age-related decline in the ability to voluntarily inhibit prepotent motor responses (cf. Hasher et al.'s, 1999, restraint function). For example, in an antisaccade task in which participants were required to move their eyes in the opposite direction to a peripheral stimulus, Nieuwenhuis et al. (2000) found that older adults were more likely than young adults to saccade toward the cue and they also took much longer to initiate correct antisaccades. Also, in a 'stopping' paradigm in which participants were asked to abort an overt response in the unlikely event that they heard a 'stop' signal, Kramer et al. (1994) showed that older adults took disproportionately longer to implement the inhibitory or stopping process in comparison with young adults.

As already noted, it appears from other domains that controlled inhibitory processes (such as required above) may be more vulnerable to the adverse effects of aging than automatic inhibitory processes (e.g., McDowd, 1997). We were therefore interested in whether this holds true for the motor domain, that is, whether or not more automatic low-level motor inhibition would be impaired in old age (Schlaghecken & Maylor, 2003). To investigate this, we employed a masked prime paradigm (e.g., Eimer & Schlaghecken, 1998; Schlaghecken & Eimer, 2000), which tracks the automatic effects on motor responses of subliminal stimuli. The basic procedure is illustrated in Figure 8a. A briefly presented visual stimulus (the prime) is

immediately followed by a masking stimulus that renders the prime unavailable to conscious awareness (Eimer & Schlaghecken, 1998, 2002; Schlaghecken & Eimer, 1997), and by a clearly visible target stimulus. Primes and targets can be simple arrows pointing to the left or right, corresponding to the required speeded responses of key presses with the left or right hand, respectively. On each trial, prime and target arrows either point in the same direction (compatible trial), in opposite directions (incompatible trial), or the prime is an unrelated symbol such as an equal sign (neutral trial). Several studies with young adults have shown that if the target follows the prime immediately (interstimulus interval [ISI] of 0 ms), behavioral benefits occur on compatible trials, while costs occur on incompatible trials, relative to neutral trials (see Figure 8b), demonstrating a positive compatibility effect (PCE; Schlaghecken & Eimer, 1997, 2000). However, if the prime-target ISI is increased to around 100 ms or more, this effect reverses and becomes a negative compatibility effect (NCE), with costs on compatible trials and benefits on incompatible trials (Eimer, 1999; Schlaghecken & Eimer, 2000).

Behavioral and electrophysiological data suggest that the pattern of results illustrated in Figure 8b is obtained because the prime, although below the threshold for conscious awareness, initially activates its corresponding motor response (Eimer, 1999; Eimer & Schlaghecken, 1998). If the target is presented immediately after the prime, target-related motor preparation begins during this initial activation phase, hence resulting in behavioral PCEs. However, with longer prime-target ISIs, target-related motor preparation begins at a later stage relative to the initial prime-related activation. Therefore, the motor activation triggered by the masked prime can take its normal time course for longer before target-related activity sets in. Evidence from behavioral and electrophysiological studies of this time course suggests the existence

of an automatic self-inhibition process, which actively inhibits the initial prime-induced activation when the sensory evidence for the prime is suddenly removed (Eimer, 1999; Eimer & Schlaghecken, 1998; Schlaghecken & Eimer, 2002). This “emergency brake” mechanism suppresses activation of the initially primed response, and allows the alternative response to reach relatively higher activation levels. Consequently, behavioural costs on compatible trials and behavioral benefits on incompatible trials (i.e., NCEs) will be obtained when preparation of the target-related response begins during the self-inhibition phase.

The masked prime paradigm provides an opportunity to begin to address the question of whether more automatic low-level motor inhibition is impaired in old age. We compared 8 young and 8 older adults, with mean ages of 22 and 76 years, in two masked priming experiments (Schlaghecken & Maylor, 2003). An initial pilot study with parameters based on those employed previously with young participants (e.g., Schlaghecken & Eimer, 2000, 2002) failed to reveal any evidence that the primes had been processed at all by the older adults (presumably a perceptual limitation - see the fifth problem discussed earlier). Prime duration was therefore increased from the typical 17 ms to 33 ms and stimulus size was larger. On each trial in Experiment 1, a central fixation point was presented for 250 ms followed by a blank screen for 750 ms. The prime was then presented for 33 ms at fixation, followed by a 100 ms mask in the same location. The target was presented for 100 ms either just above or below the central area occupied by the mask. Prime-target ISI was blocked and was either 0 ms or 150 ms. Primes and targets were left- and right-pointing double arrows, with half of the trials compatible (prime and target pointing in the same direction) and half incompatible (prime and target pointing in opposite directions). Participants were required to fixate at the center throughout and to press the left or right response button

as quickly as possible according to the direction of the target arrows. With older adults in mind, the interval between target offset and the return of the fixation point was increased slightly from previous experiments to 2200 ms.

As usual, young adults (mean correct RT = 385 ms) responded more quickly than older adults (mean correct RT = 524 ms), with similar (low) error rates across age groups. Figure 9a displays the crucial results of interest, that is, compatibility effects (incompatible – compatible RTs) as a function of ISI. It is clear that despite the slightly altered experimental parameters, the data pattern for young adults of a PCE at 0 ms turning into a NCE at 150 ms successfully replicated those of previous studies (e.g., Schlaghecken & Eimer, 1997, 2000). For older adults, in contrast, there was a PCE at 0 ms but no evidence of a NCE at 150 ms. Although the PCE at 0 ms was numerically larger for older adults, the age difference was not significant. It should also be remembered that because of the overall difference in RT between young and older adults, this small increase with age in the PCE would disappear in terms of proportional RT effects. Thus we can discount any suggestion of greater early activation in older adults (cf. Anderson's, 2002, hidden activation peak). The age difference at 150 ms, however, was significant suggesting an effect of aging on the self-inhibition component of prime-induced low-level motor control processes.

In our second experiment (Schlaghecken & Maylor, 2003), we tested whether early self-inhibition processes as reflected in NCEs in the masked prime task are completely absent or merely follow a slower time course in older adults. The participants from Experiment 1 were therefore asked to return to the laboratory for further testing, on this occasion with prime-target ISIs increased to 300 and 450 ms. Again, the young adults were faster than the older adults (364 vs. 492 ms). The results in terms of compatibility effects are shown in Figure 9b. There were no significant

effects, although it should be noted that the small NCE for older adults at 300 ms approached significance. Moreover, comparing RTs on incompatible and compatible trials for each individual participant revealed that four of the eight older adults showed reliable NCEs at 300 ms. Thus, for at least some older individuals, there was evidence that the self-inhibition component was delayed relative to young adults, whereas for other older individuals, there was no evidence of NCEs at any ISI.

Schlaghecken and Maylor (2003) concluded that motor activation triggered by subliminal primes via direct perceptuo-motor links is unaffected by old age, as evidenced by older adults' spared PCEs at 0 ms ISI. In contrast, the self-inhibition component of the activation-followed-by-inhibition process triggered by masked primes shows substantial impairment in old age (see Schlaghecken & Maylor, 2003, for further analysis and discussion). The study thus extends the inhibition deficit hypothesis of aging to low-level automatic motor inhibition.

### *Conclusions*

We have considered here the effects of normal aging on three recent examples of inhibitory processes – associated with short-term memory, prioritization in visual search, and motor control – all requiring the suppression of responses to stimuli no longer relevant to current goals. As others have observed (e.g., Burke, 1997; Kramer et al., 1994; McDowd, 1997), the overall picture emerging is that a general interpretation of the inhibition deficit hypothesis of aging (Hasher & Zacks, 1988; Hasher et al., 1999) is no longer tenable. Thus the present studies showed no evidence of reduced response suppression with aging in serial recall (Maylor & Henson, 2000), but there were age-related deficits in the visual marking of moving (though not stationary) stimuli (Watson & Maylor, 2002) and in the inhibition of motor responses automatically triggered by subliminal primes (Schlaghecken & Maylor, 2003), neither

of which could be explained in terms of generalized slowing. The motor control results were also inconsistent with the view (e.g., McDowd, 1997) that automatic inhibitory processes are preserved with aging whereas controlled inhibitory processes are impaired.

To some extent, such mixed results may seem the inevitable consequence of numerous problems complicating the interpretation of studies of the inhibition deficit hypothesis, some of which were outlined earlier. They may also reflect the possibility that researchers have overextended the use of the term inhibition and that apparently similar inhibitory functions may be quite unrelated (e.g., Friedman & Miyake, 2004) and thus differentially vulnerable to the effects of old age. Similar points have been raised in the broader context of executive functioning and its fractionation (see Mayr, Spieler, & Kliegl, 2001; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Rabbitt, 1997).

Is it possible then to provide an integrative account of age-related changes in inhibitory processes? For example, a number of researchers (e.g., Dempster, 1992) have suggested that “age-related differences in inhibitory function will be observed to the extent that performance depends on the integrity of the frontal lobes” (p. 493, Kramer et al., 1994). The frontal lobe hypothesis of cognitive aging (West, 1996) derives from evidence that the frontal lobes (traditionally associated with executive functioning) deteriorate disproportionately with normal aging (e.g., Raz, 2000) and that many age-related deficits resemble those exhibited by frontal lobe patients (but see Greenwood, 2000; Perfect, 1997; Reuter-Lorenz, 2000, for discussion). Many inhibitory findings appear consistent with this view – for example, as noted earlier, there is age-related sparing of IOR, which is associated with the superior colliculus and parietal cortex (see Klein, 2000, for a summary), whereas there is age-related

impairment in the 'stopping' paradigm (see earlier), which involves the frontal lobes (Band & van Boxtel, 1999).

To what extent are the results from the present studies consistent with this frontal approach? Such a question highlights a current practical difficulty in assessing the view, namely, that appropriate evidence to determine the exact brain region(s) responsible for the inhibitory phenomena of interest is not yet available. This certainly applies to the Ranschburg effect. For visual marking, there is preliminary evidence from fMRI to indicate the involvement of superior parietal cortex (precuneus) in the inhibition of stationary stimuli (see Watson et al., 2003, for a summary), but no evidence to date with moving stimuli. Finally, the negative compatibility effect appears to be mediated by subcortical structures, in particular the thalamus and the caudate nucleus of the basal ganglia, and not to involve the frontal lobes (Aron et al., 2003). At first sight, the observed age-related deficit therefore seems contrary to the frontal view. However, loss of neural tissue in old age is not only marked in the frontal lobes but also in the regions to which they connect, namely, the thalamus and the basal ganglia (Raz, 2000).

In summary, it seems that there are probably multiple inhibitory mechanisms subserved by both frontal and nonfrontal regions (see Andrés, 2003; Kok, 1999; Kramer et al., 1994) and that precise predictions of age-related deficits in tasks putatively requiring inhibition will ultimately depend on accurate localization of function together with detailed knowledge of brain aging.

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### Acknowledgment

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## Footnotes

<sup>1</sup>To complicate this particular issue further, a more recent meta-analysis by Gamboz, Russo and Fox (2002) concluded that there was no evidence of a significant age difference in the negative priming effect.

<sup>2</sup>This relatively slow rate of presentation ensures that all items are successfully encoded and therefore distinguishes the Ranschburg effect from repetition blindness, which refers to the inability to detect repetitions in rapid serial visual presentation at rates of more than 10 items per second (e.g., Kanwisher, Kim, & Wickens, 1996).

<sup>3</sup>We focus here on target-present trials because when the target is absent, people tend to rely on a number of different strategies and are usually more cautious in responding absent than present (e.g., Chun & Wolfe, 1996).

<sup>4</sup>The data for the single feature condition are plotted as if there were twice as many items in the display so that if search rate in the preview condition matches that of the single feature baseline, then we can conclude that the previewed items have been excluded from subsequent search.

<sup>5</sup>The single feature and conjunction conditions were therefore identical except for display sizes (2, 4 and 8 vs. 4, 8 and 16). In other words, the single feature baseline was also a conjunction search task. We continue to refer to single feature and conjunction baselines here for consistency with previous experiments.

Table 1

*Composition of List Types in Maylor and Henson's (2000) Ranschburg Experiments*

List type	Repetition format	Repetition separation	No. of lists
Control	1 2 3 4 5 6	n/a	24
Repetition	1 R R 4 5 6	1	3
Repetition	1 2 R R 5 6	1	3
Repetition	1 R 3 R 5 6	2	3
Repetition	1 2 R 4 R 6	2	3
Repetition	1 R 3 4 R 6	3	3
Repetition	1 2 R 4 5 R	3	3
Repetition	R 2 3 4 R 6	4	3
Repetition	1 R 3 4 5 R	4	3

*Note.* R = repeated item. Thus, *P T D T B V* would be an example of repetition format

1 R 3 R 5 6.

## Figure Captions

*Figure 1.* Hypothetical data from a reaction time (RT) experiment with baseline and interference conditions, which differ only in the absence and presence, respectively, of distracting information. The RT difference between the young and older groups is greater in absolute terms for the interference condition (300 ms) than for the baseline condition (200 ms), leading to the typical Age x Treatment interaction. However, in both conditions, the older group takes 1.5 times longer than the young group (proportional slowing).

*Figure 2.* Hypothetical data from, for example, a negative priming experiment. On the current trial (time 2), responses are slower to targets that were distractors on the previous trial than to new targets (baseline). One interpretation is that on the previous trial, in selecting and responding to the target, the competing distractor was inhibited. If it were possible to probe performance just prior to the onset of this suppression on the previous trial (time 1), responses to distractors would be faster than baseline (hidden activation peak). As illustrated here, data at time 2 suggest greater inhibition for young adults; however, greater initial activation of distractors at time 1 in older adults suggests similar levels of inhibitory control as indicated by the differences between time 1 and time 2.

*Figure 3.* Results from Experiment 1 of Maylor and Henson (2000) showing the mean differences between the probability of correct recall of both critical elements in repeated and control lists for young and older adults as a function of repetition separation (1-4). Error bars indicate 1 *SE* of the difference.

*Figure 4.* (a) Examples of single feature, conjunction and preview conditions in a typical visual marking experiment in which participants search for a blue H among blue As (single feature) or among blue As and green Hs (conjunction and preview). In

the preview condition, the green Hs are presented for 1000 ms before the appearance of the blue As and blue H (if present). (Blue and green letters are shown here in black and gray, respectively. The screen background and fixation point are shown with black/white reversed.) (b) Mean correct reaction times (RTs) to determine target presence from Watson and Humphreys (1997; Experiment 1) showing similar search rates in the single feature (14 ms/item) and preview (16 ms/item) conditions but a slower search rate in the conjunction (26 ms/item) condition, indicating that participants were able to ignore the previewed items while searching for the target.

*Figure 5.* Mean correct reaction times (RTs) to determine target presence for young (solid lines) and older (dashed lines) adults from Watson and Maylor (2002; Experiment 1). See Figure 4a 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 older adults. For both age groups, the single feature and preview search rates did not differ but each was faster than the conjunction search rate.

*Figure 6.* (a) Examples of single feature, conjunction and preview conditions in Experiment 2 of Watson and Maylor (2002), with stimuli (but not the fixation cross) moving linearly down the screen at a speed of 3.8 degrees visual angle per second. When an item reached the bottom of the screen, it gradually disappeared and then reappeared at the top in the same horizontal location. (b) Mean correct reaction times (RTs) to determine target presence for young (solid lines) and older (dashed lines) adults from Watson and Maylor (2002; Experiment 2). Search rates for the single feature, preview and conjunction conditions were 15, 19 and 29 ms/item, respectively, for young adults, and 28, 42 and 50 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 older adults, the preview and conjunction search rates did not differ but each was slower than the single feature search rate.

*Figure 7.* (a) Examples of single feature, conjunction and preview conditions in Experiment 3 of Watson and Maylor (2002), with stimuli (but not the fixation cross) 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. (b) Mean correct reaction times (RTs) to determine target presence for young (solid lines) and older (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 older adults, the preview and conjunction search rates did not differ but each was slower than the single feature search rate.

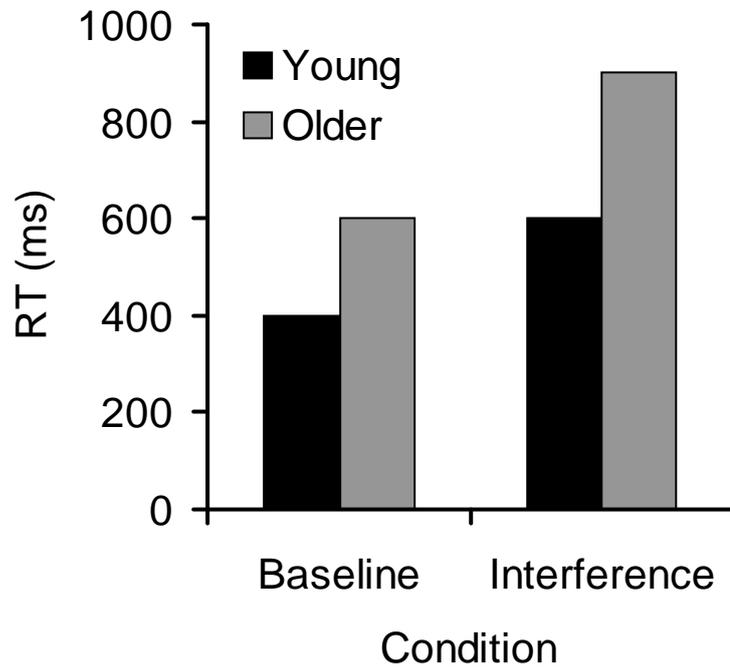
*Figure 8.* (a) Summary of the basic procedure in the masked prime paradigm, with prime-target interstimulus intervals (ISIs) of 0 and 150 ms. (b) Typical results from young adults in the masked prime paradigm for reaction times (RTs) and percentage error rates (line and bar graphs, respectively). Open symbols and bars represent 0 ms ISI (positive compatibility effects) and filled symbols and bars represent 150 ms ISI (negative compatibility effects).

*Figure 9.* (a) Mean reaction time (RT) differences (incompatible – compatible), with standard error bars, as a function of interstimulus interval (ISI = 0 and 150 ms) for young and older adults from Experiment 1 of Schlaghecken and Maylor (2003). (b) Mean RT differences (incompatible – compatible), with standard error bars, as a

function of ISI (300 and 450 ms) for young and older adults from Experiment 2 of Schlaghecken and Maylor (2003).

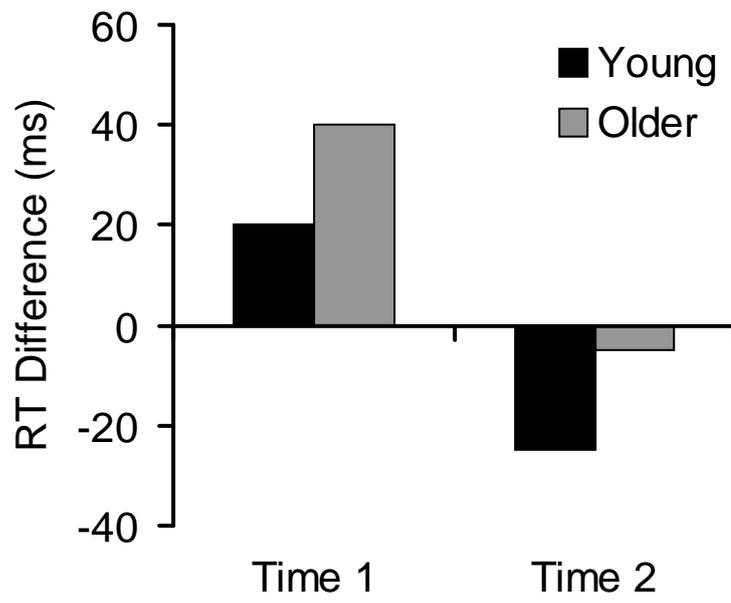
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Figure 1



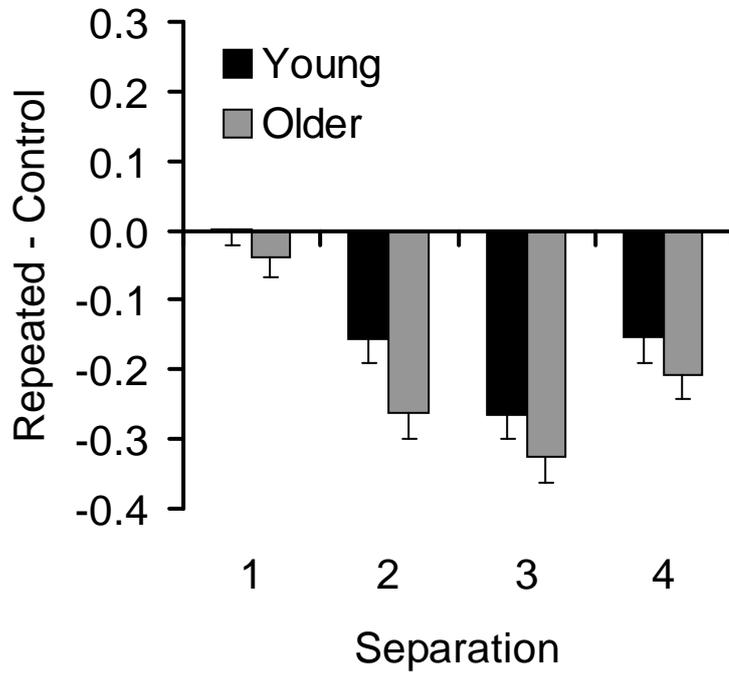
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Figure 2



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Figure 3



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Figure 4a

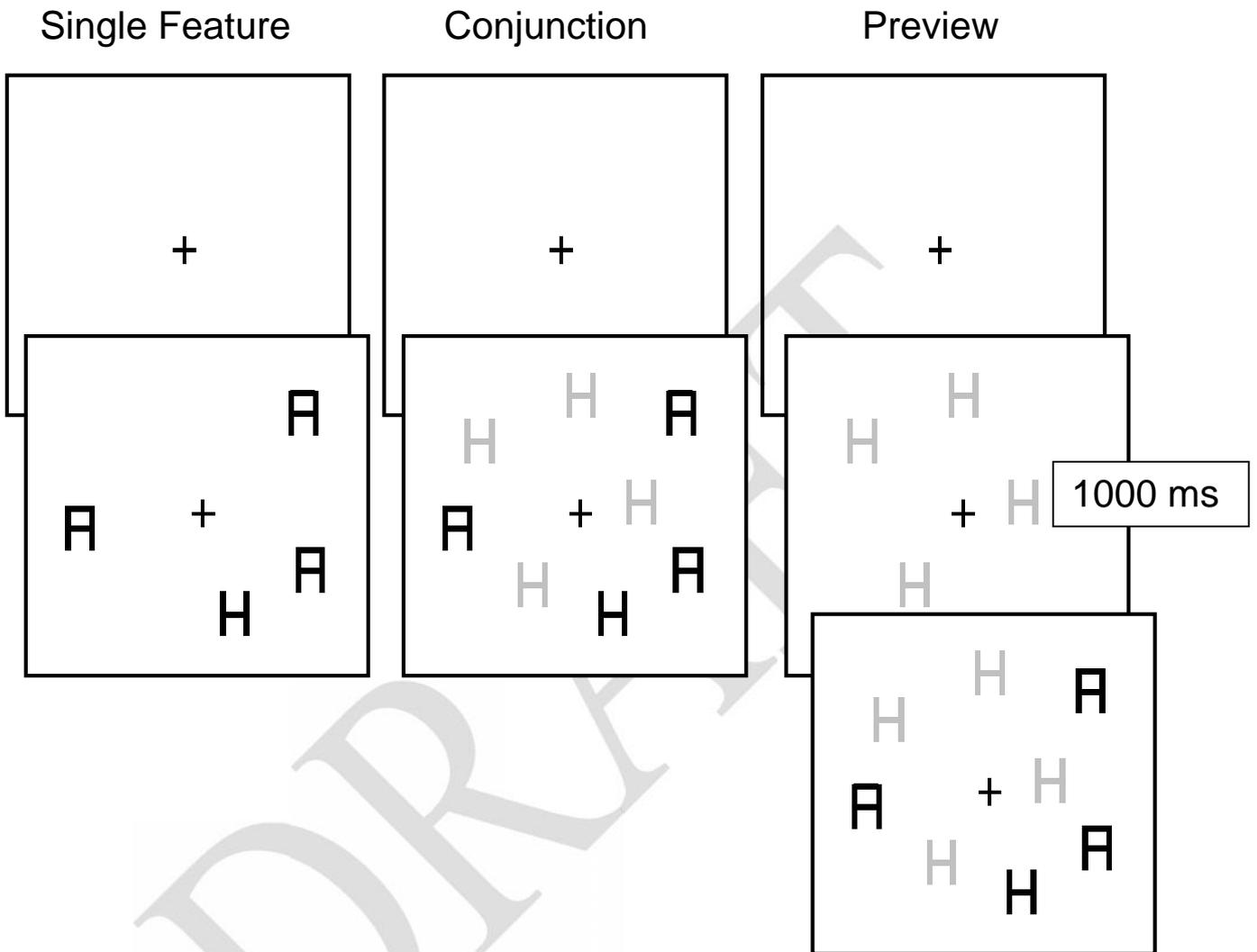


Figure 4b

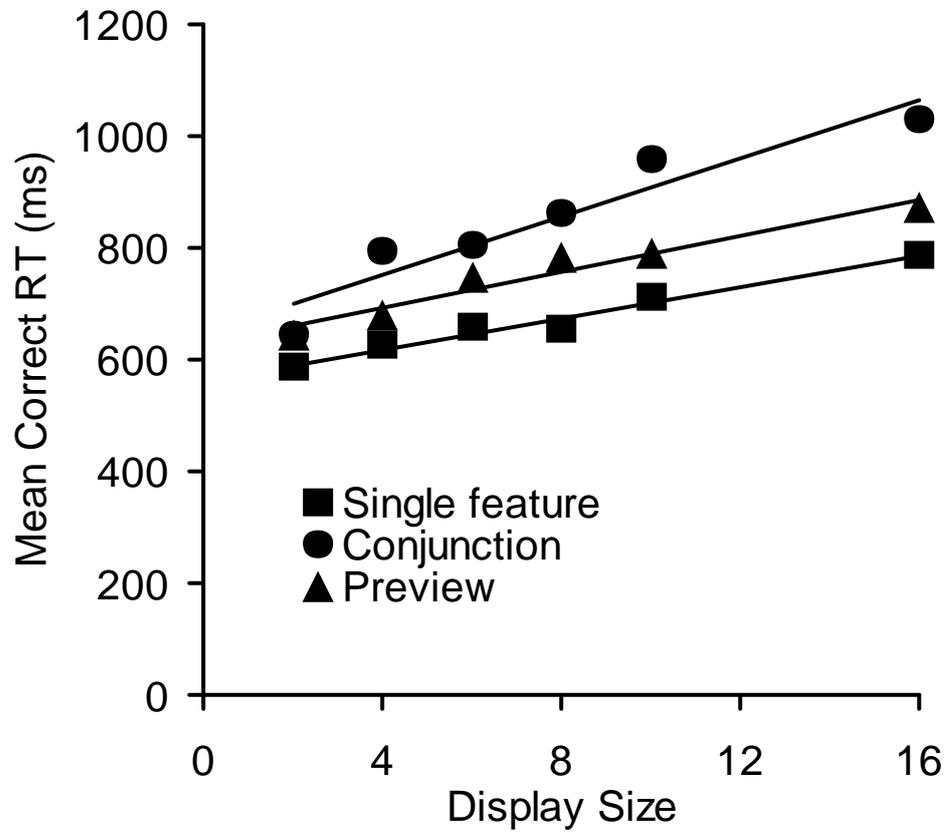


Figure 5

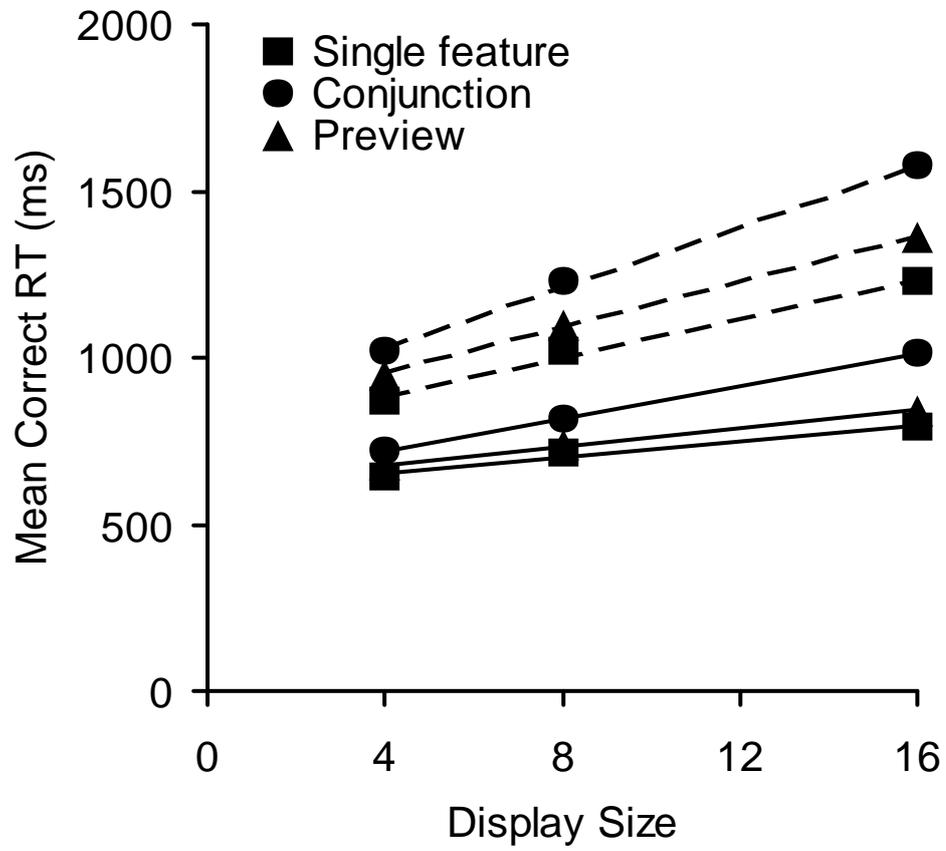


Figure 6a

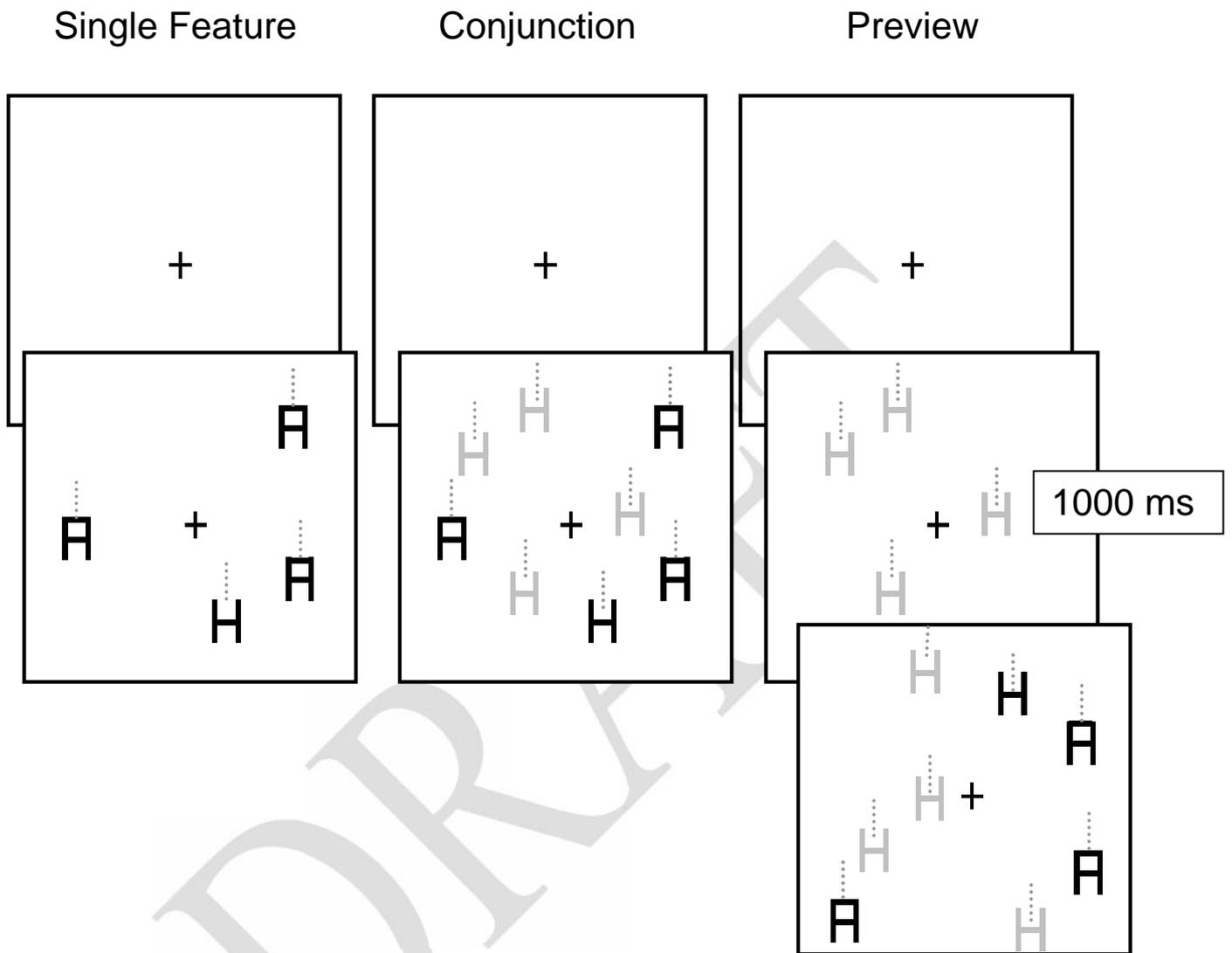


Figure 6b

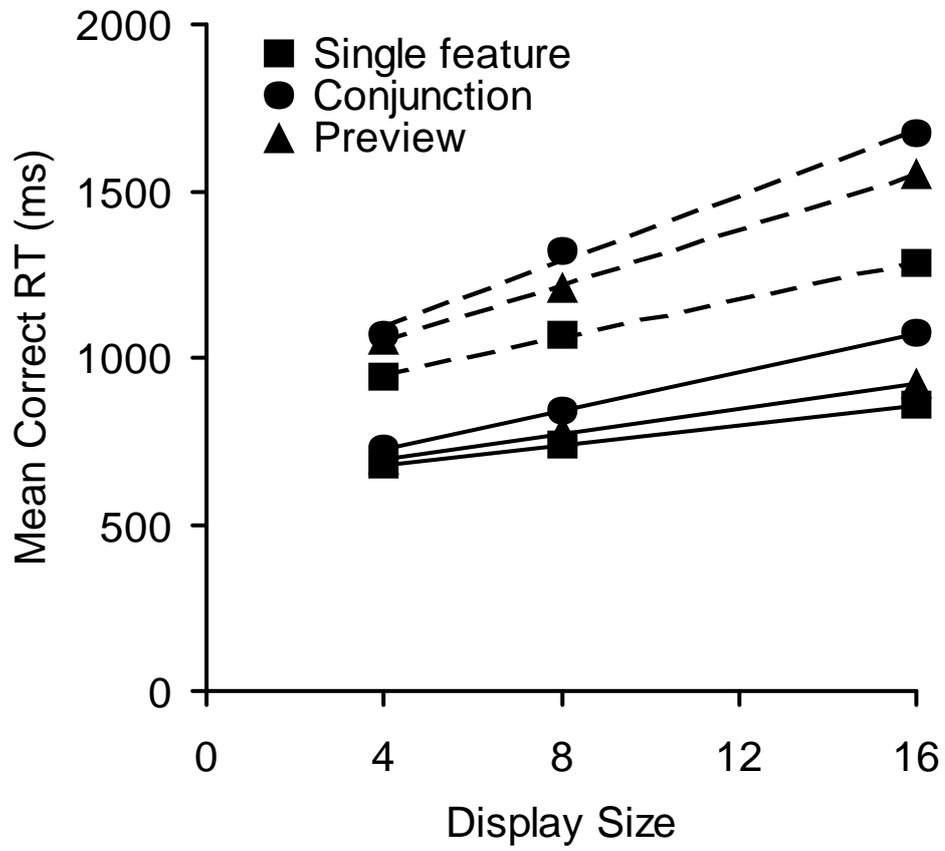


Figure 7a

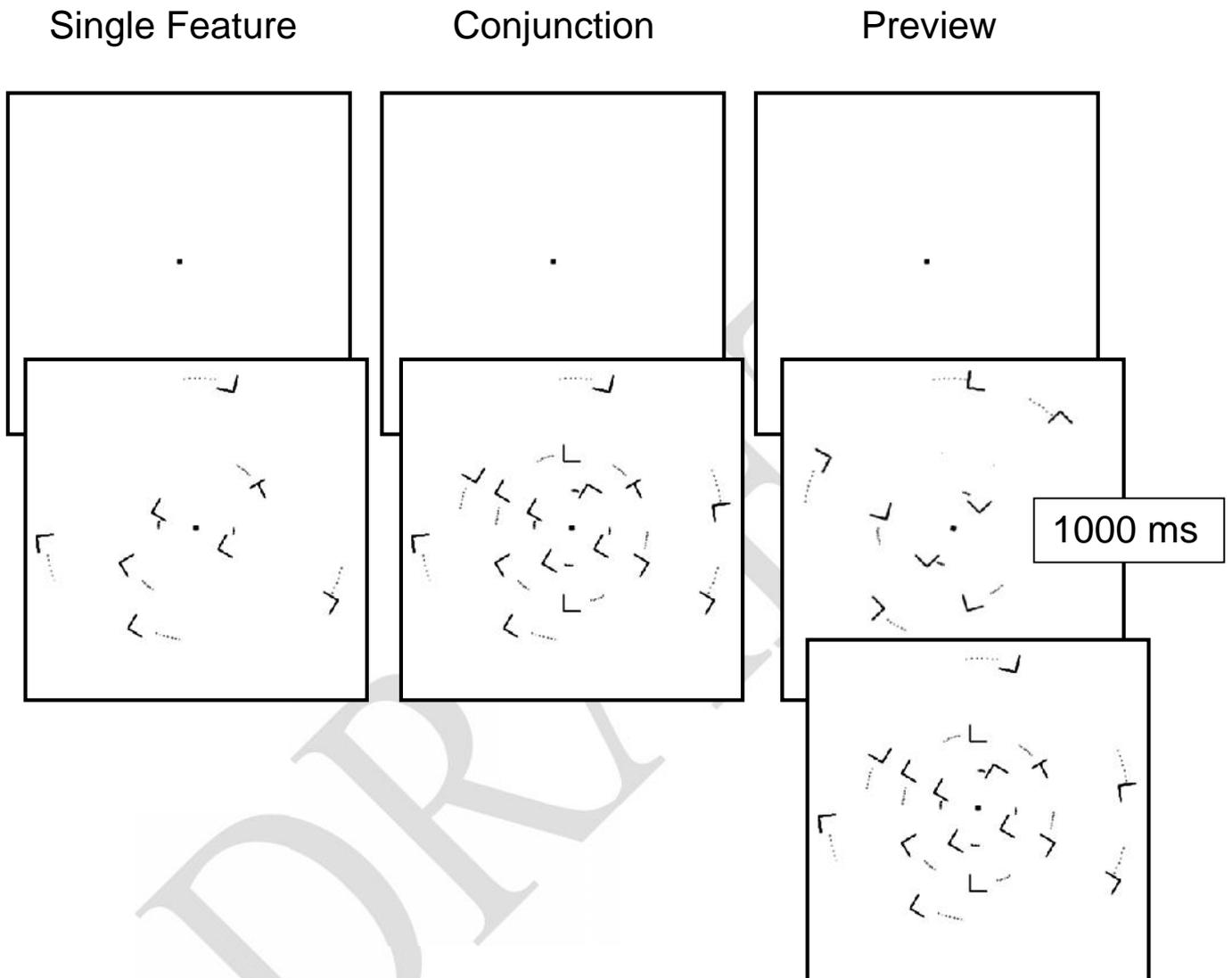


Figure 7b

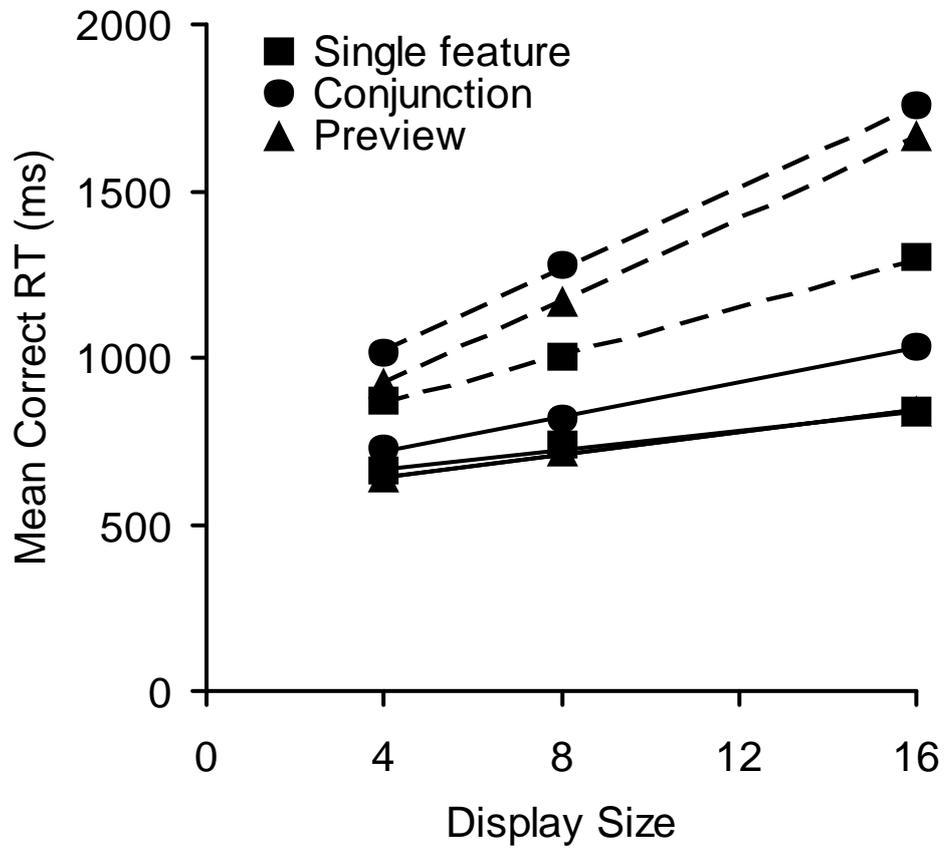
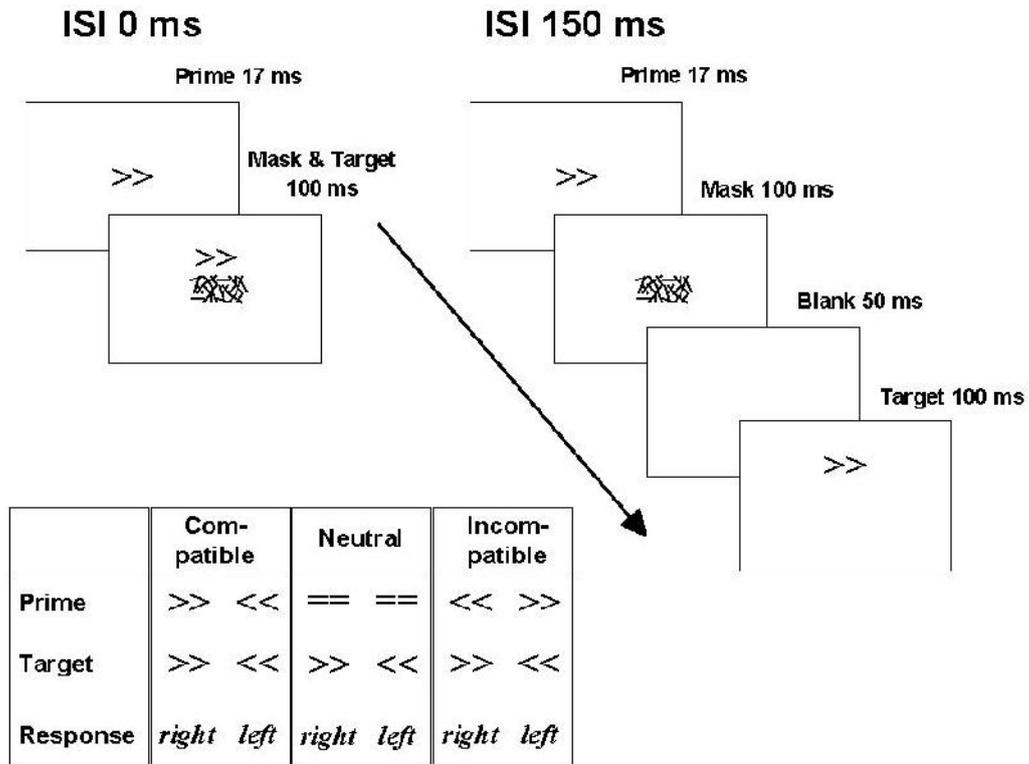


Figure 8a



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Figure 8b

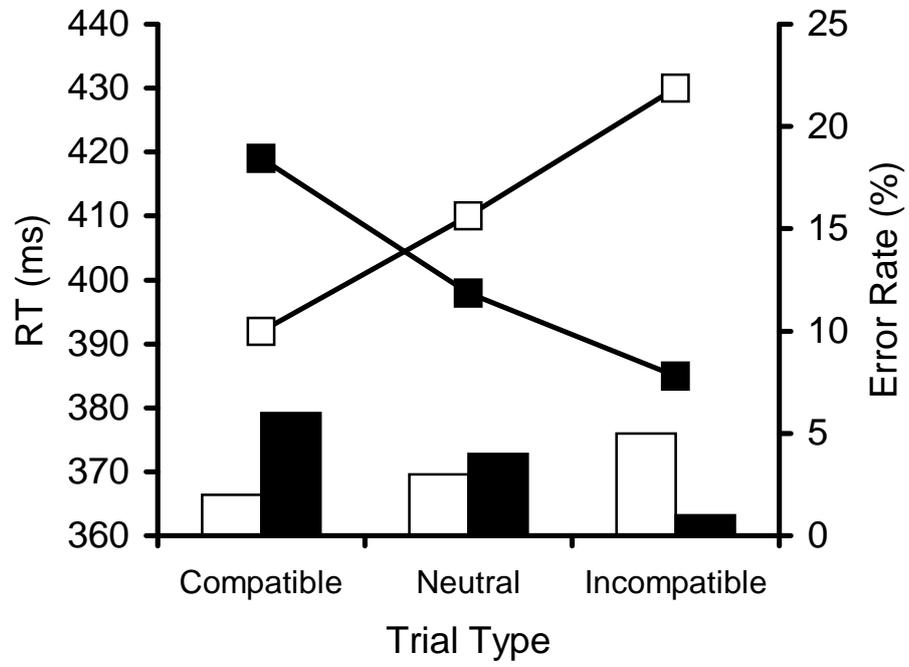
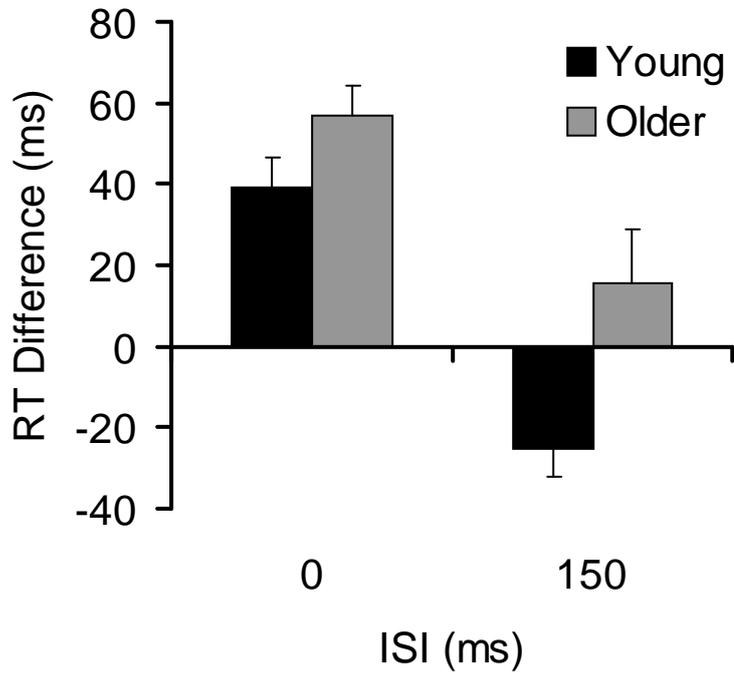
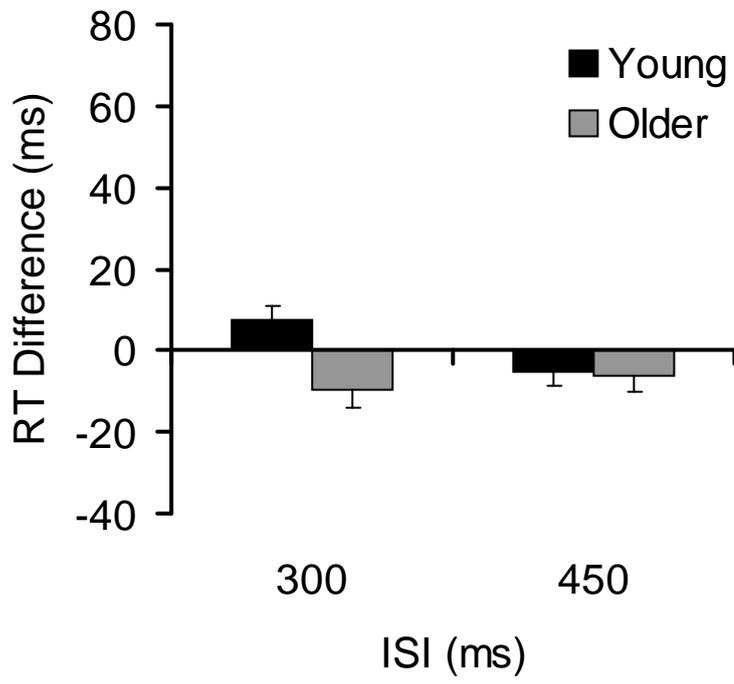


Figure 9a



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Figure 9b



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